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Review

The link between radiofrequencies emitted from wireless technologies and oxidative stress

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ABSTRACT

Wireless communication such as cellular telephones and other types of handheld phones working with frequencies of 900 MHz, 1800 MHz, 2100 MHz, 2450 MHz have been increasing rapidly. Therefore, public opinion concern about the potential human health hazards of short and long-term effect of exposure to radiofrequency (RF) radiation. Oxidative stress is a biochemical condition, which is defined by the imbalance between reactive oxygen species (ROS) and the anti-oxidative defense. In this review, we evaluated available in vitro and in vivo studies carried out on the relation between RF emitted from mobile phones and oxidative stress. The results of the studies we reviewed here indicated that mobile phones and similar equipment or radars can be thought as a factor, which cause oxidative stress. Even some of them claimed that oxidative stress originated from radiofrequencies can be resulted with DNA damage. For this reason one of the points to think on is relation between mobile phones and oxidative stress. However, more performance is necessary especially on human exposure studies.

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1. Introduction

Radiofrequency radiation (RFR) exposure emitted from wireless technologies such as cellular and cordless DECT phones, Wi-Fi, Radio and Television broadcasting stations etc. affect people in all social levels in all countries (Fragopoulou et al., 2012). Therefore, electromagnetic pollution originated from the equipment, which is almost indispensable for modern daily life is candidate to be one of major and popular health problem of future. After cellular/mobile phones became one of the fastest-growing technological developments of our daily life, a serious concern was occurred by public opinion on the possible health risks of EMF exposure emitted from wireless technologies such as mobile phones, internet communication etc. Although availability of previous occupational RFR exposure studies performed several decades ago, EMF health risk is still one of emerging research area. To clarify the issue more

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performances are necessary (Ahlbom et al., 2004). It is similarly reported that this sensitivity has led to extensive research on the electromagnetic field (EMF) health risks of wireless technologies at the cellular, lab animal and epidemiological level (Fragopoulou et al., 2012).

On the other hand, widespread use of wireless technologies such as Wireless Fidelity (Wi-Fi) communication devices has also rapidly increased over the past several years. Nowadays, it is very easy to reach access points or Wireless Local Area Networks (WLAN) in houses, workplaces, public areas, schools, etc. Rapid development of wireless technologies has increased the environmental electromagnetic field (EMF) levels while providing big comfort in our daily life. Even relatively new EMF sources like wireless headphones, wireless printer and hard discs, etc. took place in the workplaces and houses. Therefore, public and scientific awareness that was previously pointed out on the adverse health effects of EMF emitted from cellular phones has been steadily focusing on biological hazards of wireless equipment such as Wi-Fi etc. Because of the health hazards of the equipment are still unclear. The Council of Europe is advising some limitations for using cellular phones and access to the Internet in all schools to protect young children from harmful risks of EMF (Watson, 2011).

These relatively new sources of RF radiation are also raising public concern regarding the health effects of wireless Internet providers. Presumably, most popular users of these systems are children and young population. Therefore, people must be careful when exposed RFs emitted from the wireless equipment until sufficient data are available. Although availability of numerous studies on the harmful effects of RFR emitted from cellular phones, the studies on health concerns of Wi-Fi are completely insufficient.

2. Recent status of mobile/wireless technologies

The International Telecommunication Union (ITU) stated that number of Internet user will be almost 3 billion and number of mobile-broadband subscriptions will reach 2.3 billion globally at the end of 2014. They also reported that number of fixed telephone decreased during the past five years. According to their records, number of fixed telephone subscriptions will be 100 million fewer by the end of 2014 when compared to 2009. Whereas, ITU (2014) also stated that number of mobile phone subscription will be about 7 billion at the end of 2014 (ITU, 2014). It is obvious from the report of the ITU that level of radiofrequencies in the world will be rise quickly day by day and therefore more attention should be paid to this environmental problem, which is called as "Electromagnetic Pollution".

3. Some perspectives on bio-effects of radiofrequencies

The authors stated that "RFR can be harmful for genes; may alter cardiac and brain functions, circadian rhythms, healing, hormone balance; impair short term memory, concentration, learning and behavior; agitate aberrant immune, allergic and inflammatory responses; produce stress proteins and increase reproductive risks" (Bioinitiative Report, 2012).

Brain was believed to be the most affected organ simply because head is exposed to radiofrequencies (RF) due to mobile phone usage. Therefore, at the beginning, studies mainly focused on the relation between RF emitted from mobile phones and its adverse health effects especially brain tumors (Dasdag et al., 2008a, 2009, 2012; Hardel et al., 1999). Afterwards, studies on mobile phone exposure focused on other organs especially on reproductive organs (Celik et al., 2012; Nisbet et al., 2012) The results of these studies in this field are still contradictive (Agarwal et al., 2011; Akdag et al., 1999; Dasdag et al., 1999, 2003; Lee et al., 2012). Parallel to mobile phone studies, recently studies have been undertaken to focus on health hazards of other wireless technologies such as Wi-Fi, which also emits RF (Avendano et al., 2012; Atasoy et al., 2013; Saygin et al., 2011). It is obvious that RF emitted from Wi-Fi equipment affect entire body. Therefore, it is difficult to estimate sensitive organs during Wi-Fi exposure because of the whole body exposure. Thus, large scale and long duration studies are necessary to answer this question. As it is evident from other radiation types, some of the radiosensitive organs are brain, thyroid and reproductive organs etc. However, one of the main mechanisms lying under biohazard of ionizing and non-ionizing radiation may probably be oxidative stress which largely results from free radical formation.

4. Free radicals

"Free radicals are produced during the various metabolic activities carried out inside the body and also produced when the body exposed to some environmental agents such as ionizing and non-ionizing radiation, heavy metals, emotional stress, alcohol consumption, cigarette smoking, automobile exhaust etc. This type of radicals reacts with biomolecules including DNA that cause mutagenesis, carcinogenesis and aging. In other words, energy of free radicals is insufficient and therefore they are like a robber, which attack and snatch energy from other cells to satisfy themselves. ROS production is probably both useful to perform a duty developing inter and intracellular signals and harmful to modify biomolecules such as DNA, resulted or associated with numerous diseases. For instance the highly reactive hydroxyl radical ($^{\bullet}OH$) causes damage to DNA and other biological molecules. The free radicals especially $^{\bullet}OH$ can be cause a large number of modifications in DNA such as sugar and base modifications, strand breaks and DNA–protein cross-links. However, oxidative DNA damage can be repaired by the cellular repair systems" (Dizdaroglu et al., 2002; Evans et al., 2004)

Riley stated that "the most important electron acceptor in the biosphere is molecular oxygen, which is ready to accept unpaired electrons to increase the reactive oxygen species (ROS) that is potentially highly damaging to cells. ROS may interact with DNA leading to serious consequences for the cell. Oxygen ($O^{\bullet -2}$), hydroxyl ($^{\bullet}OH$), hydrogen peroxide (H_2O_2), alkoxyl ($^{\bullet}RO$) and peroxyl ($^{\bullet}ROO$) radicals are very known species to initiate and propagate free radical chain reactions. The authors also reported that although some ROS perform useful functions excessive ROS production can cause cellular damage which may give rise to certain diseases. They additionally stated that radiation is perhaps the major contributor for ROS production and $^{\bullet}OH$ which randomly attacks neighbor molecules is one of the significant radiation-induced free-radical" (Riley, 1994). Cooke et al. reported that "endogenous ROS is produced during regular cell metabolism and therefore it is normally nonpathogenic processes" (Cooke et al., 2003; Dizdaroglu, 2012). They especially noted that "oxidative mechanisms have a potential role in the initiation, promotion, and malignant conversion stages of carcinogenesis and protein oxidation may play a significant role damaging biomolecules other than DNA in the pathogenesis of neurodegenerative disease such as Alzheimer". It is recently reported that "free radicals are formed by external factors such as ionizing radiations, UV radiation, redoxcycling drugs and carcinogenic compounds" (Evans et al., 2004; Dizdaroglu, 2012). By the way, the species may lead to extensive lipid, protein and DNA damage in the case of failure to clear ROS (Jajte et al., 2002), whereas there are some antioxidant mechanisms such as SOD, CAT etc. to protect tissues. It is noted that "SOD is the first step of defense mechanism against ROS and catalyzes the dismutation of the superoxide anion into hydrogen peroxide. Following, H_2O_2 can be converted into H_2O and O_2 by CAT. On the other hand, weakness of antioxidant defense can

increase plasma lipid peroxidation (LPO) (Sarban et al., 2005). It is reported that malondialdehyde (MDA) and myeloperoxidase (MPO) are also oxidative stress markers, which involved in the pathogenesis of several diseases" (Dasdag et al., 2012; Campo et al., 2004).

5. In vitro studies related to the effects of radiofrequencies on oxidative stress

In vitro studies carried out on relation between radiofrequencies and oxidative stress is considered limited when compared to in vivo studies. We evaluated fourteen studies performed in this area. Agarwal et al. (2009) investigated role of RF emitted from cellular phone on unprocessed (neat) ejaculated human semen. The semen of each subject in the study group was exposed to RF emitted from the phone, which was in talk mode for 1 h. They found that mobile phone exposure decreased sperm motility, viability, ROS-TAC score and increased ROS level. Campisi et al. (2010) investigated acute effects of 900 MHz RF for different exposure periods (5, 10, or 20 min) on primary rat neocortical astroglial cell cultures and indicated the importance of the amplitude modulation and observed that only 20 min exposure of RF increased ROS and DNA fragmentation. Furthermore, they claimed that the "effects could be due to hyperstimulation of the glutamate receptors, which play a crucial role in acute and chronic brain damage". De Iuliis et al. (2009) have researched in vitro effect of 1800 MHz RF on ROS production and DNA damage in human spermatozoa. They exposed the spermatozoa to 1.8 GHz RF with SAR from 0.4 W/kg to 27.5 W/kg. They found that "RF reduced motility and vitality of and elevated mitochondrial ROS generation and DNA fragmentation depend on SAR increasing. Therefore, they stated that there is a significant relationship between SAR level and their findings". Luukkonen et al. (2009) investigated chemically induced ROS generation and DNA damage in human SH-SY5Y neuroblastoma cells exposed to 872 MHz RFR with 5 W/kg SAR. They reported that "RF radiation might enhance chemically induced ROS production and thus cause secondary DNA damage. They also studied combined effects of RF radiation with same frequency and ferrous chloride on DNA and ROS generation in the same cells and were not reported any effect on ROS, DNA damage and cell viability" (Luukkonen et al., 2010). Xu et al. (2010) studied effects of 1800 MHz with 2 W/kg SAR on oxidative stress in primary cultured neurons. They indicated that "1.8 GHz RFR caused oxidative damage in DNA and stated that RF radiation may be responsible from the neurotoxicity of the brain". Yao et al. (2008) investigated acute effect of 1.8 GHz RF exposure (1–4 W/kg) on cultured human lens epithelial cells. They concluded that "DNA damage induced by 1.8 GHz RF for 2 h, which was mainly single strand breaks, may be associated with the increased ROS production". Del Vecchio et al. (2009) studied the effect of 900 MHz RF exposure (with 1 W/kg SAR) on in vitro models of neurodegenerative disease and reported that "GSM modulated RFR act as a co-stressor for oxidative damage of neural cells under particular circumstances". Zmyslony et al. (2004) studied effect of 930 MHz RF continuous wave with 5 mW/cm^2 and 1.5 W/kg SAR on ROS level and found that 5 and 15 min acute RFR do not alter ROS generation. Gajski and Garaj-Vrhovac (2009) investigated the radioprotective effect of bee venom against DNA damage induced by 30 min exposure of 915-MHz RFR with 0.6 W/kg SAR. They stated that "oxidative stress can cause DNA damage in Wistar Rat lymphocytes and bee venom from Apis mellifera is radioprotective for the damage". Kahya et al. (2014) concluded that "1 h of 900 MHz RF exposure with 0.36 ± 0.02 W/kg SAR appears to induce apoptosis through oxidative stress and mitochondrial depolarization in spite of selenium treatment". Kang et al. (2014) investigated the effects of the combined 837 MHz CDMA plus 1950 MHz WCDMA RFR on ROS in neuronal cells and indicated that "neither combined RF radiation alone nor combined RF radiation with menadione or H_2O_2 influences the intracellular ROS level". Ni et al. (2013) concluded that "oxidative stress is present in HLE B3 cells exposed to 1.8 GHz low-intensity RF and that the increased production of ROS may be related to down-regulation of four antioxidant enzyme genes induced by RF exposure". Simon et al. (2013) investigated acute effect of 900 MHz RFR (2 mW g^{-1}) on human melanocytes and keratinocytes and reported that "RFR does not induce a detectable cellular stress but rather a subtle transient alteration of the epidermal differentiation which might affect, if repeated, the protective capacity of the skin against external factors". A summary of the studies discussed here can be found in Table 1.

6. In vivo studies related to the effects of radiofrequencies on oxidative stress: the studies performed on the effects of 900 MHz RFs

According to records, numbers of in vivo studies are greater than in vitro studies. Most of present studies were performed on the effects of 900 MHz RF exposure. However, frequency, SAR values and exposure setup of the studies discussed in this review are different. One of the points that should be noted in these studies differences of presented exposure values. For instance, some of the studies used power density instead of specific absorption rate (SAR). By the way, some of the authors did not present any of irradiation unit in the studies. As it is known, in the studies performed on RF biological effect, SAR is very important parameter to evaluate the results. Although the studies published in the journals indexed by Web of Science data on the exposure parameters has big deficiencies. We believe that the reason of this bad or frivolous approach is completely depend on the selected reviewers who have not competent of this field. Therefore, editors of the journals need to show more attention when they selected referees. For this reason, it is difficult to compare the studies completely under standard data. This should be noted that the idea we discuss here is cover some part of the studies. Whatever, a summary of the results of the in vivo studies carried out on the relation between RF and oxidative stress given in Table 2.

7. The studies performed on the effects of 1800 MHz RFs

As it is seen in Table 3, eight studies carried out on relation between 1800 MHz RF and oxidative stress. All of the studies indicated that 1800 MHz RFs increased the oxidative stress and DNA alteration (Avci et al., 2012; Tomruk et al., 2010; Koyu et al., 2005; Ozgur et al., 2010, 2013; Liu et al., 2013; Guler et al., 2010). Only one of the studies has contradiction between its results and conclusion investigated combine effects of RF and tramadol, which is a centrally-acting synthetic opioid analgesic drug (Bodera et al., 2013).

8. The studies performed on the effects of RFs in different frequencies

In this part, we are going to review eight studies investigated the effects of 900 MHz, 1800 MHz together or the studies tested effects of other frequencies such as 2100 MHz, 2450 MHz and 50 GHz. One of the studies indicated no changes in lipid and protein oxidation, and also in non-enzymatic defense in frontal cortex or hippocampus of rat exposed to 800 and 1800 MHz (Ferreira et al., 2006). Similarly, Dogan et al. (2012) showed that "usage of short-term 3G mobile phones with 2100 MHz frequency does not alter oxidative stress in rat brain". On the other hand, Mailankot et al. (2009) reported that "RF exposure resulted in a significant increase in lipid peroxidation (increased endogenous

Table 1
A summary of some in vitro studies on the oxidative effects of mobile phone exposure.

Author	RF frequency	SAR (W/kg)	Results
Agarwal et al. (2009, 2011)	900 MHz		RF emitted from mobile phones may lead oxidative stress in human semen. Keeping the cell phone in a trouser pocket in talk mode may negatively affect spermatozoa and impair male fertility.
Campisi et al. (2010)	900 MHz		RF radiation induces ROS production and DNA fragmentation in astrocytes in primary cultures
De Iuliis et al. (2009)	1800 MHz	0.4–27.5	In step with increasing SAR, motility and vitality were significantly reduced after RF exposure, while the mitochondrial generation of reactive oxygen species and DNA fragmentation were significantly elevated
Luukkonen et al. (2009)	872 MHz	5	RF radiation might enhance chemically induced ROS production and thus cause secondary DNA damage. However, no effects of the GSM signal were seen on either ROS production or DNA damage.
Luukkonen et al. (2010)	872 MHz	5	No effects from either CW or modulated RF radiation on ROS production, DNA damage or cell viability.
Xu et al. (2010)	1800 MHz	2	RF radiation could cause oxidative damage to mtDNA in primary cultured neurons and oxidative damage to mtDNA may account for the neurotoxicity of RF radiation in the brain.
Yao et al. (2008)	1800 MHz	1–4	DNA damage induced RF field for 2 h, which may be associated with the increased ROS production.
Del Vecchio et al. (2009)	900 MHz		RFs act as a co-stressor for oxidative damage of neural cells.
Zmyslony et al. (2004)	930 MHz	1.5	Acute (5 and 15 min) RF exposure does not affect the number of produced ROS.
Gajski and Garaj-Vrhovac (2009)	915 MHz	0.6	Oxidative stress is responsible for the DNA damage induced by microwave radiation.
Kahya et al. (2014)	900 MHz	0.36	RF appears to induce apoptosis effects through oxidative stress and mitochondrial depolarization
Kang et al. (2014)	837 MHz–1950 MHz	2	Neither combined RF radiation alone nor combined RF radiation with menadione or H_2O_2 influences the intracellular ROS level in neuronal cells such as U87, PC12 or SH-SY5Y.
Ni et al. (2013)	1800 MHz	2, 3 or 4	The ROS and MDA levels significantly increased in the RF exposure group and that the cellular viability, mRNA expression of four genes, and expression of four proteins significantly decreased.
Simon et al. (2013)	900 MHz	2 mW g^{-1}	RF does not induce a detectable cellular stress but rather a subtle transient alteration of the epidermal differentiation which might affect, if repeated, the protective capacity of the skin against external factors.

MDA) and low GSH (glutathione) content in both the testis and the epididymis". Two of the studies investigated the effects of 2450 MHz reported that RF increases the DNA damage in both brain tissues and plasma of the rats whereas it increases protein oxidation only in plasma and antioxidant enzymes such as glutathione peroxidase and superoxide dismutase decreased while catalase increased on male brain rats after 2.45 GHz RF exposure (Gurler et al., 2014; Kesari et al., 2010). Two studies investigated the effects of 900 MHz, 1800 MHz and 2450 MHz in the same studies. Eser et al. (2013) found that "RFs may lead to impair the oxidative stress, inflammatory cytokine system and structural alteration in the frontal cortex, brain stem and cerebellum that these degradations can cause to disease including loss of these areas function and cancer development". Ozorak et al. (2013) stated that "EMF emitted from wireless communication's equipment may cause oxidative damage in kidney and testis and precocious puberty in growing rats". Kesari and Behari (2009) found that "50 GHz chronic microwave exposure causes DNA double-strand break, decrease in glutathione peroxidase and superoxide dismutase activity in brain cells while catalase activity increase". A summary of the studies also can be seen Table 4.

9. Human studies

We found only two in vivo human study that one of them investigated the oxidant/antioxidant status by measuring MDA and 8-oxo-7,8-dihydro-20-deoxyguanosine (8-Oxo-dG) in saliva of 1800 MHz cell phone users at the end of 15 and 30 min calls and suggested that there is no relationship between RFR and changes in the salivary oxidant/antioxidant profile (Khalil et al., 2014). In the another study, Moustafa et al. (2001) investigated acute effect of RFR emitted from 900 MHz cellular phones on some oxidative stress parameters such as lipid peroxide, superoxide dismutase, total glutathione peroxidase and catalase in healthy adult male volunteers. The authors found that "the plasma level of lipid peroxide was increased after 1, 2 and 4 h of RF exposure in standby position (Moustafa et al., 2001). They additionally reported that SOD and GSH-Px in human erythrocytes reduced while catalase did not decrease (Moustafa et al., 2001). Finally, they stated that cellular phone exposure may modulate the oxidative stress by enhancing lipid peroxidation and reducing the activation of SOD and GSH-Px, which are free radical scavengers" (Moustafa et al., 2001).

10. Occupational exposure and oxidative stress

Peraica et al. (2008) measured the malondialdehyde and glutathione in blood of workers professionally exposed to microwave radiation by means of GEM radar equipment (Power density range: 10 $\mu W/cm^2$ to 10 mW/cm^2; Frequency range: 1.5–10.9 GHz). They stated that "MDA level in the exposed group was found higher than the controls while the GSH concentration in exposed group was lower than the controls (Peraica et al., 2008). They therefore reported that RFR is one of the important oxidative stress parameter" (Peraica et al., 2008).

Garaj-Vrhovac et al. (2011) also studied effects of occupational exposure of pulsed microwave, originating from marine radars (Frequencies: 3 GHz, 5.5 GHz and 9.4 GHz) that SAR levels were well below the thermal-effect based exposure limit of 4 W/kg. They reported that "glutathione concentration decreased and malondialdehyde increased in the occupationally exposed group (Garaj-Vrhovac et al., 2011). They finally suggested that pulsed microwaves from working environment can be the reason of genetic and cell alterations and that oxidative stress can be one of the possible mechanisms of DNA and cell damage" (Garaj-Vrhovac et al., 2011).

Table 2
A summary of some in vivo 900 MHz RF exposure studies on the oxidative effects of mobile phone exposure.

Authors	RF frequency	SAR, E Field, Power Density	Results
Tkalec et al. (2007)	400 and 900 MHz	10, 23, 41 and 120 V m^{-1}	Non-thermal exposure to investigated radiofrequency fields induced oxidative stress in duckweed as well as unspecific stress responses, especially of antioxidative enzymes. Lipid peroxidation and H_2O_2 content were significantly enhanced in duckweed exposed to EMFs of 23 and 120 V m^{-1}
Dasdag et al. (2009)	900 MHz	0.17–0.58 W/kg	Final score for apoptosis, total antioxidant capacity and catalase in rat brain might be altered by 900 MHz radiation
Dasdag et al. (2012)	900 MHz	0.17–0.58 W/kg	900 MHz radiation emitted from mobile/cellular phones enhanced malondialdehyde level and caused protein oxidation in brain.
Dasdag et al. (2008b)	900 MHz	0.0782 mW/cm^2	RF radiation emitted from GSM cellular phone may play a role to induce oxidative damage by; increasing lipid peroxidation and oxidative stress.
Erguder et al. (2010)	900 MHz		RF exposure caused an inhibition in 5′-NT and CAT activities in brain. However, RF reduced GSH-Px activity and the MDA but the comparison was not statistically significant. Vitamin C may play a protective role against detrimental effects of mobile phone radiation in brain tissue.
Jing et al. (2012)	900 MHz		Significant differences in the contents of SOD, GSH-Px, and; the contents of SOD and GSH-Px decreased and the content of MDA increased.
Kesari et al. (2011)	900 MHz	0.9 W/kg	A reduction or an increase in antioxidative enzyme activities, protein kinase C, melatonin, caspase 3, and creatine kinase were related to overproduction of reactive oxygen species (ROS) in animals under mobile phone radiation exposure.
Meral et al. (2007)	900 MHz	0.9 W/kg	Electromagnetic field emitted from cellular phone might produce oxidative stress in brain tissue of guinea pigs
Sokolovic et al. (2008)	900 MHz	0.043–0.135 W/kg	Mobile phones caused oxidative damage biochemically by increasing the levels of MDA, carbonyl groups, xanthine oxidase (XO) activity and decreasing CAT activity; and that treatment with the melatonin significantly prevented oxidative damage in the brain.
Moustafa et al. (2001)	900 MHz		Acute exposure to radiofrequency fields of commercially available cellular phones may modulate the oxidative stress of free radicals by enhancing lipid peroxidation and reducing the activation of SOD and GSH-Px, which are free radical scavengers.
Ozguner et al. (2005a)	900 MHz	0.016–4 W/kg	CAPE exhibits a protective effect on mobile phone-induced and free radical mediated oxidative heart impairment in rats.
Devrim et al. (2008)	900 MHz	1.2 W/kg	RF altered some oxidative parameters in red blood cells, kidneys and hearth. mobile telephone radiation leads to oxidative stress in corneal and lens tissues and that antioxidants such as vitamin C can help to prevent these effects.
Balci et al. (2007)	900 MHz	1.2 W/kg	Mobile phone exposure leads to oxidative stress in corneal and lens tissues and that antioxidants such as vitamin C can help to prevent these effects.
Ilhan et al. (2004)	900 MHz	0.25 W/kg	Oxidative damage originated from RF was evident by the: (i) increase in malondialdehyde and nitric oxide levels in brain tissue, (ii) decrease in brain superoxide dismutase (SOD) and glutathione peroxidase activities and (iii) increase in brain xanthine oxidase and adenosine deaminase activities.
Ozguner et al. (2005b)	900 MHz	0.016–4 W/kg	RF induced renal tissue damage by means of increase in NO and MDA levels of renal tissue, and in urinary NAG with the decrease in renal SOD, CAT, GSH-Px activities
Irmak et al. (2002)	900 MHz	0.02 mW/cm^2	Serum SOD activity increased, and serum NO levels decreased in EMR-exposed animals
Oktem et al. (2005)	900 MHz	1.04 mW/cm^2	RF increased MDA and urine NAG levels and reduced SOD, CAT, and GSH-Px activities. Melatonin treatment inhibited these effects.
Ozguner et al. (2004)	900 MHz	0.016–4 W/kg	RF caused mild skin changes and melatonin treatment could reduce these changes.
Ayata et al. (2004)	900 MHz		Rats irradiated with RF suffer from increased fibrosis and lipid peroxidation and that melatonin can reduce the fibrosis and lipid peroxidation caused by MW
Guney et al. (2007)	900 MHz		Oxidative endometrial damage plays an important role in the 900 MHz mobile phone-induced endometrial impairment and the modulation of oxidative stress with vitamins E and C reduces the 900 MHz mobile phone-induced endometrial damage both at biochemical and histological levels.
Koylu et al. (2006)	900 MHz		Lipid peroxidation in the brain cortex and hippocampus increased in the RF exposed group although the levels in the hippocampus were decreased by combined administration of MW and melatonin.
Khalil et al. (2014)	00 MHz	1.09 W/kg	There is no relationship between exposure to radio frequency radiation and changes in the salivary oxidant/antioxidant profile.
Narayanan et al. (2014)	900 MHz	1.58 W/kg	RF exposure for a month induced oxidative stress in rat brain, but its magnitude was different in different regions studied and RF-induced oxidative stress could be one of the underlying causes for the behavioral deficits seen in rats after RF exposure
Fragopoulou et al. (2012)	900 MHz	0.012–0.028 W/kg and 0.17–0.37 W/kg	Long-term irradiation from both RF emitted from Mobile phone and DECT phone altered totaly the expression of 143 proteins in brain. The observed protein expression changes may be related to brain plasticity alterations, indicative of oxidative stress in the nervous
Deshmukh et al. (2013)	900 MHz	8.4738×10^{-5} W/kg	Low level MW radiation had significant effect on cognitive function and was also capable of leading to oxidative stress.
Kerman and Senol (2012)	900 MHz		EMR exposed group, while tissue MDA levels increased, SOD, CAT, and GSH-Px activities were reduced.
Maaroufi et al. (2014)	900 MHz	0.05–0.18 W/kg	RF induces cognitive deficits but these deficits are not revealed in all spatial tasks and had a weak impact on oxidative stress. No synergistic effects between EMF and a high content of iron in the brain.
Tkalec et al. (2013)	900 MHz		The hypothesis of the involvement of the oxidative stress in the observed genotoxic effect was partially supported by the oxidative damage on the lipids and proteins, along with the induction of antioxidative enzymes.

Table 2 (*Continued*)

Authors	RF frequency	SAR, E Field, Power Density	Results
Bilgici et al. (2013)	900 MHz	1.08 W/kg	Increase in brain lipid and protein oxidation after RF radiation exposure and that garlic has a protective effect against this oxidative stress.
Imge et al. (2010)	900 MHz		Vitamin C may play a protective role against detrimental effects of mobile phone radiation in brain tissue.
Furtado-Filho et al. (2014)	950 MHz	1.0–1.3 W/kg	RF does not cause oxidative stress, and it is not genotoxic to the livers of neonates or those of 6 and 15 day old rats, but it changes the concentrations of polyunsaturated fatty acid in neonates.
Odaci et al. (2014)	900 MHz	0.024 W/kg	Increased MDA levels in the experimental group and decreased SOD and CAT levels. EMF applied during the prenatal period can caused pathological changes in kidney tissue in 21-day-old male rats owing to oxidative stress and decreased antioxidant enzyme levels
Lu et al. (2012)	900 MHz	0.43 W/kg	Cell apoptosis can be induced in human PBMC by the radiation of 900 MHz GSM RFEMF at a specific absorption rate of ~0.4 W/kg when the exposure lasts longer than 2 h. The apoptosis is induced through the mitochondrial pathway and mediated by activating ROS and caspase-3, and decreasing the mitochondrial potential.

Table 3
A summary of some in vivo 1800 MHz RF exposure studies on the oxidative effects of mobile phone exposure.

Authors	RF frequency	SAR, E field	Results
Guler et al. (2010)	1800 MHz	14 V m^{-1}	MDA and 8-OHdG levels of non-pregnant and pregnant-RFR (1800 MHz) exposed animals significantly increased
Tomruk et al. (2010)	1800 MHz		RF radiation exposure may lead to oxidative destruction as being indicators of subsequent reactions that occur to form oxygen toxicity in tissues.
Koyu et al. (2005)	1800 MHz	2 W/kg	Caffeic Acid Phenethyl Ester (CAPE) may prevent MW-induced oxidative changes in liver by strengthening the antioxidant defense system, by reducing reactive oxygen species, and by increasing antioxidant enzyme activities.
Ozgur et al. (2010)	1800 MHz	0.38 W/kg	Significant increases in malondialdehyde (MDA) and total nitric oxide (NO) levels and decreases in activities of superoxide dismutase (SOD), myeloperoxidase (MPO) and glutathione peroxidase (GSH-Px) were observed in the liver of guinea pigs after RFR exposure.
Avci et al. (2012)	1800 MHz	4 W/kg	RF leads to protein oxidation in brain tissue and an increase in serum NO.
Ozgur et al. (2013)	1800 MHz		Whole-body RFR exposure may lead to oxidative stress and changes on some blood chemistry parameters.
Bodera et al. (2013)	1800 MHz		Single EMF exposure in 1800 MHz frequency significantly reduced antioxidant capacity both in healthy animals and those with paw inflammation. A certain synergic mode of action was observed between applied electromagnetic fields and administered tramadol in rats treated with Complete Freund's Adjuvant (CFA) Was observed.
Liu et al. (2013)	1800 MHz	1, 2 and 4 W/kg	The extent of DNA migration was significantly increased at a SAR of 4 W/kg. Levels of the DNA adduct 8-oxoguanine (8-oxoG) were also increased at a SAR of 4 W/kg.

Table 4
A summary of some in vivo studies carried out on different frequencies related to the oxidative effects of mobile phone exposure.

Authors	RF frequency	SAR (W/kg)	Results
Mailankot et al. (2009)	0.9/1.8 GHz		RF-EMR exposure resulted in a significant increase in lipid peroxidation (increased endogenous MDA) and low GSH (glutathione) content in both the testis and the epididymis.
Ferreira et al. (2006)	800–1800 MHz	0.41–0.98 W/kg	No changes in lipid and protein damage, and also in non-enzymatic defense in frontal cortex or hippocampus.
Dogan et al. (2012)	2100 MHz		Usage of short-term 3G mobile phones does not seem to have a harmful effect on rat brain tissue.in terms of oxidative stress
Gurler et al. (2014)	2.45 GHz	0.02 W/kg	RF increases the DNA damage in both brain tissues and plasma of the rats whereas it increases protein oxidation only in plasma.
Kesari et al. (2010)	2.45 GHz	0.11 W/kg	Antioxidant enzymes such as glutathione peroxidase and superoxide dismutase decreased while catalase increased on male brain rats after 2.45 GHz RF exposure.
Ozorak et al. (2013)	900–1800 MHz, 2.45 GHz	0.01–1.2 W/kg	Wi-Fi- and mobile phone-induced EMR may cause precocious puberty and oxidative kidney and testis injury in growing rats.
Eser et al. (2013)	900–1800–2450 MHz		RFs causes to structural changes in the frontal cortex, brain stem and cerebellum and impair the oxidative stress and inflammatory cytokine system. This deterioration can cause to disease including loss of these areas function and cancer development.
Kesari and Behari (2009)	50 GHz	$8{\cdot}10^{-4}$ W/kg	Chronic exposure to 50 GHz microwave radiations causes DNA double-strand break (head and tail length, intensity and tail migration) and a significant decrease in glutathione peroxidase (GPx) and superoxide dismutase (SOD) activity in brain cells, whereas catalase activity shows significant increase in the exposed group of brain samples

11. Discussion

Long-term and low-intensity RF exposures emitted from wireless equipment are crazily increasing everyday in all of habitats such as homes, offices, schools, hospitals, common living areas etc. Numerous biological effects may occur after exposures RF radiation but potential hazardous oxidative effects sourced from mobile phones are still not well established in spite of the availability of a great numbers of the studies indicate evidence.

However, Belyaev (2010) reported that besides well-known dependencies on carrier frequency and modulation, emerging data suggest dependencies of non-thermal microwave effects on

polarization, intermittence and coherence time of exposure, static magnetic field, electromagnetic stray fields, genotype, gender, physiological and individual traits, cell density during exposure. He also reported that duration of exposure may be as important as power density and specific absorption rate (SAR). Number of studies investigates a relation between the long term RF exposure and oxidative stress, which is completely different than effects of short term exposure are still limited although we presented some studies here. We evaluated fourteen articles investigated the in vitro effects of RF emitted from mobile phones on the oxidative stress (Table 1). Nine of the studies tested the oxidative effects of 900 MHz RF while others investigated 1800 MHz RF. Because of the methodology and specific absorption rate are different in these studies it is not easy to compare the studies between each other completely. However, two studies carried out by Luukkonen et al. (2009, 2010), which have same SAR value indicated "no effects from either CW or modulated RF radiation (872 MHz; 5 W/kg) on ROS production, DNA damage or cell viability" whereas, they reported that "RF radiation might enhance chemically induced ROS production and thus cause secondary DNA damage". The results of these two studies really interesting because of showing extraordinary effect of RFs related to chemically induced ROS production. Another striking result is the studies performed by De Iuliis et al. (2009). They exposed purified human spermatozoa to 1.8 GHz RF (SAR from 0.4 W/kg to 27.5 W/kg) and indicated that "in step with increasing SAR, motility and vitality were significantly reduced after RF exposure, while the mitochondrial generation of reactive oxygen species and DNA fragmentation were significantly elevated" (De Iuliis et al., 2009). Furthermore, they also reported "highly significant relationships between SAR, the oxidative DNA damage bio-marker, 8-OH-dG, and DNA fragmentation after RF exposure" (De Iuliis et al., 2009). Therefore, the result of this in vitro study may be remarkable for mobile phone users to pay attention to SAR level of mobile equipment. However, there are contradictions between the results of the in vitro studies that are seen in Table 1. Data given in Table 1 is very informative to evaluate the contradictions although most of studies support oxidative effects of RFs emitted from mobile phones.

Our investigations showed that numbers of in vivo studies are greater than in vitro studies to clarify the topic. Most of the in vivo studies investigated relation between 900 MHz (or around) RF radiation and oxidative stress while some of the studies performed on 1800 MHz RF exposure. However, some of the studies investigated the effects of both frequencies. Additionally, four of the studies performed on the effect of 2.45 GHz. Additional one of the study was on 2100 MHz and other was on 50 GHz. In total, forty-seven in vivo articles are discussed to indicate the relation between oxidative stress and RF exposures. Only two studies, which are performed by Tkalec et al. (2007) was on duckweed *Lemna minor* L and earthworms. They investigated effects of 400 and 900 MHz RFs with power density of 10, 23, 41 and 120 V m^{-1} on oxidative stress in duckweed and found that "non-thermal exposure of RFR induced oxidative stress in duckweed as well as unspecific stress responses, especially of anti-oxidative enzymes (Tkalec et al., 2007). However, lipid peroxidation and H_2O_2 content were also significantly enhanced in duckweed exposed to EMFs of 23 and 120 V m^{-1}". Other study of them was on the effects of 900 MHz on Earthworm Eiseniafetida (Tkalec et al., 2013). They stated that "hypothesis of the involvement of the oxidative stress in the observed genotoxic effect was partially supported by the oxidative damage on the lipids and proteins, along with the induction of antioxidative enzymes" (Tkalec et al., 2013). The results of both studies are important in terms of ecological balance and therefore more attention is necessary when RF equipment established somewhere because of plants produced in soil, which is consumed by human being and others (Tkalec et al., 2007, 2013). It means that consumers can be unconsciously consumed foods have high oxidative stress produced in soil. The implications of such situation are worth discussion. In our opinion, necessary new regulation should be implemented for the court made agriculture and animal husbandry if required. Overwhelming majority of the studies discussed in this review (Tables 1–4) indicates that mobile phones or similar equipment that emit radiofrequency radiation have a potential to increase oxidative stress resulting DNA damage. The damage, which also called as oxidative DNA damage may play an important role in mutagenesis, carcinogenesis and aging. It should not forget that this outcome is vital for the living beings or entities that created them. Meanwhile, it should be remembered that standardization of methodology of the studies far from each other mostly. For instance some authors used mobile phones directly that is far from standard exposure condition. Additionally, SAR values of some studies are not available or measurement methods are controversial. Therefore, the authors have to pay more attention to these details including the remarks recommended by Belyaev (2010) when designed further performances. However, the greatest responsibility is belonging to the editors who do not care about these details or cannot spend enough time to find the right referees.

Four human studies are present and third of them pointing oxidative effects of radiofrequencies (Khalil et al., 2014; Moustafa et al., 2001; Peraica et al., 2008; Garaj-Vrhovac et al., 2011). The results of human study are very remarkable to evaluate the oxidative effects of radiofrequencies emitted by different mobile or fixed equipment. Therefore, regulations on these fields should be reconsidered. Another interesting result of human studies performed on RF emitted from mobile phones is efficiency of frequencies in terms of oxidative stress. Because it seems that 900 MHz is more effective than 1800 MHz in terms of oxidative stress.

We can summarize the results of the articles presented here under some headings.

1 Overwhelming of the studies reviewed here indicated that mobile phones or similar wireless equipment increase the oxidative stress.
2 Some of the researchers definitely believe that mobile phones cause oxidative damage and therefore they investigated radio-protective effects of some drugs such as Vitamin C, Vitamin E, melatonin, caffeic Acid Phenethyl Ester, garlic.
3 Some of the authors believe that mobile phones cause DNA damage by means of increasing of oxidative stress.
4 A few of the studies claimed that mobile phones have not any oxidative effects.
5 Human studies are very informative and their results are quite disturbing. However, numbers of the studies are very limited and further studies should be performed as soon as possible.
6 Regulation on working conditions of the radar technicians should be reconsidered in terms of occupational oxidative stress originated from radars.

In conclusion, most of the articles reported that mobile phones and similar equipment or radars can be thought as a factor, which cause oxidative stress. Some of the authors claimed that oxidative stress originated from radiofrequencies can be resulted with DNA damage. However, maximum attention should be paid methodology, exposure setup and other exposure parameters when new studies programed. More human exposure studies are necessary to clarify the topic.

References

Agarwal, A., Singh, A., Hamada, A., Kesari, K., 2011. Cell phones and male infertility: a review of recent innovations in technology and consequences. Int. Braz. J. Urol. 37, 432–454.

Agarwal, A., Desai, N.R., Makker, K., Varghese, A., Eagles, R., Sabanegh, E., Sharma, R., 2009. Effects of radiofrequency electromagnetic waves (RF-EMW) from cellular phones on human ejaculated semen: an in vitro pilot study. Fertil. Steril. 92, 1318–1325.
Ahlbom, A., Gren, A., Kheifets, L., Savitz, D., Swerdlow, A., 2004. Epidemiology of health effects of radiofrequency exposure. Environ. Health Perspect. 112, 1741–1754.
Akdag, Z., Celik, M.S., Ketani, M.A., Nergiz, Y., Deniz, M., Dasdag, S., 1999. The effect of chronic low-intensitiy microwave radiation on sperm count, sperm morphology, testicular and epididymal tissues of rats. Electro Magnetobiol. 18, 133–145.
Atasoy, H.I., Gunal, M.Y., Atasoy, P., Elgun, Bugdayci, G.S., 2013. Immunohistopathologic demonstration of deleterious effects on growing rat testes of radiofrequency waves emitted from conventional Wi-Fi devices. J. Pediatr. Urol. 9, 223–229.
Avci, B., Akar, A., Bilgici, B., Tuncel, O.K., 2012. Oxidative stress induced by 1.8 GHz radio frequency electromagnetic radiation and effects of garlic extract in rats. Int. J. Radiat. Biol. 88, 799–805.
Avendano, C., Mata, A., Sanchez Sarmiento, C.A., Doncel, G.F., 2012. Use of laptop computers connected to internet through Wi-Fi decreases human sperm motility and increases sperm DNA fragmentation. Fertil. Steril. 97, 39–45.
Ayata, A., Mollaoglu, H., Yilmaz, H.R., Akturk, O., Ozguner, F., Altuntas, I., 2004. Oxidative stress mediated skin damage in an experimental mobile phone model can be prevented by melatonin. J. Dermatol. 31, 878–883.
Balci, M., Devrim, E., Durak, I., 2007. Effects of mobile phones on oxidant/antioxidant balance in cornea and lens of rats. Curr. Eye Res. 32, 21–25.
Belyaev, I. 2010. Dependence of non-thermal biological effects of microwaves on physical and biological variables: implications for reproducibility and safety standards. Eur. J. Oncol. – Library Non-Thermal Effects and Mechanisms of Interaction Between Electromagnetic Fields and Living Matter. An ICEMS Monograph. L. Giuliani and M. Soffritti. Bologna, Italy, Ramazzini Institute, vol. 5, pp. 187–218, http://www.icems.eu/papers.htm?f=/c/a/2009/12/15/MNHJ1B49KH.DTL.
Bilgici, B., Akar, A., Avci, B., Tuncel, O.K., 2013. Effect of 900 MHz radiofrequency radiation on oxidative stress in rat brain and serum. Electromagn. Biol. Med. 32, 20–29.
BioInitiative Report, 2012. Section 1; Summary for the public (2012 Supplement). In: Cindy, S., Carpenter, D.O. (Eds.), A rationale for biologically-based public exposure standards for electromagnetic radiation. BioInitiative Working Group USA, Santa Barbara, CA, pp. 1–26, www.bioinitiative.org.
Bodera, P., Stankiewicz, W., Zawada, K., Antkowiak, B., Paluch, M., Kieliszek, J., Kalicki, B., Bartosiński, A., Wawer, I., 2013. Changes in antioxidant capacity of blood due to mutual action of electromagnetic field (1800 MHz) and opioid drug (tramadol) in animal model of persistent inflammatory state. Pharmacol. Rep. 65, 421–428.
Campisi, A., Gulino, M., Acquaviva, R., Bellia, P., Raciti, G., Grasso, R., Musumeci, F., Vanella, A., Triglia, A., 2010. Reactive oxygen species levels and DNA fragmentation on astrocytes in primary culture after acute exposure to low intensity microwave electromagnetic field. Neurosci. Lett. 473, 52–55.
Campo, G.M., Avenose, A., Campo, S., Ferlazzo, A.M., Micali, C., Zanghí, L., Calatroni, A., 2004. Hyalurinic acid and chondroitin-4-sulphate treatment reduces damage in carbon tetrachloride-induced acute rat liver injury. Life Sci. 74, 1289–1305.
Celik, S., Aridogan, I.A., Izol, V., Erdoğan, S., Polat, S., Doran, S., 2012. An evaluation of the effects of long-term cell phone use on the testes via light and electron microscope analysis. Urology 79, 346–350.
Cooke, M.S., Evans, M.D., Dizdaroğlu, M., Lunec, J., 2003. Oxidative DNA damage: mechanisms, mutation, and disease. FASEB J. 17, 1195–1214.
Dasdag, S., Akdag, M.Z., Ulukaya, E., Uzunlar, A.K., Yegin, D., 2008a. Mobile phone exposure does not induce apoptosis on spermatogenesis in rats. Arch. Med. Res. 39, 40–44.
Dasdag, S., Akdag, M.Z., Ulukaya, E., Uzunlar, A.K., Ocak, A.R., 2009. Effect of mobile phone exposure on apoptotic glial cells and status of oxidative stress in rat brain. Electromagn. Biol. Med. 28, 342–354.
Dasdag, S., Akdag, M.Z., Kizil, G., Kizil, M., Cakir, D.U., Yokus, B., 2012. Effect of 900 MHz radio frequency radiation on Beta amyloid protein, protein carbonyl, and malondialdehyde in the brain. Electromagn. Biol. Med. 31, 67–74.
Dasdag, S., Ketani, M.A., Akdag, Z., Ersay, A.R., Sari, I., Demirtaş, O.C., Çelik, M.S., 1999. Whole-body microwave exposure emitted by cellular phones and testicular function of rats. Urol. Res. 27, 219–223.
Dasdag, S., Akdag, M.Z., Aksen, F., Yılmaz, F., Bashan, M., Dasdag, M.M., Celik, M.S., 2003. Whole body exposure of rats to microwaves emitted from a cell phone does not affect the testes. Bioelectromagnetics 24, 182–188.
Dasdag, S., Bilgin, H.M., Akdag, M.Z., Celik, H., Aksen, F., 2008b. Effect of long term mobile phone exposure on oxidative and antioxidative process and nitric oxide in rats. Biotechnol. Biotechnol. Equip. 22, 992–997.
Del Vecchio, G., Giuliani, A., Fernandez, M., Mesirca, P., Bersani, F., Pinto, R., Ardoino, L., Lovisolo, G.A., Antico, L., Calzà, L., 2009. Effect of radiofrequency electromagnetic field exposure on in vitro models of neurodegenerative disease. Bioelectromagnetics 30, 564–572.
De Iuliis, G.N., Newey, R.J., King, B.V., Aitken, R.J., 2009. Mobile phone radiation induces reactive oxygen species production and DNA damage in human spermatozoa in vitro. PLoS ONE 4, e6446.
Devrim, E., Erguder, I.B., Kılıcoglu, B., Yaykasli, E., Cetin, R., Durak, I., 2008. Effects of electromagnetic radiation use on oxidant/antioxidant status and DNA turn-over enzyme activities in erythrocytes and heart, kidney, liver, and ovary tissues from rats: possible protective role of vitamin C. Toxicol. Mech. Methods 18, 679–683.
Deshmukh, P.S., Banerjee, B.D., Abegaonkar, M.P., Megha, K., Ahmed, R.S., Tripathi, A.K., Mediratta, P.K., 2013. Effect of low level microwave radiation exposure on cognitive function and oxidative stress in rats. Indian J. Biochem. Biophys. 50, 114–119.
Dizdaroglu, M., 2012. Oxidatively induced DNA damage: mechanisms, repair and disease. Cancer Lett. 327, 26–47.
Dizdaroglu, M., Jaruga, P., Birincioglu, M., Rodriguez, H., 2002. Free radical induced damage to DNA: mechanism and measurement. Free Radic. Biol Med. 32, 1102–1115.
Dogan, M., Turtay, M.G., Oguzturk, H., Samdanci, E., Turkoz, Y., Taşdemir, S., Alkan, A., Bekir, S., 2012. Effects of electromagnetic radiation produced by 3G mobile phones on rat brains: magnetic resonance spectroscopy, biochemical, and histopathological evaluation. Hum. Exp. Toxicol. 31, 557–564.
Erguder, I.B., Kilicoglu, B., Devrim, E., Cetin, R., Durak, I., 2010. Effects of mobile phone use on brain tissue from the rat and a possible protective role of vitamin C: a preliminary study. Int. J. Radiat. Biol. 86, 1044–1049.
Eser, E., Songur, A., Aktas, C., Karavelioglu, E., Çağlar, V., Aylak, F., Ozguner, F., Kanter, M., 2013. The effect of electromagnetic radiation on the rat brain: an experimental study. Turk. Neurosurg. 23, 707–715.
Evans, M.D., Dizdaroglu, M., Cooke, M.S., 2004. Oxidative DNA damage and disease: induction, repair and significance. Mutat. Res. 567, 1–61.
Ferreira, A.R., Bonatto, F., de Bittencourt Pasquali, M.A., Polydoro, M., Dal-Pizzol, F., Fernández, C., De Salles, A.A.A., Moreira, J.C.F., 2006. Oxidative stress effects on the central nervous system of rats after acute exposure to ultra high frequency electromagnetic fields. Bioelectromagnetics 27, 487–493.
Fragopoulou, A.F., Samara, A., Antonelou, M.H., Xanthopoulou, A., Papadopoulou, A., Vougas, K., Koutsogiannopoulou, E., Anastasiadou, E., Stravopodis, D.J., Tsangaris, G.T., Margaritis, L.H., 2012. Brain proteome response following whole body exposure of mice to mobile phone or wireless DECT base radiation. Electromagn. Biol. Med. 31, 250–274.
Furtado-Filho, O.V., Borba, J.B., Pizzolato, T.M., Henriques, J.A., Moreira, J.C., Saffi, J., 2014. Effect of 950 MHz UHF electromagnetic radiation on biomarkers of oxidative damage, metabolism of UFA and antioxidants in the livers of young rats of different ages. Int. J. Radiat. Biol. 90, 159–168.
Gajski, G., Garaj-Vrhovac, V., 2009. Radioprotective effects of honeybee venom (*Apis mellifera*) against 915-MHz microwave radiation-induced DNA damage in Wistar rat lymphocytes: in vitro study. Int. J. Toxicol. 28, 88–98.
Garaj-Vrhovac, V., Gajski, G., Pazanin, S., Sarolić, A., Domijan, A.M., Flajs, D., Peraica, M., 2011. Assessment of cytogenetic damage and oxidative stress in personnel occupationally exposed to the pulsed microwave radiation of marine radar equipment. Int. J. Hyg. Environ. Health. 214, 59–65.
Guler, G., Tomruk, A., Ozgur, E., Seyhan, N., 2010. The effect of radiofrequency radiation on DNA and lipid damage in non-pregnant and pregnant rabbits and their newborns. Gen. Physiol. Biophys. 29, 59–66.
Guney, M., Ozguner, F., Oral, B., Karahan, N., Mungan, T., 2007. 900 MHz radiofrequency-induced histopathologic changes and oxidative stress in rat endometrium: protection by vitamins E and C. Toxicol. Ind. Health 23, 411–420.
Gurler, H.S., Bilgici, B., Akar, A., Tomak, L., Bedir, A., 2014. Increased DNA oxidation (8-OHdG) and protein oxidation (AOPP) by low level electromagnetic field (2.45 GHz) in rat brain and protective effect of garlic. Int. J. Radiat. Biol. 90, 892–896.
Hardel, L., Nasman, B., Pahlson, B., Hallquist, B., Hansson Hafif, K., 1999. Use of cellular telephones and the risk for brain tumours: a case-control study. Int. J. Oncol. 1, 113–116.
Ilhan, A., Gurel, A., Armutcu, F., Kamisli, S., Iraz, M., Akyol, O., Ozen, S., 2004. Ginkgo biloba prevents mobile phone-induced oxidative stress in rat brain. Clin. Chim. Acta 340, 153–162.
Irmak, M.K., Fadillioglu, E., Gulec, M., Erdogan, H., Yagmurca, M., Akyol, O., 2002. Effects of electromagnetic radiation from a cellular telephone on the oxidant and antioxidant levels in rabbits. Cell Biochem. Funct. 20, 279–283.
Imge, E.B., Kilicoglu, B., Devrim, E., Cetin, R., Durak, I., 2010. Effects of mobile phone use on brain tissue from the rat and a possible protective role of vitamin C: a preliminary study. Int. J. Radiat. Biol. 86, 1044–1049.
ITU, (October 10, 2014) http://www.itu.int/net/pressoffice/press_releases/2014/23.aspx#.VF-Ipvl_sh8.
Jajte, J., Grzegorczyk, J., Zmyslony, M., Rajkowska, E., 2002. Effect of 7 mT static magnetic field and iron ions on rat lymphocytes: apoptosis, necrosis and free radical processes. Bioelectrochemistry 57, 107–111.
Jing, J., Yuhua, Z., Xiao-qian, Y., Rongping, J., Dong-mei, G., Xi, C., 2012. The influence of microwave radiation from cellular phone on fetal rat brain. Electromagn. Biol. Med. 31, 57–66.
Kahya, M.C., Nazıroglu, M., Cig, B., 2014. Selenium reduces mobile phone (900 MHz)-induced oxidative stress, mitochondrial function, and apoptosis in breast cancer cells. Biol. Trace Elem. Res. 160, 285–293.
Kang, K.A., Lee, H.C., Lee, J.J., 2014. Effects of combined radiofrequency radiation exposure on levels of reactive oxygen species in neuronal cells. J. Radiat. Res. 55, 265–276.
Kerman, M., Senol, N., 2012. Oxidative stress in hippocampus induced by 900 MHz electromagnetic field emitting mobile phone: protection by melatonin. Biomed. Res. 23, 147–151.

Kesari, K.K., Behari, J., 2009. Fifty-gigahertz microwave exposure effect of radiations on rat brain. Appl. Biochem. Biotechnol. 158, 126–139.
Kesari, K.K., Behari, J., Kumar, S., 2010. Mutagenic response of 2.45 GHz radiation exposure on rat brain. Int. J. Radiat. Biol. 86, 334–343.
Kesari, K.K., Kumar, S., Behari, J., 2011. 900 MHz microwave radiation promotes oxidation in rat brain. Electromagn. Biol. Med. 30, 219–234.
Khalil, A.M., Khadra, K.M., Aljaberi, A.M., Gagaa, M.H., Issa, H.S., 2014. Assessment of oxidant/antioxidant status in saliva of cell phone users. Electromagn. Biol. Med. 33, 92–97.
Koylu, H., Mollaoglu, H., Ozguner, F., Naziroglu, M., Delibas, N., 2006. Melatonin modulates 900 MHz microwave-induced lipid peroxidation changes in rat brain. J. Toxicol. Ind. Health 22, 211–216.
Koyu, A., Naziroglu, M., Ozguner, F., Yilmaz, H.R., Uz, E., Cesur, G., 2005. Caffeic acid phenethyl ester (CAPE) modulates 1800 MHz microwave-induced oxidative stress in rat liver. Electromagn. Biol. Med. 24, 135–142.
Lee, H.J., Jin, Y.B., Kim, T.H., Pack, J.K., Kim, N., Choi, H.D., Lee, J.S., Lee, Y.S., 2012. The effects of simultaneous combined exposure to CDMA and WCDMA electromagnetic fields on rat testicular function. Bioelectromagnetics 33, 356–364.
Liu, C., Duan, W., Xu, S., Chen, C., He, M., Zhang, L., Yu, Z., Zhou, Z., 2013. Exposure to 1800 MHz radiofrequency electromagnetic radiation induces oxidative DNA base damage in a mouse spermatocyte-derived cell line. Toxicol. Lett. 218, 2–9.
Lu, Y.S., Huang, B.T., Huang, Y.X., 2012. Reactive oxygen species formation and apoptosis in human peripheral blood mononuclear cell induced by 900 MHz mobile phone radiation. Oxid. Med. Cell. Longev. 2012,, http://dx.doi.org/10.1155/2012/740280, 740280.
Luukkonen, J., Hakulinen, P., Mäki-Paakkanen, J., Juutilainen, J., Naarala, J., 2009. Enhancement of chemically induced reactive oxygen species production and DNA damage in human SH-SY5Y neuroblastoma cells by 872 MHz radiofrequency radiation. Mutat. Res. 662, 54–58.
Luukkonen, J., Juutilainen, J., Naarala, J., 2010. Combined effects of 872 MHz radiofrequency radiation and ferrous chloride on reactive oxygen species production and DNA damage in human SH-SY5Y neuroblastoma cells. Bioelectromagnetics 31, 417–424.
Maaroufi, K., Had-Aissouni, L., Melon, C., Sakly, M., Abdelmelek, H., Poucet, B., Save, E., 2014. Spatial learning, monoamines and oxidative stress in rats exposed to 900 MHz electromagnetic field in combination with iron overload. Behav. Brain Res. 258, 80–89.
Mailankot, M., Kunnath, A.P., Jayalekshmi, H., Koduru, B., Valsalan, R., 2009. Radio frequency electromagnetic radiation (RF-EMR) from GSM (0.9/1.8 GHz) mobile phones induces oxidative stress and reduces sperm motility in rats. Clinics 64, 561–565.
Meral, I., Mert, H., Mert, N., Deger, Y., Yoruk, I., Yetkin, A., Keskin, S., 2007. Effects of 900-MHz electromagnetic field emitted from cellular phone on brain oxidative stress and some vitamin levels of guinea pigs. Brain Res. 1169, 120–124.
Moustafa, Y.M., Moustafa, R.M., Belacy, A., Abou-El-Ela, S.H., Fadel, M.A., 2001. Effects of acute exposure to the radiofrequency fields of cellular phones on plasma lipid peroxide and antioxidase activities in human erythrocytes. J. Pharm. Biomed. Anal. 26, 605–608.
Narayanan, S.N., Kumar, R.S., Kedage, V., Nalini, K., Nayak, S., Bhat, P.G., 2014. Evaluation of oxidant stress and antioxidant defense in discrete brain regions of rats exposed to 900 MHz radiation. Bratisl. Lek. Listy 115, 260–266.
Ni, S., Yu, Y., Zhang, Y., Wu, W., Lai, K., Yao, K., 2013. Study of oxidative stress in human lens epithelial cells exposed to 1.8 GHz radiofrequency fields. PLoS ONE 8, e72370, http://dx.doi.org/10.1371/journal.pone.0072370.
Nisbet, H.O., Nisbet, C., Akar, A., Cevik, M., Karayigit, M.O., 2012. Effects of exposure to electromagnetic field (1.8/0.9 GHz) on testicular function and structure in growing rats. Res. Vet. Sci. 93, 1001–1005.
Odaci, E., Unal, E., Mercantepe, T., Topal, Z., Hanci, H., Türedi, S., Erol, H.S., Mungan, S., Kaya, H., Colakoglu, S., 2014. Pathological effects of prenatal exposure to a 900 MHz electromagnetic fi eld on the 21-day-old male rat kidney. Biotech. Histochem. 2015 90 (2), 93–101.
Oktem, F., Ozguner, F., Mollaoglu, H., Koyu, A., Uz, E., 2005. Oxidative damage in the kidney induced by 900-MHz-emitted mobile phone: protection by melatonin. Arch. Med. Res. 36, 350–355.
Ozguner, F., Altinbas, A., Ozaydin, M., Doğan, A., Vural, H., Kisioglu, A.N., Cesur, G., Yıldırım, N.G., 2005a. Mobile phone-induced myocardial oxidative stress: protection by a novel antioxidant agent caffeic acid phenethyl ester. Toxicol. Ind. Health 21, 223–230.
Ozguner, F., Oktem, F., Ayata, A., Koyu, A., Yilmaz, H.R., 2005b. A novel antioxidant agent caffeic acid phenethyl ester prevents long-term mobile phone exposure-induced renal impairment in rat prognostic value of malondialdehyde, N-acetyl-β-D-glucosaminidase and nitric oxide determination. Mol. Cell. Biochem. 277, 73–80.
Ozguner, F., Aydin, G., Mollaoglu, H., Gökalp, O., Koyu, A., Cesur, G., 2004. Prevention of mobile phone induced skin tissue changes by melatonin in rat: an experimental study. Toxicol. Ind. Health 20, 133–139.
Ozgur, E., Kismali, G., Guler, G., Akcay, A., Ozkurt, G., Sel, T., Seyhan, N., 2013. Effects of prenatal and postnatal exposure to GSM-like radiofrequency on blood chemistry and oxidative stress in infant rabbits, an experimental study. Cell Biochem. Biophys. 67, 743–751.
Ozgur, E., Guler, G., Seyhan, N., 2010. Mobile phone radiation-induced free radical damage in the liver is inhibited by the antioxidants n-acetyl cysteine and epigallocatechin-gallate. Int. J. Radiat. Biol. 86, 935–945.
Ozorak, A., Nazıroglu, M., Celik, O., Yüksel, M., Özçelik, D., Özkaya, M.O., Çetin, H., Kahya, M.C., Köse, S.A., 2013. Wi-Fi (2.45 GHz)- and mobile phone (900 and 1800 MHz)-induced risks on oxidative stress and elements in kidney and testis of rats during pregnancy and the development of offspring. Biol. Trace Elem. Res. 156, 221–229.
Peraica, M., Marjanovic, A., Flajs, D., Domijan, A.M., Gaiski, G., Garaj-Vrhovac, V., 2008. Oxidative stress in workers occupationally exposed to microwave radiation. Toxicol. Lett. 180, 38–39.
Riley, P.A., 1994. Free radicals in biology: oxidative stress and the effects of ionizing radiation. Int. J. Radiat. Biol. 65, 27–33.
Sarban, S., Kocyigit, A., Yazar, M., Isikan, U.E., 2005. Plasma total antioxidant capacity, lipid peroxidation, and erythrocyte antioxidant enzyme activities in patients with rheumatoid arthritis and osteoarthritis. Clin. Biochem. 38, 981–986.
Saygin, M., Caliskan, S., Karahan, N., Koyu, A., Gumral, N., Uguz, A., 2011. Testicular apoptosis and histopathological changes induced by a 2.45 GHz electromagnetic field. Toxicol. Ind. Health 27, 455–463.
Simon, D., Daubos, A., Pain, C., Fitoussi, R., Vié, K., Taieb, A., de Benetti, L., Cario-André, M., 2013. Exposure to acute electromagnetic radiation of mobile phone exposure range alters transiently skin homeostasis of a model of pigmented reconstructed epidermis. Int. J. Cosmet. Sci. 35, 27–34.
Sokolovic, D., Djindjic, B., Nikolic, J., Bjelakovic, G., Pavlovic, D., Kocic, G., Krstic, D., Cvetkovic, T., Pavlovic, V., 2008. Melatonin reduces oxidative stress induced by chronic exposure of microwave radiation from mobile phones in rat brain. J. Radiat. Res. 49, 579–586.
Tomruk, A., Guler, G., Dincel, A.S., 2010. The influence of 1800 MHz GSM-like signals on hepatic oxidative DNA and lipid damage in nonpregnant, pregnant, and newly born rabbits. Cell Biochem. Biophys. 56, 39–47.
Tkalec, M., Malaric, K., Pevalek-Kozlina, B., 2007. Exposure to radiofrequency radiation induces oxidative stress in duckweed *Lemna minor* L. Sci. Total Environ. 388, 78–79.
Tkalec, M., Stambuk Srut, M., Malaric, K., Klobuc, G.I.V., 2013. Oxidative and genotoxic effects of 900 MHz electromagnetic fields in the earthworm Eiseniafetida. Ecotoxicol. Environ. Saf. 90, 7–12.
Watson, R., 2011. Radiation fears prompt possible restrictions on Wi-Fi and mobile phone use in schools. Br. Med. J. 342, d3428, http://dx.doi.org/10.1136/bmj.d3428.
Xu, S., Zhong, M., Zhang, L., Yu, Z., Zhang, W., Wang, Y., Wang, X., Li, M., Chen, Y., Chen, C., He, M., Zhang, G., Zhong, M., 2010. Exposure to 1800 MHz radiofrequency radiation induces oxidative damage to mitochondrial DNA in primary cultured neurons. Brain Res. 1311, 189–196.
Yao, K., Wu, W., Wang, K., Ni, Ler., Siz, P., Yu, Y., Ye, J., Güneş, L., 2008. Electromagnetic noise inhibits radiofrequency radiation-induced DNA damage and reactive oxygen species increase in human lens epithelial cells. Mol. Vis. 14, 964–969.
Zmyslony, M., Politanski, P., Rajkowska, E., Szymczak, W., Jajte, J., 2004. Acute exposure to 930 MHz CW electromagnetic radiation in vitro affects reactive oxygen species level in rat lymphocytes treated by iron ions. Bioelectromagnetics 25, 324–328.