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A Summary of Recent Literature (2007-2017) on Neurological Effects of Radiofrequency Radiation

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Introduction

Neurological effects are caused by changes in the nervous system. Factors that act directly or indirectly on the nervous system causing morphological, chemical, or electrical changes in the nervous system can lead to neurological effects. The final manifestation of these effects can be seen as psychological/behavioral changes, e.g., memory, learning, and perception. The nervous system is an electrical organ. Thus, it should not be surprising that exposure to electromagnetic fields could lead to neurological changes. Morphological, chemical, electrical, and behavioral changes have been reported in animals and cells after exposure to nonionizing electromagnetic fields (EMF) across a range of frequencies. The consequences of physiological changes in the nervous system are very difficult to assess. We don't quite understand how the nervous system functions and reacts to external perturbations. The highly flexible nervous system could easily compensate for external disturbances. On the other hand, the consequence of neural perturbation is also situation-dependent. For example, an EMF-induced change in brain electrical activity could lead to different consequences depending on whether a person is watching TV or driving a car.

The following is a summary of the research literature on the neurological effects of exposure to radiofrequency radiation (RFR), a part of the EMF spectrum that is used in wireless communications, published between 2007- 2017. The database came from survey of the Medline and understandably does not include all the relevant papers published during the period.

The Studies

There are many new studies on human subjects. Many of them are on changes in brain electrical activities after exposure to cell phone radiation. Bak et al (2010) (Global System for Mobile Communication (GSM) 935 MHz, 217 Hz pulses, 20 min, 0.0052 mW/cm^2) reported effects on event-related brain potentials. Maganioti et al. (2010) (900 MHz and 1800 MHz, 45 min) further reported that RFR affected the gender-specific components of event-related

potentials (see also Hountala et al., 2008). Croft et al (2008) (GSM 895 MHz, modulated at 217 Hz, 0.11 W/kg over 10 gm tissue, 30 min) reported changes of the alpha-wave power of electroencephalogram (EEG). They (Croft et al., 2010) further reported that effects differed between 2-G and 3-G cell phone transmission systems (2-G 894.6 MHz 217-Hz modulation, 0.7 W/kg over 10 gm tissue; 1900-MHz 3-G-modulated signal, 1.7 W/kg over 10 gm tissue; 55 min) on resting alpha activity in young adults. They observed effects after exposure to 2G but not 3G cell phone radiation, whereas Leung et al. (2011) (conditions similar to Croft et al. (2010)) found similar EEG effects (delayed ERD/ERS responses of the alpha power) with both 2G and 3G radiations. However, it is difficult to compare the 2-G and 3-G exposure conditions with different SAR and energy distributions. Ghosn et al. (2015) (GSM 900 MHz, peak specific absorption rate (SAR) 0.93 W/kg, 26 min) also reported GSM EMF affected alpha band of resting human EEG. Lustenberger et al. (2013) (900 MHz RFR pulsed with 500 msec bursts, spatial peak SAR 0.15 W/kg over 10 gm tissue) found increased slow-wave activity in humans during exposure to pulse-modulated RFR toward the end of the sleep period. Vecchio and associates reported that cell phone RFR affected EEG and the spread of neural synchronization conveyed by inter-hemispherical functional coupling of EEG rhythms (Vecchio et al., 2007) (GSM signal at 902.4 MHz, 8.33 and 217 Hz modulations, peak SAR 0.5 W/kg, 45 min) and modulated event-related desynchronization of alpha rhythms and enhanced human cortical neural efficiency (Vecchio et al., 2012a) (exposure conditions same as Vecchio et al., 2007). Naziroğlu and Gümral (2009) (2450 MHz pulsed at 217 Hz, 1.73 W/kg, 60 min/day for 28 days) reported a significant change in cortical EEG spikes in rats after chronic RFR exposure. RFR exposure modulated the spontaneous low frequency fluctuations in some brain regions (Lv et al., 2014a) (2573 MHz, spatial peak SAR 0.9 and 1.07 W/kg over 10 gm tissue, 30 min) and the synchronization patterns of EEG activation across the whole brain (Lv et al., 2014b) (exposure conditions similar to Lv et al., 2014a) in humans. An interesting finding is that RFR could interact with the activity of brain epileptic foci in epileptic patients (Tombini et al., 2013; Vecchio et al., 2012b). Roggeveen et al. (2015 a,b) (1929.1 to 1939.7 MHz, 0.69 W/kg, 15 min) reported significant changes in several bands of human EEG and detection of radiation peaks when exposed to the RFR from a 3G mobile phone. These effects were observed only when the phone was placed on the ear, and not on the heart. Yang et al. (2017) reported a reduction in spectral power in the alpha and beta bands in the frontal and temporal cortical regions of humans exposed to Long-Term Evolution (LTE) cell phone radiation. However, no significant effect on human EEG was reported by Perentos et al. (2007) (CW RFR 15 min, pulsed RFR 15 min) and Trunk et al. (2013) (1947-MHz 3G Universal Mobile Telecommunication System (UMTS), 1.75 W/kg 2 cm from surface of head model, 30 min), Trunk et al. (2014) (1947-MHz 3G UMTS signals, peak SAR 1.75 W/kg, 15 min)), and Kleinlogel et al. (2008 a, b) (1950 MHz UMTS (SAR 0.1 and 1 W/kg) and pulsed 900 MHz GSM (1 W/kg), ~30 min) also reported no significant effects on resting EEG and event-related potentials in humans after exposure to cell phone RFR. Furthermore, Krause et al. (2007) (902 MHz continuous-wave (CW) or pulsed at 217 Hz, pulse width 0.577 msec, averaged SAR 0.738 W/kg over 10 gm of tissue, peak 1.18W/kg) reported no significant effect of cell phone radiation on brain oscillatory activity, and Inomata-Terada et al. (2007) (800 MHz Time-Division Multiple Access (TDMA), 0.054 W/kg over 10 gm of tissue, 30 min) concluded that cell phone radiation does not affect the electrical activity of the motor cortex.

There are studies on the effects of cell phone radiation on EEG during sleep. Changes in sleep EEG have been reported by Hung et al. (2007) (GSM 900 MHz, SAR over 10 gm of tissue varied from < 0.001 – 0.133 W/kg depending the mode the cell phone was in, during sleep), Loughran et al. (2012) (894.6 MHz pulse-modulated at 217 Hz, peak spatial SAR 0.674 W/kg over 10 gm of tissue, 30 min prior to sleep), Lowden et al (2011) (GSM 884 MHz, spatial peak SAR 1.4W/kg, 3 hr prior to sleep), Regel et al. (2007) (pulse-modulated GSM 900 MHz signal, 0.2 or 5 W/kg, 30 min prior to sleep), and Schmid et al. (2012 a,b) (900 MHz modulated at 2 Hz, 2 W/kg). No significant effect was reported by Fritzer et al (2007) (GSM 900 with 2, 8, 217, 1733 Hz modulations, peak SAR within head 1 W/kg, during sleep), Mohler et al. (2010, 2012) (no details on exposure conditions), and Nakatani-Enomoto et al. (2013) (W-Code-Division Multiple Access (CDMA)-like signal, SAR over 10 gm tissue in the head and brain 1.52 and 0.13 W/kg, respectively, 3 hr). Loughran et al. (2012) provided an interesting conclusion in their paper: "These results confirm previous findings of mobile phone-like emissions affecting the EEG during non-rapid eye movement (REM) sleep. Importantly, this low-level effect was also shown to be sensitive to individual variability. Furthermore, this indicates that "previous negative results are not strong evidence for a lack of an effect…" More recently, Lustenberger et al. (2015) (900 MHz, 2 Hz pulse, peak spatial SAR 2 W/kg over 10 gm tissue, 30 min) reported pulsed-RFR-exposure-related increases in delta-theta EEG frequency range in several fronto-central brain areas in humans during non-REM sleep. Increase in REM sleep (Pelletier et al., 2013) (CW 900 MHz, 1 V/m, 0.0001 – 0.0003 W/kg, 5 weeks) and increases in duration and frequency of slow-wave sleep (Pelletier et al., 2014) (exposure conditions same as Pelletier et al., 2013) have been reported in developing rats after chronic RFR exposure. Mohammed et al. (2013) reported a disturbance in REM sleep EEG in the rat after long term exposure (1 hr/day for 1 month) to a 900-MHz modulated RFR.

Studies on the effects of RFR on the blood-brain barrier continued. Increase in blood-brain barrier permeability in animals after exposure to RFR was first reported in the 1970s. Such change could lead to entry of toxic substances into the brain. On the other hand, the possibility of using RFR to open up the blood-brain barrier to facilitate entry of therapeutic drugs into the brain has also be explored. In the last decade, the Salford group in Sweden continued to confirm their earlier findings on blood-brain barrier permeability and cell death in the brain (Eberhardt et al., 2008, Nittby et al., 2008a, 2009). Effects were observed after a single exposure (2 hr) to RFR at low SAR (0.00012-0.12 W/kg). In the meantime, there are several studies reporting effects of RFR on the blood-brain barrier. Sirav and Seyhan (2009, 2011) reported increased blood-brain barrier permeability in the rat after a 20-min exposure to continuous-wave 900 MHz and 1800 MHz RFR. The SARs in the 2011 study were 0.00426 W/kg for 900-MHz and 0.0014 W/kg for 1800 MHz. Interestingly, effect was observed only in male and not female rats. In a more recent study, Sirav and Seyhan (2016) studied the effects of pulse-modulated (217 Hz, 557 μs) 900-MHz and 1800-MHz RFR at 0.02 W/kg. They reported an increase in blood-brain barrier permeability in male rats after 20 min of exposure to either 900-MHz or 1800-MHz pulsed RFR, whereas an effect was found in female rats only after exposure

to the 900-MHz field. Tan et al. (2015) also reported an increase in blood-brain barrier permeability in rats after repeated exposure (14 or 28 days, 3 hr/day) to a 900 MHz field (brain SAR 2 W/kg). They suggested the involvement of the mkp-1/extracellular signal regulated kinase (ERK) for the effect. Wang LF et al. (2015), using an in vitro model, reported broadening of tight junctions in ECV304 cells and astrocytes. The authors implied the involvement of the vascular endothelial growth factor (VEGF)/Flk-1-ERK pathway in the effect. There is a related series of experiments on human subjects by Söderqvist et al. (2009 a,b,c). The authors reported a leakage of the blood-cerebrospinal fluid barrier and not the brain-brain barrier in subjects exposed to cell phone or cordless phone radiation. There are studies that reported no significant effect of RFR exposure on the blood-brain barrier. Kumlin et al. (2007) reported no neuronal cell death and significant change in the blood-brain barrier in juvenile rats after exposure to RFR (900 MHz, 0.3-3 W/kg, 2 hr/day, 5 days/week, 5 weeks). de Gannes et al. (2009) reported no significant effect on blood-brain barrier permeability and apoptosis of brain cells in rats after a 2hr-exposure to GSM 900 MHz at brain SAR of 0.14 and 20 W/kg. Finnie et al. (2009a,b) also reported no significant effects on the blood-brain barrier (based on expression of the water channel protein AQP-4 in the brain) in mice after exposure to RFR (900 MHz, 4 W/kg, 60 min or 60 min/day, 5 days/week for 104 weeks). More recently, Poulletier de Gannes et al. (2017) reported no significant changes in blood-brain barrier and neuronal degeneration in rats after a single (2 hr) or repeated (2 h/day, 5 days/week for 4 weeks) exposure to GSM-1800 and UMTS-1950 signals up to a brain-average SAR of 13 W/kg. However, an increase in albumin leakage was observed at 50 days after exposure in the brain of rats repeatedly exposed to both RF signals at 13 W/kg. Regarding "dark neurons" in the brain of rats exposed to RFR reported by Salford et al. (2003), which is apparently related to change in the blood-brain barrier. There are five reports showing an increase in dark neurons (Eberhardt et al., 2008; Kerimoğlu et al., 2016a; Köktürk et al., 2013; Jorge-Mora et al., 2013; Odaci et al., 2016), whereas de Gannes et al. (2009), Grafström et al. (2008), and Masuda et al. (2009) did not observe such an effect in the brain of RFR-exposed animals.

Related to the blood-brain barrier is a group of studies on astrocyte and microglia. These are cells in the blood-brain barrier that support the endothelial cells that form the barrier. Effects of RFR on these cells could conceivably affect the function of the blood-brain barrier. RFR-induced effects of astrocytes have been reported by Ammari et al. (2008a, 2010), Brillaud et al. (2007), Choi and Choi (2016), Liu et al. (2012), Lu et al. (2014), Maskey et al. (2010b, 2012), and Zhao et al. (2007), whereas no significant effect was reported by Bouji et al. (2012), Chen et al. (2014), Kumari et al. (2017) and Watilliaux et al. (2011). In studies on microglia, Hao et al. (2010), He et al. (2016), Lu et al. (2014) and Yang et al. (2010) reported effects of RFR exposure, whereas no significant effect was reported by Finnie et al. (2010), Hirose et al. (2010), and Watilliaux et al. (2011).

There are studies on the effects of cell phone radiation and the auditory system. Most research (Bhagat et al., 2016; Gupta et al., 2015; Kwon 2009, 2010a, b; Parazzini et al., 2009;

Stefanics et al., 2007, 2008) reported no effects, which seems to agree with the pre-2007 studies in this area. However, there are two reports by Kaprana et al. (2011) and Khullar et al (2013) showing effects on auditory brainstem response, two papers by Panda et al (2010, 2011) that concluded: "Long-term and intensive GSM and CDMA mobile phone use may cause damage to cochlea as well as the auditory cortex.", and a paper (Mandalà et al., 2014) reporting effect on auditory-evoked cochlear nerve response. Maskey and Kim (2014) reported a decrease in neurotrophins that are important in the regulation of neuron survival in the superior olivary complex, a neural component of the auditory system, in mice after chronic exposure to RFR. Velayutham et al. (2014) reported hearing loss in cell phone users and Sudan et al. (2013) observed weak associations between cell phone use and hearing loss in children at age 7. These effects may not be caused by the radiation. However, there is a study (Seckin et al., 2014) showing structural damage in the cochlea of the rat after prenatal exposure to RFR. And, Ozgur et al. (2015) reported neuronal degeneration in the cochlear nucleus of the auditory system in the rat after chronic exposure to RFR. Kwon et al. (2010a) reported that short-term exposure to cell phone radiation did not significantly affect the transmission of sensory stimuli from the cochlea to the midbrain along the auditory nerve and brainstem auditory pathways, and (Kwon et al., 2010b) no significant effect on auditory sensory memory in children. More recently, Çeliker et al. (2017) also reported no significant change in auditory brainstem responses, but increases in neuronal degeneration and apoptosis in the cochlear nucleus in rats exposed to a 2100-MHz field for 30 days.

There are several studies that showed neurological changes in humans after use of wireless devices, but those changes apparently were not caused by exposure to the radiation. Abramson et al. (2009) reported changes in cognitive functions in young adolescents. ("The accuracy of working memory was poorer, reaction time for a simple learning task shorter, associative learning response time shorter and accuracy poorer in children reporting more mobile phone voice calls"). Arns et al. (2007) observed more focused attention in frequent cell phone users, which was probably a "cognitive training effect". Yuan et al. (2011) reported morphological changes in the brain of adolescents with "internet addiction disorder".

There are several studies showing differential effects of different waveforms. This is an important consideration in understanding how EMF interacts with living organisms. Croft et al. (2010) reported that 2G, but not 3G, cell phone radiation affected resting EEG. Hung et al. (2007) showed that 2, 8, 217 Hz-modulated RFR differentially affected sleep. Lopez-Martin et al. (2009) reported that modulated and non-modulated RFR had different effects on gene expression in the brain. Nylund et al. (2010) found that different carrier-frequencies (900 MHz verses 1800 MHz) had different effects on protein expression. Schmid et al. (2012a) concluded that "modulation frequency components (of a RFR) within a physiological range may be sufficient to induce changes in sleep EEG". Mohammed et al. (2013) reported that EEG power spectrum during REM sleep is more susceptible to modulated RFR than the slow-wave sleep (SWS). Schneider and Stangassinger (2014) reported different effects of 900-MHz and 1.966-GHz EMFs on social memory functions in the rat. Zhang et al. (2008) reported that an intermittent exposure to RFR had a more potent effect on gene expression in the brain than continuous exposure. Apparently, extremely-low frequency (ELF)-modulation plays a role on

determining the biological effects of RFR. One can find many studies showing the same neurological effects of RFR described above in animals exposed to extremely-low frequency electromagnetic field (ELF EMF) e.g., Carrubba et al., 2007, 2010; Cook et al., 2009; Cui et al., 2012; Perentos et al., 2008. This is of considerable importance, since all cell phone signals are modulated by low frequency components. Furthermore, effects can also depend on the modulation frequency. Bawin et al. (1975) reported an increase in efflux of calcium ions from chick brain tissue after 20 min of exposure to a 147-MHz RFR (1 to 2 mW/cm^2). The effect occurred when the radiation was sinusoidally amplitude-modulated at 6, 9, 11, 16, or 20 Hz, but not at modulation frequencies of 0, 0.5, 3, 25, or 35 Hz. Blackman et al. (1979) also reported a "modulation-frequency window" in RFR-induced calcium ion efflux from brain tissue.

On the neurological effects of RFR, there are many papers published in the last decade indicating that oxidative stress played a role in the effects observed: Akbari et al., 2014; Bodera et al., 2015; Cetin et al., 2014; Dasdag et al., 2009, 2012; Del Vecchio et al., 2009a,b; Deshmukh et al., 2013a; Dragicevic et al., 2011; Eser et al., 2013; Gao et al., 2013; Ghazizadeh and Naziroglu, 2014; Hidisoglu et al., 2016; Hu S. et al., 2014; Hu et al., 2016; İkinci et al., 2016; Imge et al., 2010; Jing et al., 2012; Kerimoğlu et al., 2016a, b; Kesari et al., 2011; Kim JY et al., 2017; Liu et al., 2011; Maaroufi et al., 2014; Megha et al., 2012; Meral et al., 2007; Motawi et al., 2014; Narayanan et al., 2014; Nazıroğlu and Gümral, 2009; Nazıroğlu et al., 2012; Nirwane et al., 2016; Othman et al., 2017; Qin et al., 2014; Saikhedkar et al., 2014; Sharma et al., 2017; Shehu et al., 2016; Sokolovic et al., 2008; Varghese et al., 2017; Xu et al., 2010; Yang et al., 2010. (Dragicevic et al. (2011) reported a decrease in mitochondrial free radical production in the hippocampus and cerebral cortex of the mouse after RFR exposure.) There was one study (Poulletier de Gannes et al, 2011) that found no significant oxidative stress in brain cells after exposure to Enhanced Data rate for GSM Evolution (EDGE) signal. Kang et al (2014) reported that "neither combined RF radiation alone nor combined RF radiation with menadione or H_2O_2 influences the intracellular reactive oxygen species (ROS) level in neuronal cells." The mediating roles of cellular free radicals and oxidative status on the biological effects of EMF are worth looking into. Interestingly, there is a study (Cao et al., 2015) showing that RFR interacts with circadian rhythmicity on antioxidative processes in the rat.

An important issue that has been extensively debated in the media is whether children are more vulnerable to the effect of cell phone radiation than adults? The claim that children have thinner skulls and thus absorb more energy is not valid. And the claim that a child's head absorbs more energy from a cell phone is also debatable. It is quite possible that the pattern of energy distribution of cell phone energy absorption in the head is significantly different between a child and an adult (cf. Christ and Kuster, 2005; Christ et al. 2010; Gandhi et al. 2012). Scientific data on whether a child is biologically more vulnerable to cell phone radiation is sparse. There are several studies that indicate that animals (including humans) of different ages respond differently to cell phone radiation. Bouji et al. (2012) reported differences in neuro-immunity, stress, and behavioral responses to GSM signals between 'young adult' (6 weeks-old) and 'middle age' (12-month old) rats. Croft et al. (2010) showed that GSM signals affected certain electrical activities of the brain in young human adults (19-40 years old) but not in adolescents (13-15 years old) or elderly (55-70 years old) subjects. Leung et al. (2011)

reported that performance in a cognitive test was affected by GSM signal in adolescents but not in young or old human subjects. Noor et al. (2011) reported differences in neurochemical responses to 900-MHz RFR between adult and young rats. And, Vecchio et al. (2010) found differences in brain electric activities between young and elderly human subjects responding to GSM signals. It must be pointed out that although these studies reported an age-dependent effect of cell phone radiation, they do not necessarily imply that children are more vulnerable to cell phone radiation than adults. There are several papers showing effects of exposure to RFR during perinatal periods on the development and functions of the nervous system (Aldad et al., 2012; Bas et al., 2013; Cetin et al., 2014; Daniels et al. 2009; Divan et al., 2008, 2011, 2012; Erdem Koç et al., 2016; Gao et al., 2013; Haghani et al., 2013; İkinci et al., 2013; Jing et al., 2012; Kokturk et al., 2013; Lee and Yang, 2014; Odaci et al., 2008, 2013, 2016; Othman et al., 2017; Ragbetli e al., 2010; Razavinasab et al., 2016; Zareen et a., 2009; Zhang et al., 2015). These studies point to the vulnerability of the development nervous system to RFR. The cerebellum seems to be a structure especially vulnerable to the exposure (Eser et al. 2013; Haghani et al., 2013; Kokturk et al., 2013; Odaci et al., 2016; Ragbetli e al., 2010). Chen et al. (2014) reported that exposure to an1800-MHz RFR impaired neurite outgrowth of embryonic neural stem cells, which play a critical role in brain development. More recently, Xu et al. (2017) reported that effect of exposure to an 1800-MHz field on stem and progenitor cell proliferation in the hippocampus of mouse depended on the age of the animal. Stem cells play an important role in embryonic development. And, it turns out that they are very sensitive to electric current, particularly in their migration in the body during organogenesis. It has been suggested that electric current can be used as a guidance of migration of stem cells for the treatment of neurodegenerative diseases (Feng et al., 2017). On the other hand, disturbance of stem cells by induced electric currents of electromagnetic fields can cause defects in pre- and postnatal development. This can occur at low intensities of the field. Indeed, there are reports on effects of extremely-low frequency (ELF) magnetic and electric fields on stem cells (Bai et al., 2013; Choi et al., 2014; Cho et al., 2012; Kim et al., 2013; Takahashi et al., 2017). ELF EMF is more effective in generating induced electric currents.

With these physiological changes in the brain, what behavioral effects have been reported? Data are summarized in the tables below.

Table 1. Behavioral Effects of Radiofrequency Radiation

Human studies that showed behavioral effects:

	Behavior studied/Results	**Experimental conditions**
Danker-Hopfe et al. (2015)	Sleep of individuals affected differently- showing both improvements and deteriorations.	GSM 900 MHz and Wideband Code Division Multiple Access (WCDMA)/UMTS, during sleep
de Tommaso et al. (2009)	Reduction in behavioral	GSM 900 MHz, 10 min

	arousal	
Deniz et al. (2017)	Poorer attention in high exposure group	Low (<30 min/day) vs high (>90 min/day) cell phone radiation exposure
Hung et al. (2007)	Sleep latency	GSM 900 MHz with 2, 8, or 217-Hz modulations, 30 min
Leung et al. (2011)	Cognitive functions	2G and 3G cell phone radiation, 10 min
Luria et al. (2009)	Spatial working memory (In a subsequent study (Hareuveny et al., 2011), the authors indicated that some of the effects observed may not be related to RFR exposure.)	GSM phone, 60 min
Lustenberger et al. (2013)	Sleep-dependent motor-task performance improvement	0.25-0.8 Hz pulsed 900 MHz RFR, all-night
Mortazavi et al. (2012)	Decreased reaction time	Cell phone radiation, 10 min
Mortazavi et al. (2013)	Decreased reaction time; poorer short-term memory performance	Occupational exposure to military radar radiation
Movvahedi et al. (2014)	Better short-term memory in elementary school students	Cell phone radiation, 10 min
Redmayne et al. (2013)	Well-being	Use of cellphone and cordless phone
Regel et al. (2007)	Cognitive functions	pulse-modulated GSM 900 MHz signal, 0.2 or 5 W/kg, 30 min
Schoeni et al. (2015)	A change in memory performance	Based on cumulative duration of wireless phone use and RF-EMF dose over one year (GSM and UMTS)
Thomas et al. (2010)	Overall behavioral problems in adolescents	RFR measured by a personal dosimeter over 24 hr
Vecchio et al. (2012a)	Better performance in a	GSM signal at 902.4 MHz, 8.33

	cognitive- motor test	and 217 Hz modulations, peak SAR 0.5 W/kg, 45 min
Vecchio et al. (2012b)	Enhanced cognitive-motor processes in epileptic patients	GSM phone radiation, 45 min
Vecsei et al. (2013)	Decreased thermal pain perception	UMTS phone-like radiation, 1.75 W/kg, 30 min
Wiholm et al. (2009)	'Virtual' spatial navigation task	884 MHz, peak head SAR 1.4 W/kg, 150 min
Yogesh et al. (2014)	Sleep disturbance, latency and day dysfunction especially in females	> 2 hr/day of mobile phone use
Zheng et al. (2014)	Inattention in adolescents	Use of cell phone >60 min per day

Human studies that showed no significant behavioral effects:

	Behavior studied	**Experimental conditions**
Calvente et al. (2016)	No definite conclusion can be drawn on cognitive and behavioral functions of 10-year old boys	Environmental RFR 100 kHz to 6 GHz; root mean square 0.286 mW/cm^2; maximum power density 2.76 mW/cm^2
Cinel et al. (2007)	Order threshold task	GSM or unmodulated carrier frequency wave to head, 40 min
Cinel et al. (2008)	Subjective symptoms	GSM or unmodulated carrier frequency wave to head, 40 min
Curcio et al. (2008)	Reaction time task, sequential figure tapping task	GSM (902.4 MHz, 217 Hz modulation, 0.5 W/kg), 3 x 15 min
Curcio et al. (2009)	objective and subjective vigilance	GSM (902.4 MHz, 8.33 Hz and 217-Hz modulation, 0.5 W/kg), 40 min
Curcio et al. (2012)	Somatosensory task	GSM (902.4 MHz, 8.33 Hz and 217-Hz modulation, 0.5

		W/kg), 40 min
Danker-Hopfe et al. (2011)	Effect on sleep	GSM 900 or WCDMA/UMTS, during sleep
Eltiti et al. (2009)	Cognitive functions	GSM 900 or UMTS, 0.001 mW/cm^2, 50 min
Fritzer et al. (2007)	Sleep and cognitive functions	GSM900 with 2, 8, 217, 1733 Hz modulations, peak SAR within head 1 W/kg, during sleep
Haarala et al. (2007)	Cognitive functions	902 MHz, continuous-wave or pulsed (27 Hz, 0.577 ms), head peak SAR 1.18 W/kg, 90 min
Irlenbusch et al. (2007)	Visual discrimination threshold	GSM 902.4 MHz 217 Hz pulses, 0.1 mW/cm^2, 30 min
Kleinlogel et al. (2008a)	Well being	1950 MHz UMTS (0.1 and 1 W/kg) or 900 MHz GSM (1 W/kg), 30 min
Kleinlogel et al. (2008b)	Continuous performance test measuring reaction time and false reaction	1950 MHz UMTS (0.1 and 1 W/kg) or 900 MHz GSM (1 W/kg), exposed during measurements
Krause et al. (2007)	Auditory memory task	902 MHz CW or pulsed at 217 Hz, pulse width 0.577 msec, averaged SAR 0.738 W/kg over 10 gm tissue, peak 1.18 W/kg
Kwon et al. (2010b)	Auditory sensory memory in children	GSM 902 MHz pulsed at 217 Hz, temporal lobe peak SAR 1.21 W/kg, average 0.82 W/kg over 10 gm tissue
Loughran et al. (2013)	Cognitive effects and EEG in 11-13 years old adolescences	Modulated GSM900 (peak SAR 1.4 W/kg or 0.35 W/kg), 30-60 min
Malek et al. (2015)	Cognitive functions in	Pulse-modulated GSM (945 MHZ and 1840 MHz, 28

	sensitive humans	mW/cm^2) and UMTS (2140 MHz, 38 mW/cm^2), 1 V/m, whole body exposure, Short-term
Mohler et al. (2010, 2012)	Effect on sleep	Environmental far-field RFR and cell and cordless phone radiation
Nakatani-Enomoto et al. (2013)	Effect on sleep	W-CDMA, 3 hr
Redmayne et al. (2016)	Cognitive functions in 8-11 years old children	Use of cellular and cordless phone
Riddervold et al. (2008)	Trail making B test	2140 MHz continuous-wave and 2140 MHz modulated as UMTS, 45 min
Roser et al. (2016)	No change behavioral problem and concentration capacity	Self-reported and operator-recorded wireless communication device use
Sauter et al. (2011)	Cognitive functions	GSM900 and WCDMA, 7 hr 15 min in two episodes
Sauter et al. (2015)	Cognitive functions and well-being	Terrestrial Trunked Radio (TETRA) (385 MHz) signals, 2.5 hr
Schmid et al. (2012a)	Cognitive functions	900 MHz pulse modulated at 14 and 217 Hz, peak spatial SAR 2 W/kg, 30 min
Schmid et al. (2012b)	Cognitive functions	900 MHz pulse modulated at 2 Hz, 2 W/kg, 30 min
Trunk et al. (2013)	Automatic deviance detection processes	1947-MHz 3G UMTS, 1.75 W/kg 2 cm from surface of head model, 30 min
Trunk et al. (2014)	Reaction time to a stimulus	1947-MHz 3G UMTS signals, peak SAR 1.75 W/kg, 15 min
Trunk et al. (2015)	Reaction time to a visual target detection task	1947-MHz UMTS signals, peak SAR 1.75 W/kg, 15 min

Unterlechner et al. (2008)	attention	UMTS signals, peak SAR 0.63 W/kg at cortex of temporal lobe, 90 min
Wallace et al. (2012)	Cognitive functions	420 MHz TETRA, 0.001 mW/cm^2, 10- 50 min, whole body exposure

Animal studies that showed behavioral effects:

	Behavior studied/results	**Experimental conditions**
Aldad et al. (2012)	Hyperactive, impaired memory (mouse)	800 and 1900 MHz cell phone radiation, gestation days 1-17 (24 hr/day), tested at 8, 12, and 16 weeks old
Arendash et al. (2010, 2012)	Improved cognitive behavior in mouse model of Alzheimer’s disease	918 MHz pulse modulated at 217 Hz, 0.25-1.05 W/kg, 2-6 months or 12 days, 2 hr/day
Banaceur et al. (2013)	Improved cognitive functions in mouse model of Alzheimer’s disease	2409 MHz, 1.6 W/kg, 2 hr/day for a month
Barthélémy et al. (2016)	Memory, emotionality, and locomotion in plus maze and open field (rat)	900 MHz modulated at 217 MHz, 15 min (1.5 or 6 W/kg) or 45 min (6 W/kg)
Bouji et al. (2012)	Contextual emotional behavior deficit (rat) (age-depended effect observed)	900 MHz, 6 W/kg, 15 min
Cammaerts et al. (2012)	Olfactory and/or visual memory deficit in ants	GSM900 MHz (GSMK modulated), 0.77 V/m, in several periods 1.5-6 days
Cammaerts et al. (2013)	Deterioration of food collection behavior in ants	GSM900 MHz (GSMK modulated), 0.77 V/m, 180 hr
Cammaerts et al. (2014)	Changes in locomotor and general behaviors in ants	940 MHz pulse-modulated 577 μs width, 0.5-1.5 V/m, 10 min exposure before

		behavioral observation
Choi and Choi (2016)	Delayed hyperactivity-like behavior (mouse)	Smart phone, 10 min/day, 9-11 weeks
Daniels et al. (2009)	Decreased motor activity and increased grooming (rat)	840 MHz, 6 x 10^{-6} mW/cm^2, pups exposed 3hr/day from postnatal day 2 to day14, tested at postnatal day 58
Deshmukh et al. (2013a)	Impaired cognitive functions (plus maze and water maze) (rat)	900 MHz, 8.47 x 10^{-5} W/kg, 2 hr/day, 30 days
Deshmukh et al. (2015)	Impaired cognitive functions (plus maze and water maze) (rat)	900 MHz (5.953 x 10^{-4} W/kg), 1800 MHz (5.835 x 10^{-4} W/kg), 2450 MHz (6.672 x 10^{-4} W/kg), 2 hr/day, 180 days
Deshmukh et al. (2016)	Impaired cognitive functions (plus maze and water maze) (rat)	900 MHz (5.953 x 10^{-4} W/kg), 1800 MHz (5.835 x 10^{-4} W/kg), 2450 MHz (6.672 x 10^{-4} W/kg), 2 hr/day, 90 days
Favre (2011)	Induced piping behavior in honeybee workers	Cell phone put close to bee hive
Fragopoulou et al. (2010)	Spatial memory deficit (mouse)	GSM 900 MHz, 0.41-0.98 W/kg, 2 hr/day, 4 days
Hao et al. (2013)	Learning and memory deficit (rat)	916 MHz, 1 mW/cm^2, 6 hr/day, 5 days/week, 10 weeks
Hassanshahi et al. (2017)	Impaired object recognition (rat)	2400 MHz, 12 hr/day, 30 days
Hu et al. (2014)	Spatial memory deficit (rat)	High power microwave, 30 mW/cm^2, average brain SAR 21 W/kg, 15 min/day, 14 days
İkinci et al. (2013)	Learning and memory deficit (rat)	900 MHz, 13^{th} to 21^{st} day of pregnancy, 1 hr/day, offspring tested at 26 days old

Júnior et al. (2014)	Observed stress behavioral patterns (rat)	GSM 180 MHz, 2 V/m, 25 sec every 2 min for 3 days
Kim JH et al. (2017a)	Hyperactivity-like behavior (mouse)	835 MHz, 4 W/kg, 5 hr/day for 12 weeks
Kumar et al. (2009)	Hypoactivity, anxiety behavior (rat)	GSM 900 MHz and 1800 MHz, 50 missed call/day, 4 weeks
Kumari et al. (2017)	Spatial learning deficit and impairment of memory measured by passive avoidance test (mouse)	7.5 KHz magnetic field, 12 or 120 μT, 5 weeks
Kumlin et al. (2007)	Improved spatial learning and memory (rat)	90 MHz, 0.3 or 3 W/kg, 2 hr/day, 5 days/week, 5 weeks
Lee et al. (2015)	Locomotor activity after feeding (fish Poecilia reticulata and Danio rerio)	RFR from an 1800 MHz cell phone
Li et al. (2015)	Spatial learning and memory deficits (rat)	2.856 MHz 5, 10, 20, or 30 mW/cm^2, 6 min 3 times a week up to 6 weeks
Li et al. (2012)	Spatial learning and memory deficits (rat)	GSM 900 phone, 2 hr/day for 1 month, 0.52-1.08 W/kg
Lu et al. (2012)	Spatial memory deficit (rat)	2450 MHz pulsed, 1 mW/cm^2, 3 hr/day, 30 days
Maaroufi et al. (2014)	Spatial learning and memory deficit (rat)	900 MHz, 0.05-0.18 W/cm^2, 1 hr/day, 21 days
Mathur (2008)	Analgesic effect (rat)	73.5 MHz, amplitude-modulated at 16 Hz, 0.4 W/kg, 2 hr/day, 45 days
Megha et al. (2012)	Cognitive functions (plus maze and water maze) (rat)	900 MHz (5.953 x 10^{-4} W/kg) or 1800 MHz (5.845 x 10^{-4} W/kg), 2 hr/day, 30 days
Mohammed et al. (2013)	Increased latency of REM sleep (rat)	900 MHz continuous-wave, 900 MHz modulated at 8 and 16 Hz, spatial peak SAR 0.245

		W/kg, 1 hr/day for 1 month
Narayanan et al. (2009)	Spatial learning and memory deficit (rat)	GSM 900/1800 MHz, 50 missed call/day, 4 weeks
Narayanan et al. (2010)	Passive avoidance deficit (rat)	GSM 900/1800 MHz, 50 missed call/day, 4 weeks
Narayanan et al. (2013)	Elevated plus maze-emotionality test deficit (rat)	GSM 900 MHz phone, peak power density 0.1466 mW/cm^2, 1 hr/day for 28 days
Narayanan et al. (2015)	Spatial memory deficit (rat)	GSH 90 MHz phone, peak power density 0.1466 mW/cm^2, 1.15 W/kg, 1 hr/day for 28 days
Nirwane et al. (2016)	Change in social behavior, anxiety behavior, learning impairment (zebrafish)	GSM 900 MHz phone, 1.34 W/kg, 1 hr/day for 14 days
Nittby et al. (2008b)	Reduced memory functions (rat)	GSM 900 MHz, 0.0006 and 0.06 W/kg, 2 hr/week, 55 weeks
Ntzouni et al. (2011)	Non-spatial memory deficit (mouse)	GSM 1800-MHz phone, 022 W/kg, 90 min/day, 17 days
Ntzouni et al. (2013)	Spatial and non-spatial memory deficit (mouse)	GSM 1800-MHz phone, 011 W/kg, 90 min/day, 66-148 days
Odacı et al. (2013)	Motor function (rat)	900 MHz, 10 V/m, exposed 1 hr/day from day 13 to day 21 of pregnancy, offspring tested at 21 days of age
Othman et al. (2017)	Anxiety and deficits in neuromotor maturation mainly in male offspring (rat)	2450 MHz, 2 hr/day from conception to parturition, offspring tested at 28, 30 and 31 days of age
Pelletier et al. (2013)	Food intake increase; changes in sleep parameters; increased food intake (rat)	900 MHz, 1 V/m, 0.3-0.1 W/kg depending on age, 23.5 hr/day, 5 weeks

Pelletier et al. (2014)	Preferred to sleep in a different temperature environment than controls; sleep parameters (rat)	900 MHz, 1 V/m, 0.3-0.1 W/kg depending on age, 23.5 hr/day, 5 weeks
Qiao et al. (2014)	Spatial memory deficit (rat)	2856 MHz, 30 mW/cm^2, 14 W/kg, 5 min
Qin et al. (2014)	Learning and memory deficits (mouse)	1800 MHz, 0.208 mW/cm^2, 2 hr/day, 30 days
Razavinasab et al. (2016)	Passive avoidance and spatial learning and memory deficits (rat)	900 MHz pulsed RFR, 0.3-0.9 W/kg, 6hr/day from conception to birth, tested at 30 days of age
Saikhedkar et al. (2014)	Learning and memory deficits (rat)	900 MHz phone, 0.9 W/kg, 4 hr/day, 15 days
Sarapultseva et al. (2014)	Motor activity (protozoa Spirostomum ambiguum)	1000 MHz 0r 10,000 MHz, 0.005-0.05 mW/cm^2, 0.05-10 hr
Schneider and Stangassinger (2014)	Social memory effect (rat)	GSM 900 MHz and UMTS 1966 MHz, 0.4 Wkg, up to 6 months
Sharma et al. (2014)	Spatial learning memory deficit (mouse)	10,000 MHz, 0.25 mW/cm^2, 0.179 W/kg, 2 hr/day, 30 days
Sharma et al. (2017)	Spatial learning and memory deficit (mouse)	10,000 MHz, 0.25 mW/cm^2, 0.179 W/kg, 2 hr/day, 15 days
Shehu et al. (2016)	Anxiety-like behavior (rat)	GSM 900/1800 phones, 10 min call per day for 4 weeks
Sokolovic et al. (2012)	Anxiety-related behavior (rat)	GSM900 phone, 9.88-13.356 V/m, 0.43-0.135 W/kg, 4 hr/day for 20, 40, 60 days
Tang et al. (2015)	Spatial long-term memory deficit (rat)	900 MHz, 1 mW/cm^2, 0.016 W/kg, 3 hr/day for 14-28 days

Vácha et al. (2009)	Magnetoreception disruption (cockroach)	Onset of disruption: 1.2 MHz 12-18 nT; 2.4 MHz 18-44 nT
Varghese et al. (2017)	Learning and memory deficits and expression of anxiety behavior (rat)	2450 MHz, 4 hr/day for 45 days; at power density of 0.778 mW/cm^2, calculated power absorption in the body = 0.04728 W
Wang H. et al. (2013)	Spatial memory deficit (rat)	Pulsed 2856 MHz RFR, 5, 10, and 50 mW/cm^2, 6 min
Wang H. et al. (2015)	Spatial learning and memory deficits (rat)	Pulsed 2856 MHz RFR, 50 mW/cm^2, 6 min
Wang H. et al. (2017)	Spatial learning and memory deficits (rat)	2856 MHz (1.75, 3.5, or 7 W/kg), 6 min/day, 5 days/week, 6 weeks
Wang K. et al. (2017)	Increased recognition memory (mouse)	1800 MHz, >2.2 W/kg, 30 min
Wang LF et al. (2016)	Spatial memory impairment (rat)	GSM 1800 MHz, 30 mW/cm^2, 5 min/day, 5 days /week, 2 months
Zhang et al. (2015)	Increased anxiety-related behavior; spatial memory and learning deficits in male offspring (mouse)	9417 MHz, 200 V/m, 2 W/kg, 12 hr/day on gestation days 3.5-18, offspring tested at 5 weeks of age
Zhang et al. (2017)	Increased anxiety-related behavior (mouse)	1800 MHz, 6 hr/day for 28 days, whole body and brain SAR at 2.7 W/kg and 2.2 W/kg, respectively

Animal studies that showed no significant behavioral effects:

	Behavior studied	**Experimental conditions**
Ammari et al. (2008c)	spatial memory (rat)	GSM900, brain SRR 1.5 W/kg 45 min/day or 6 W/kg 15

		min/day, 8 or 24 weeks
Fasseas et al. (2015)	Chemotaxis, short-term memory (Caenorhabditis elegans)	GSM 1800 MHz (15.4 V/m), WiFi router (9.7 V/m), Digital Enhanced Cordless Telecommunication (DECT) phone (11.3 V/m); various lengths of time (30 min to 24 hr)
Haghani et al. (2013)	Motor function (rat)	Pulsed 900MHz RFR, SAR 0.5-0.9 W/kg; 6 hr/day during gestation period
Klose et al. (2014)	Learning skills and motor behavior (rat)	GSM-modulated 900 MHz RFR, head only exposure 2 hr/day, 5 days/week from 14 days to 19 months old, 0.7, 2.5 or 10 W/kg
Shirai et al. (2014)	Spatial memory and motor function on F_1, F_2, and F_3 offspring (rat)	2140 MHz WCDMA 20 hr/day from gestation Day 7 to weaning with dam, and offspring alone to 6 weeks old, 3-generations; 0.067-0.14 for a fetus, 0.12-0.36 W/kg for offspring before weaning, 0.12-0.24 W/kg for offspring after weaning
Salunke et al. (2015)	Anxiety, obsessive compulsive disorder (OCD) and depression-like behavior (mouse)	Bluetooth device, 2450 MHz, 60 min/day for 7, 30, 60, 90, or 120 days
Son et al. (2016)	Spatial and non-spatial memory functions (mouse)	1950 MHz; 2 h/day, 5 days/ week, 3 months; 5 W/kg

A majority of the animal studies reported effects, whereas more human studies reported no significant effects than effects. This may be caused by several possible factors: (a) Humans are less susceptible to RFR than are animals. (b) It may be more difficult to do human than animal experiments, since it is, in general, easier to control the variables and confounding factors in an animal experiment. (c) In the animal studies, the cumulative exposure duration was generally longer and studies were carried out after exposure, whereas in the human studies, the exposure was generally one time and testing was measurements were carried out

mostly during exposure. This raises the question of whether the effects of RFR are cumulative. This consideration could have very important implication on real life human exposure to EMF. However, it must be pointed out that neurophysiological and behavioral changes have been reported in both animals and humans after acute (one time) exposure to RFR, and most of the human EEG studies mentioned above are acute exposure experiments. (d) Most of the human studies are head exposure experiments whereas most of the animal studies involved whole body exposure. Could this have made a difference? Does it mean that effects of RFR on other parts of the body can also affect the nervous system? (e) The nervous system has the capability to adapt to perturbations. Physiological changes in the nervous system do not always manifest as behavioral effects, e.g., see Haghani et al. (2013) (changes in electrophysiology of cerebellar Purkinje cells after RFR exposure without behavioral effect in rats) and Schmid et al. (2012a) (RFR exposure induced EEG change but did not affect cognitive test performance in human subjects). May be the human brain has higher capability to tolerate and adapt to perturbations than other animals. (f) In the animal studies, the effects studies were mostly learning and memory functions. The hippocampus in the brain, particularly the cholinergic system, plays a major role in learning and memory functions. Various studies indicated that RFR affected electrical activities/morphology/chemistry of the hippocampus in animals (Aboul Ezz et al., 2013; Ammari et al., 2008 a, b; 2010; Barcal and Vozeh, 2007; Barthélémy et al., 2016; Baş et al., 2009, 2013; Carballo-Quintas et al., 2011; Choi and Choi, 2016; Erdem Koç et al., 2016;Fragopoulous et al., 2012; Gevrek, 2017; Gökçek-Saraç et al., 2017; Hao et al., 2013; Hassanshahi et al., 2017; Hu et al., 2014; İkinci et al., 2013; Kerimoğlu et al., 2016b; Kesari et al., 2011; Kim JH et al., 2017b; Kim JY et al., 2017; Kumari et al., 2017; Li et al., 2014; Lopez-Martin et al., 2009; Li et al., 2012; Lu et al., 2012; Maskey et al., 2010 a,b, 2012; Megha et al., 2015; Mugunthan et a., 2016; Narayanan et al., 2010, 2014, 2015; Ning et al., 2007; Nittby et al., 2008a; Odaci et al., 2008; Razavinasab et al., 2016; Şahin et al., 2015; Saikhedkar et al., 2014; Sharma et al., 2017; Tang et al., 2015; Tong et al., 2013; Wang H. et al., 2013, 2015, 2017; Wang K. et al., 2017; Wang LF et al., 2016; Xiong et al. 2015; Xu et al., 2017; Yang et al., 2012; Zhang et al., 2017). As early as 1987, we (Lai et al., 1987) have reported that RFR affected the cholinergic system in the hippocampus of the rat leading to spatial learning and memory deficits. Interestingly, the effect of RFR on the hippocampus apparently involves a sequence of neurological responses in the brain, including activation of endogenous opioids and release of the stress hormone corticotropin releasing factor (Lai, 1994). Thus, it is not surprising that 'learning and memory' functions are affected in the rodents by RFR since in most of the studies, the Morris water-maze was used to study learning and memory functions. The water-maze measures spatial memory, a function specifically involves the hippocampus. In the human studies listed above, the most common effect studied was cognitive functions. Since the exposure in most of these human studies was localized in the brain, particularly in the temporal cortical area, it is questionable whether the psychological tests used were appropriate.

Discussion

1. A major concern is that in some of the studies details of the exposure setup and dosimetry are not provided. This is important, since details of the independent variables

are very important in interpreting the validity of the experimental results, i.e., dependent variables. In many of these studies, a cell phone was used in the exposure of animals and humans. But information on how the cell phone was activated, in many instances, was not provided. Thus, the amount of energy deposited in the body was not known. Some studies used the phone in 'stand-by' mode. Mild et al. (2012) reported that when a stationary cell phone is on 'stand-by' mode, it actually infrequently emits a very small amount of energy. It is very surprising that in all papers on the effects of RFR on EEG mentioned at the beginning of this paper, only two provided significant information on the exposure parameters. This is alarming. It may indicate that the researchers did not understand the properties of the entity that they were studying. It is good that competent researchers from other disciplines are contributing to the advancement of bioelectromagnetics. But, I sincerely think that EMF researchers should get themselves acquainted with the physics of nonionizing electromagnetic fields.

2. Most of the studies were carried out with relatively high levels of RFR compared to environmental level. However, if you look through the narrative about, there are studied that reported effects at very low level, e.g., Bak et al, 2010. Indeed, biological/health effects of RFR at levels much lower than most international RFR-exposure guidelines, e.g., the International Commission on Non-ionizing Radiation Protection (ICNIRP), have been reported (see Table 1 in Levitt and Lai, 2010). This raises the question on whether the guidelines used in most countries nowadays are actually obsolete and new exposure guidelines have to be set.
3. Thus, there is ample evidence that RFR exposure affects the nervous system from both acute and long-term exposure experiments. Brain electric activities, nerve cell functions and chemistry and behavior can be affected. Some explanatory mechanisms for these effects have emerged. One consistent finding is that animals exposed RFR suffered from memory and learning deficits. These effects can be explained by the results of numerous reports that showed RFR affected the hippocampus, a brain region involved in memory and learning. However, the location and configuration of the human hippocampus are quite different from those of a rodent. There has not been much studies on the effect of RFR on the human hippocampus. Several studies did reported deficit in memory in human subjects exposed to RFR, particularly on short-term memory, a function specifically related to the hippocampus. One recent study (Deniz et al., 2017) showed that chronic cell phone use did not significantly affect the volume of the hippocampus in human subjects. But, the subjects showed poorer attention which is probably not related to the hippocampus. An interesting fact is that learning and memory deficits have also been reported in insects that do not have a hippocampus. Another related aspect is that several papers (Adrendash et al., 2010, 2012; Banaceur et al., 2013; Dragicevic et al., 2011) have indicated that RFR exposure could reverse some of the

defects in an animal model of Alzheimer's disease, a neurological disorder involved degeneration of cholinergic innervations in the hippocampus. Interestingly, similar claim has been reported (Hu et al., 2016) with exposure to extremely-low frequency magnetic field.

4. Another very consistent finding is that RFR affects free radical metabolism in the brain. This may explain some of the cellular and physiological effects of RFR on the nervous system. As a matter of fact, oxidative changes in cells and tissues after exposure to RFR is a very common phenomenon (cf. Yakymenko et al., 2016). This happened in many organs of the body and can provide explanation on many reported biological effects of RFR.
5. Many of the effects of RFR on the nervous system, e.g., on the hippocampus, oxidative effect, and behavioral effects, are also observed with exposure to extremely-low frequency electromagnetic field (cf. my section on the neurological effects of ELF EMF in the Bioinitiative Report, www.bioinitiative.info/bioInitiativeReport2012.pdf). There has been speculation whether biological effects observed with low-frequency modulated-RFR were actually caused by the modulation. There are two reports published in the last decade that seemed to refute this hypothesis. Perentos et al. (2013) reported in human EEG "…a suppression of the global alpha band activity was observed under the pulsed modulated RF exposure, and this did not differ from the continuous RF exposure. No effect was seen in the extremely low frequency condition." This means that pulsing is not essential for the effect observed. Schmid et al. (2012b) compared the effects of a 2-Hz modulated 900-MHz field with a 2-Hz magnetic field on human sleep EEG. Both fields affect sleep EEG but not identically. The authors concluded that "the study does not support the hypothesis that effects of radiofrequency exposure are based on demodulation of the signal only." However, in another study, Schmid et al (2012a) concluded in a study on sleep EEG that "…that modulation frequency components within a physiological range may be sufficient to induce these effects." In our earlier studies (e.g., Lai and Singh, 1995), we found that continuous-wave and pulsed RFR produced different effects. Indeed, different effects produced by continuous-wave and modulated RFR with the same frequency, exposure conditions, and SAR is a strong indication of the existence of "nonthermal" effects. Another question is whether one type of modulation is different from another in causing biological effects. Cell phone advances from one generation to another. Do the research data of 3G phone apply to 4G or 5G phone radiation? RFR is a complex entity. Its biological effects depend on many of its physical properties, e.g., frequency, direction of the incident waves relative to the object exposed, dielectric properties and size and shape of the exposed object, polarization of the waves, etc. Thus, it is unlikely that one can easily extrapolate the effects from one form of RFR to another. An assumption that 3G radiation is safe does

not necessary imply that 5G radiation is safe. Each one of them has to be investigated separately.

6. An important area of research is on how RFR in the environment affects humans and wildlife. Environmental RFR level has become higher and higher over the past decades due to the employment of RFR-wireless devices. Take the example of Bak et al. (2010) mentioned above, effect on human event-related brain potential was reported after 20 min of exposure to a GSM signal at a power density of 0.0052 mW/cm^2. This is very close to the levels found in some cities. The highest power density of ambient RFR measured near schools and Hospitals in Chandigarh, India was reported to be 0.001148 mW/cm^2 in 2012 (Dhami, 2012). The maximum total RFR power density emitted by FM and TV broadcasting stations and mobile phone base stations in centers of the major cities in the West Bank-Palestine was 0.00386 mW/cm^2 (Lahham and Hammash, 2012). One also has to take into consideration that exposure in the Bak et al. (2010) study was acute (20 min), whereas environmental exposure is chronic. Related to the neurological effect is the magnetic-sense possessed by many species of animals. It is essential for their survival. Interference by RFR of magnetic compass orientation in animals has been reported (e.g., Landler et al., 2015; Malkemper et al., 2015; Pakhomov et al., 2017; Schwarze et al., 2016; Vácha et al., 2009). Understanding the effects could help in preserving the ecosystem and ensure survival of the species on this earth.

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