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REVIEW

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Threshold of radiofrequency electromagnetic field effect on human brain

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ABSTRACT

Purpose: This review aims to estimate the threshold of radiofrequency electromagnetic field (RF EMF) effects on human brain based on analyses of published research results. To clarify the threshold of the RF EMF effects, two approaches have been applied: (1) the analyses of restrictions in sensitivity for different steps of the physical model of low-level RF EMF mechanism and (2) the analyses of experimental data to clarify the dependence of the RF EMF effect on exposure level based on the results of published original neurophysiological and behavioral human studies for 15 years 2007–2021.

Conclusions: The analyses of the physical model of nonthermal mechanisms of RF EMF effect leads to conclusion that no principal threshold of the effect can be determined. According to the review of experimental data, the rate of detected RF EMF effects is 76.7% in resting EEG studies, 41.7% in sleep EEG and 38.5% in behavioral studies. The changes in EEG probably appear earlier than alterations in behavior become evident. The lowest level of RF EMF at which the effect in EEG was detected is 2.45 V/m (SAR = 0.003 W/kg). There is a preliminary indication that the dependence of the effect on the level of exposure follows rather field strength than SAR alterations. However, no sufficient data are available for clarifying linearity-nonlinearity of the dependence of effect on the level of RF EMF. The finding that only part of people are sensitive to RF EMF exposure can be related to immunity to radiation or hypersensitivity. The changes in EEG caused by RF EMF appeared similar in the majority of analyzed studies and similar to these in depression. The possible causal relationship between RF EMF effect and depression among young people is highly important problem.

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Low-level RF EMF; nonthermal model; threshold; linearity; depression

Introduction

The world population has been exposed to man-made coherent electromagnetic radiation, different from the natural radiation emitted by the Sun, over a very long period of time without remarkable effects on health. The people are adapted to the level of radio and TV broadcasting radiofrequency electromagnetic field (RF EMF) about 0.1 V/m. During recent decades, the applications of mobile telecommunication technology have drastically changed the situation. The sources of RF EMF have moved closer to people and the levels of exposure are much higher. The current guidelines recommend health protection limits up to 61 V/m (ICNIRP 2020). Hundreds of studies have detected biological RF EMF effects in humans, animals and cells at the levels of exposure much less than existing health protection limits. According to the Ericsson Mobility Report, the number of mobile subscriptions by technology is over eight billion in 2020 (Ericsson Mobility Report 2020). This number is higher than the world population. The wide applications of RF EMF rise concern about possible consequences on health.

The increased oxidative stress caused by RF EMF exposure has been reported in many animal and cellular studies (Schuermann and Mevissen 2021). The relevant consequences on health (genome stability, immune system, neurodegeneration, reproduction) are likely. The radiofrequency electromagnetic field was classified as possibly carcinogenic to humans (class 2B) by the International Agency for Research on Cancer (IARC 2013).

The RF EMF effects on brain bioelectrical activity, cognition and behavior, not obligatory related to genome instability, have been a topic of interest over the past decades. The neurophysiological effects on humans have been detected in many experimental studies but the results are controversial (Valentini et al. 2007; Marino and Carruba 2009; Kwon and Hämäläinen 2011). The large variations in applied methods, different frequencies, levels of exposure and modulation parameters cause high diversity of the effects and results. The recent cohort study does not provide sufficient confirmation about the correlation between more extensive use of mobile phones and the reported symptoms nor sleep quality (Auvinen et al. 2019; Tettamanti et al. 2020). It is complicated to determine causal relationship between RF EMF biological effects and its health consequences due to diversity of exposure conditions and numerous concomitant other factors.

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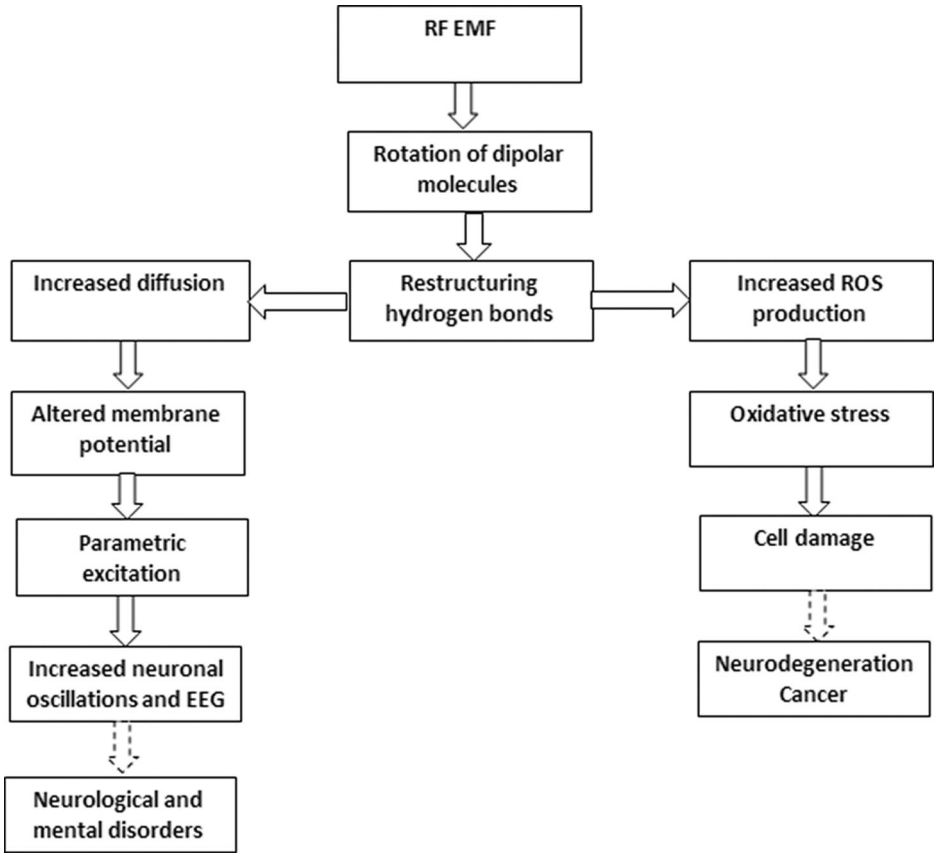


Figure 1. Model of nonthermal mechanisms of low-level RF EMF: left track neurophysiological effect, right track neurodegeneration.

Does the RF EMF has a threshold, lower of which the RF EMF does not have biological effect? This is an important question and crucial to avoid possible consequences on health.

Theoretical estimations for the sensitivity of living cells to electric field provided the threshold values about $10^{-6} - 10^{-7}$ V/m $Hz^{1/2}$ (Weaver and Astumian 1990; Hinrikus et al. 1998). In the case of wide-band telecommunication technology, the threshold rises: at 1 MHz bandwidth, the sensitivity is $10^{-3} - 10^{-4}$ V/m. However, these estimations used a simple single-cell model. Realistic model involving combinations of different cells, molecules and partly nonlinear physiological processes is highly complex. To the best of our knowledge, the calculations using complex model have been not performed.

To clarify the threshold of RF EMF effects, two approaches are applied in the current review: (1) the analyses of restrictions in sensitivity for different steps of the physical model of low-level RF EMF mechanism and (2) the analyses of experimental data to clarify the dependence of the effect on exposure level.

Analyses of different steps of the physical model of low-level RF EMF mechanism

The RF EMF is a physical stressor. Electric forces keep together atoms and molecules. The coherent RF EMF, due to regular synchronous electrical forces, causes stronger cumulative impact in a medium compared to random thermal processes (Hinrikus et al. 2018). Therefore, a nonthermal physical model based on electrical phenomena (Hinrikus et al. 2018) has been selected as a base for estimations. Figure 1 presents the logical structure of the mechanisms of the model. The low-level RF EMF approach, without heating, is appropriate in considering threshold of the effect.

Origin of the effect

The RF EMF causes displacement of free and bound charges in a dielectric medium and dielectric polarization of the medium. Displacement of electrons or ions inside a molecule leads to electronic or molecular, rotation of dipolar molecules to orientational polarization (King and Smith 1981). The intermolecular and even intramolecular electrical fields are much stronger than the applied RF EMF. Therefore, the imbalances in the spatial distribution of charges created by a RF EMF are very small. The synchronization of the displacements in a very large number of molecules leads to the measureable dielectric permittivity of materials (Zahn 2003).

Whereas the intramolecular electric forces are weaker than intermolecular forces, the orientational polarization dominates. Traditionally, the rotation of dipolar molecules caused by high-level RF EMF is considered as the origin of RF EMF thermal effect. However, the measureable electric permittivity exists also in low-level RF EMF and, consequently, the rotation of dipolar molecules takes place in

low-level RF EMF at constant temperature. The synchronous cumulative impact of coherent RF electric field makes possible the low-level field-induced effect despite the energy of RF EMF is lower thermal energy causing random displacements (Hinrikus et al. 2018).

The polarization in dielectrics and water as well as dielectric parameters of tissues have been investigated in many studies (Hasted 1973; Pethig 1979; Mudgett 1985; Foster and Schwan 1995; Gabriel, Gabriel, et al. 1996; Gabriel, Lau, et al. 1996). The relaxation time of orientational polarization decreases with temperature due to increasing number of collisions disturbing the rotation. Therefore, the orientational polarization of tissues decreases with temperature (Pethig 1979).

Orientational polarization depends on the frequency and decreases with frequency due to inertia of molecules. Experimental data indicate that the dielectric constant has the frequency independent value of 1.8 at frequencies close to 100 GHz where the dielectric constant is determined only by the molecular polarization (Hasted 1973).

No theoretical nor experimental data about the threshold of polarization are available. In a linear medium, dielectric constant most probably is constant and does not depend on the level of EMF. The linearity of the response of living tissues to electromagnetic forces can be presumed at low level of EMF. Therefore, the rotation of dipolar molecules has no a determined threshold.

The synchronous rotation of dipolar molecules presumes unavoidable restructuring and weakening of hydrogen bonds between these molecules (Hinrikus et al. 2018). Hydrogen bonds are responsible for the properties of water and for holding together the DNA double helix. Hydrogen bonds are being constantly broken and reformed in liquid water because of random thermal motion of molecules despite the bonding energy is higher kT (Petrucci et al. 2007). The induced by low-level microwave radiation alterations in the properties of water demonstrate restructuring of hydrogen bonds by RF EMF (Fesenko and Gluvstein 1995). Consequently, kT does not determine the threshold of the phenomenon. There are no data about the threshold of restructuring the intramolecular bonds.

Neurophysiological effect

The left tract in Figure 1 presents the model of neurophysiological RF EMF effect that presumes no oxidative stress nor cellular damage.

Hydrogen bonds are responsible for many of the properties of water including viscosity. Weakening of hydrogen bonds decreases viscosity and increases diffusion. The caused by RF EMF increase in diffusion at constant temperature has been demonstrated by experiments in water and supported by the results of in vitro study (Hinrikus et al. 2015; Aly et al. 2008). Diffusion plays crucial role in many physiological processes including neuronal membrane potential and transfer of neurotransmitters in synapses. There are no factors nor data determining the threshold of the effect on diffusion.

Alterations in diffusion cause change in resting neuronal potential and misbalance of membrane currents (Malmivuo and Plonsey 1995; Hinrikus et al. 2017). No factors causing the threshold of membrane potential change have been reported (Malmivuo and Plonsey 1995).

The modulation of RF EMF at low frequencies close to the brain physiological frequencies is important and determines the intensity of the effect (Sanders et al. 1985; Hinrikus, Bachmann, Lass, Tomson, et al. 2008; Hinrikus, Bachmann, Lass, Karai, et al. 2008; Juutilainen et al. 2011). Low-level pulse-modulated RF EMF causes periodic alterations in neuronal electric parameters.

Periodic alterations of neuronal parameters can lead to parametric excitation of neuronal oscillations at predetermined electroencephalographic (EEG) frequencies (Hinrikus, Bachmann, Karai, et al. 2011). The process of excitation of parametric oscillation in a system has a threshold determined by the damping factor and losses in the system (Tso and Caughey 1965; Butikov 2004). However, biochemical energy compensates the losses in neuronal oscillations in brain. Therefore, the lower limit of parametric excitation is not defined. Disturbances in brain bioelectrical activity probably lead to alterations in cognition and behavior.

The brain's defense mechanisms can easily compensate the mild alterations caused by RF EMF (Bachmann, Tomson, et al. 2007). The fast compensation has been demonstrated in the experiments with RF EMF one minute ON-OFF pulse modulation: the effect has appeared statistically significant during first 30 s of ON-pulse but not significant during second 30 s (Hinrikus, Bachmann, Lass, Tomson, et al. 2008). However, in the case of continuous long-term exposure in RF EMF environment, the effect becomes permanent and consequences on health are possible.

Neurodegeneration

The right tract in Figure 1 presents the possible biological model of RF EMF effect that presumes oxidative stress and cellular damage.

The experimental results have demonstrated low-level RF EMF induced increase in the level of reactive oxygen species (ROS) (Xing et al. 2016; Marjanovic Cermak et al. 2018). The RF magnetic fields have been shown to affect the concentrations of ROS via the radical pair mechanism (Usselman et al. 2014; Castello et al. 2014; Barnes and Greenebaum 2015). The low-level RF EMF caused oxidative stress has been reported in many animal and cellular studies (Schuermann and Mevissen 2021). Oxidative stress can lead to cell damage. Further consequences in health including genome instability, neurodegeneration, immune system, male and female reproduction system are possible (Schuermann and Mevissen 2021).

Whereas body's defense mechanisms can repair the temporal changes in ROS formation process in brain cells, the health effect does not necessarily become evident. However, the probability that the defense mechanism can repair the changes caused by permanent exposure by RF EMF is much smaller.

The analyses of both models indicated no data about the factors determining the threshold of low-level RF EMF effect. The radiological protection system in low-level ionizing radiation still bases also on 'linear, no threshold' model, which assumes that there is no dose so small that it has no effect (McLean 2017).

Analyses of experimental data

Search of studies

The current review analyses the results of published original RF EMF human studies for 15 years 2007–2021. The EMF portal database was used for searching of publications. The filters: radio frequency, mobile communication, experimental studies and keywords: EEG, cognition, behavior were used for selection. Further individual evaluation excluded animal and in vitro studies. The quality of all studies was evaluated and the studies with drawbacks in used methods (insufficient data about exposure, limited numbers of subjects, incorrect statistics) were excluded. Finally, 76 relevant studies were included for the analyses.

RF EMF effects

Table 1 summarizes the RF EMF effects reported in the selected publications. The results are presented according to the formulations used by the authors. Unfortunately, the majority of studies do not report quantitative information about the effect – the numerical values of the analyzed parameters (e.g. values of changes in the powers of EEG rhythms or other parameters).

The effects are divided into four categories: changes in resting electroencephalography (EEG), in sleep EEG and sleep quality, in event-related potentials (ERP) plus cognition-behavior and others (changes in cortex oxygenation and brain glucose metabolism). Figure 2 presents the distribution of studies according to these categories. The resting EEG constitutes the largest part 47% of the total studies. The resting eyes closed EEG is most thoroughly investigated. The part of studies in sleep EEG and sleep quality constitutes 15%. The part of event-related potentials (ERP) connected to cognition and behavior effects constitutes 34% of total findings and the part of others only 4%.

Figure 3 presents the rate of studies, which revealed RF EMF effect in different categories. The relative part of

Table 1. Distribution of studies according to the reported RF EMF effects in different categories.

Resting EEG	
Increased theta	Bardasano et al. 2007
Increased alpha	Bardasano et al. 2007; Regel, Tinguely, et al. 2007; Vecchio et al. 2007; Krause et al. 2007; Hinrikus, Bachmann, Lass, Tomson, et al. 2008; Hinrikus et al. 2009; Hinrikus et al. 2011; Croft et al. 2008; Croft et al. 2010; Suhhova et al. 2013; Roggeveen, van Os, Viechtbauer, et al. 2015; Ghosn et al. 2015; Hinrikus et al. 2017; Loughran et al. 2019
Decreased alpha	Yang et al. 2017; Vecsei et al. 2018
Increased beta	Bachmann, Tomson, et al. 2007; Hinrikus, Bachmann, Lass, Karai, et al. 2008; Hinrikus et al. 2011; Suhhova et al. 2013; Roggeveen, van Os, Lousberg, et al. 2015; Hinrikus et al. 2017
Decreased beta	Yang, et al. 2017
Increased gamma	Hinrikus et al. 2009; Roggeveen, van Os, Lousberg, et al. 2015; Curcio et al. 2015
Increased complexity	Bachmann, Tomson, et al. 2007 (LDLVP); Vecchio et al. 2010 (coherence); Hinrikus, Bachmann, Karai, et al. 2011 (HFD)
No effect	Kleinlogel et al. 2008a; Loughran et al. 2013; Zentai et al. 2015; Eggert et al. 2015; Trunk et al. 2015, 2013; Nakatani-Enomoto et al. 2020
Sleep EEG and sleep quality	
Increased spindles 11-12 Hz	Schmid, Murbach et al. 2012; Lowden et al. 2019
Increased delta and theta	Lustenberger et al. 2015
Increased slow-wave activity 0.75-4.5 Hz, redused motor task	Lustenberger et al. 2013
Increased delta, theta, alpha	Schmid, Loughran et al. 2012
No effect	Regel, Gottselig et al. 2007; Fritzer et al. 2007; Leitgeb et al. 2008; Nakatani-Enomoto et al. 2013; Danker-Hopfe et al. 2011, 2010, 2020
Event related potential (ERP), cognition and behavior	
Improved memory and motor tasks	Meo et al. 2019
Visual ERP, increased P1 amplitude and N1 latency	Dalecki et al. 2018
Reduced reaction time	Verrender et al. 2016
Decrease correct answers	Sauter et al. 2015
Pain threshold increase	Vecsei 2013
Increased N100	Leung et al. 2011
Acoustic ERP, amplitude decrease, adaptation increase	de Tommaso et al. 2009
Response time change	Luria et al. 2009
Reducing psychological arousal	Augner et al. 2009
Attention increase	Wiholm et al. 2009
No effect	Regel, Tinguely et al. 2007; Haarala et al. 2007; Krause et al. 2007; Cinel et al. 2008; Stefanics et al. 2008; Kleinlogel et al. 2008b; Curcio et al. 2008; Hillert et al. 2008; Eltiti et al. 2009; Kwon et al. 2009; Riddervold et al. 2010; Kwon et al. 2010; Sauter et al. 2011; Loughran et al. 2013; Vecsei et al. 2018; Hosseini et al. 2019
Others	
Cortex oxygenation	Curcio et al. 2009
Brain glucose metabolism	Kwon et al. 2011; Volkow et al. 2011

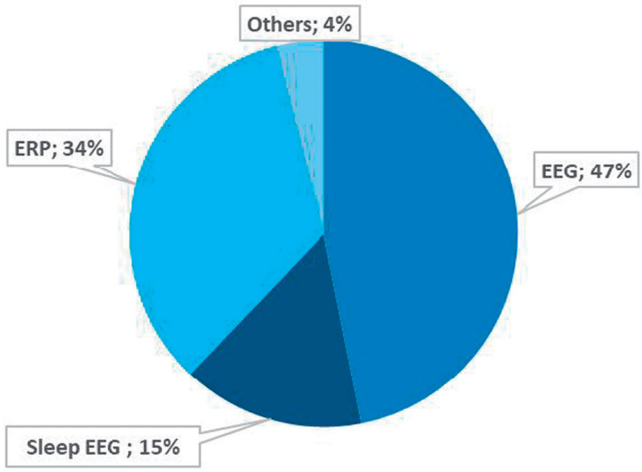


Figure 2. Relative distribution of studies according different categories of the RF EMF effects.

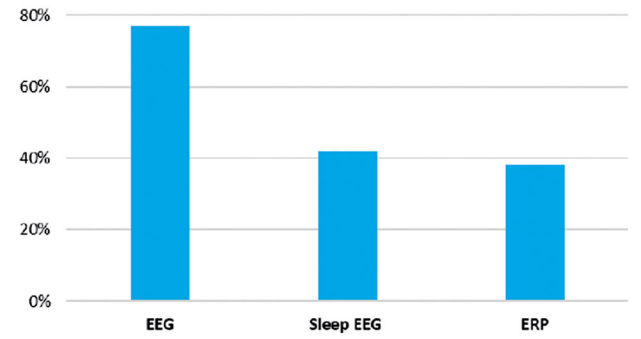


Figure 3. The rate of studies revealing RF EMF effects according different categories.

studies reporting the effect in the resting EEG category is about twofold higher than in the other sleep EEG or ERP categories. All three studies in the category others reported RF EMF effects. However, three studies are too few to make a conclusion about the rate of RF EMF effects.

Resting EEG

The rate of positive findings in resting EEG category (in total 30 studies) is 76.7%. The increased alpha power was most frequently reported (14 studies). Somewhat less studies reported increased beta power (6 studies). Decrease in alpha power was revealed only in two studies and beta power in one study. Increase in gamma power was detected in three and theta power in one study. Increased complexity was evident in three studies. Such distribution of the reported effects is obviously caused by the properties of the resting eyes closed EEG where alpha power (band 8–12 Hz) peak is much higher other bands. Therefore, the alterations in alpha power are detectable more easily.

Only few studies have applied advanced EEG analyses to detect alterations in more complicated nonlinear processes in the brain (Hinrikus, Bachmann, Karai, et al. 2011; Bachmann, Tomson, et al. 2007). The results of these studies demonstrated that RF EMF affected complexity of the brain bioelectrical activity. The RF EMF increased scores of both applied measures, Higuchi's fractal dimension (HFD) and Length distribution of low variability periods (LDLVP).

The results demonstrate that RF EMF causes excitation of brain and related increase in resting EEG alpha and beta bands powers. Exposure to radiation leads also to the higher complexity of brain bioelectrical activity.

Sleep EEG and sleep quality

The rate of positive findings in sleep EEG and sleep quality group is 41.7%. All five studies that reported the effect, declared increase in sleep EEG rhythms or spindles. The increase was evident in slow wave (delta and theta) and in alpha band. No disturbances in sleep quality were reported.

These results suggest that the radiation causes changes in neuronal activity earlier than the subjective feelings become evident.

Event-related potentials (ERP), behavior and cognition

The rate of positive findings in ERP, behavior and cognition group is 38.5%. The reported findings are diverse. Two studies reported changes in ERP. Improved behavior (memory, attention, reaction time) was demonstrated in four studies and reduced behavior (psychological arousal, correct answers, pain threshold) were shown also in four studies.

Exposure to low-level RF EMF, stimulating brain, can cause some improvement of behavior. On the other side, negative impact on behavior and arousal is evident.

Others

Positron emission tomography (PET) study reported significantly correlated with the estimated RF EMF amplitudes changes in brain glucose metabolism and its increase in the region closest to the antenna (Volkow et al. 2011). Another PET study indicated reduced cerebral metabolic rate of glucose in in the area close to the antenna (Kwon et al. 2011). The exposure did not affect task performance (reaction time, error rate). One study, using functional near-infrared spectroscopy, reported a slight influence of the RF EMF on frontal cortex oxygenation (Curcio et al. 2009).

These results support the suggestion that short-term changes in brain physiology are not obligatory related to human performance.

Dependence on exposure level

To study the dependence on exposure level, the selected for analyses studies are divided into groups according to exposure level (Table 2). While studies at SAR $>$ 2 W/kg are considered as a single group, the numbers of studies per group are following: 7 studies in the group of SAR $>$ 2; 22 studies in the group of SAR = 2–1.5 W/kg; 19 studies in the group of SAR = 1.5–1 W/kg; 10 studies in the group of SAR = 1–0.5 W/kg; 15 studies in the group of SAR =0.5–0.1 W/kg; and three studies in the group of SAR $<$ 0.1 W/kg.

Table 2. Studies grouped according to the level of exposure.

SAR W/kg	Effect	No effect
10.98		Sauter et al. 2011
7.82		Sauter et al. 2011
6	Sauter et al. 2015	Eggert et al. 2015
5		Regel, Gottselig, et al. 2007
3.75		Trunk et al. 2013
2.18	Lv, Su et al. 2014; Lv, Chen et al. 2014	
2-1.5	Croft et al. 2010; Leung et al. 2011; Lowden et al. 2011; Schmid et al. 2012; Vecsei et al. 2013; Sauter et al. 2015; Lustenberger et al. 2015; Verrender et al. 2016; Yang et al. 2017; Vecsei et al. 2018; Dalecki et al. 2018; Loughran et al. 2019; Lowden et al. 2019	Stefanics et al. 2008; Croft et al. 2010; Riddervold et al. 2010; Danker-Hopfe et al. 2011; Nakatani-Enomoto et al. 2013, 2020; Trunk et al. 2015; Eggert et al. 2015
1.5-1	Regel, Tinguely et al. 2007; Hung et al. 2007; Krause et al. 2007; Luria et al. 2009; Wiholm et al. 2009; Lustenberger et al. 2015; Verrender et al. 2016; Yang et al. 2017; Dalecki et al. 2018; Loughran et al. 2019	Fritzer et al. 2007; Haarala et al. 2007; Krause et al. 2007; Kleinlogel et al. 2008a, 2008b; Hillert et al. 2008; Kwon et al. 2009, 2010, 2011; Loughran et al. 2013
1-0.5	Bardasano et al. 2007; Curcio et al. 2008; Croft et al. 2008; de Tommaso et al. 2009; Curcio et al. 2009; Croft et al. 2010; Vecchio et al. 2010; Leung et al. 2011; Ghosn et al. 2015; Curcio et al. 2015	
0.5-0.1	Bachmann, Tomson, et al. 2007; Bachmann et al. 2018: Hung et al. 2007; Hinrikus Bachmann, Lass, Tomson, et al. 2008; Hinrikus, Bachmann, Lass, Karai, et al. 2008; Hinrikus et al. 2009; Suhhova et al. 2009; Hinrikus et al. 2011; Hinrikus, Bachmann, Lass et al. 2011; Lustenberger et al. 2013; Suhhova et al. 2013; Hinrikus et al. 2017	Regel, Gottselig, et al. 2007; Eltiti et al. 2009
<0.1	Suhhova et al. 2013	Zentai et al. 2015; Bueno-Lopez et al. 2021

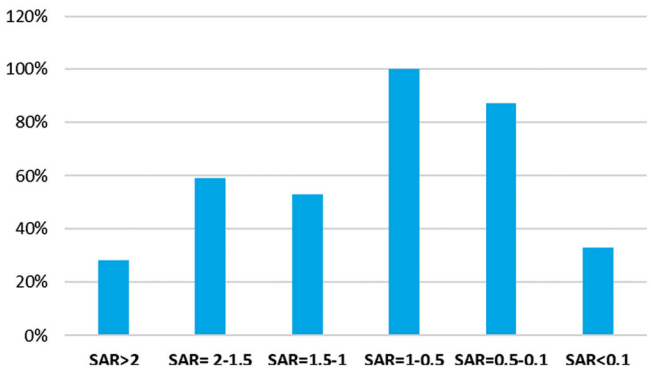


Figure 4. The rate of detected RF EMF effects in the groups of different SAR (W/kg) levels.

Figure 4 presents the rate of detected RF EMF effects in the groups. No any regular trend on the dependence of the effect on SAR level occurs. Unfortunately, only very few studies reported quantitative data about the intensity of the detected effects. The differences in the results can be caused rather by diversity of applied methods and used types of radiation. The fact that all studies at SAR = 1-0.5 W/kg indicated the effect can be considered as a chance. The group includes studies from different groups and various kind of the effects, no any reason exists for systematic advantage. The high rate of the detection 87% in the group SAR =0.5-0.1 W/kg can be explained by fact, that the majority of studies belong to one team. The team (Bachmann, Hinrikus, et al. 2007) has modified the modulation method used in Dicke radiometer (Tiuri 1964) to increase the sensitivity for the detection of changes in EEG. Therefore, small hidden in the variability of EEG changes can be detected and alteration not only in alpha but also in beta and gamma bands become evident.

The other reason for uncertainty of the results of analyses is that the majority of studies have been performed within quite narrow diapason of SAR levels between 2 and 0.1. Only few studies used higher and lower exposure levels.

According to the origin of low-level RF EMF effect mechanism (Figure 1), the effect is related to electric field strength causing rotation of dipolar molecules, not absorbed power. Therefore, electric field strength is more appropriate parameter for determining the experimental condition. Unfortunately, only very few authors have indicated field strength used in their experiments.

The dependence of the effect on exposure level can be evaluated better comparing data at two or more levels of exposure within the same study. Several studies performed experiments at two different SAR values. However, some of these studies reported no effect (Kleinlogel et al. 2008a, 2008b; Sauter et al. 2011; Danker-Hopfe et al. 2011; Eggert et al. 2015). Some others did not provide quantitative data for the results (Leung et al. 2011; Loughran et al. 2013; Sauter et al. 2015; Verrender et al. 2016; Dalecki et al. 2018).

Only one study reported quantitative data about changes at two different levels of exposure (Suhhova et al. 2013). At the higher SAR = 0.303 W/kg ($E = 24.5$ V/m) level, increases in the EEG beta2 (157%), beta1 (61%) and alpha (68%) frequency bands were detected. At the lower SAR = 0.003 W/kg ($E = 2.45$ V/m) level, increase only in the beta2 (39%) frequency band was evident. The decrease in the intensity of the effect at lower level about four times is much less than

expected according to the decrease of SAR (100 times). The relative decrease of the effect is rather close to the change in field strength (10 times).

The performed analyses are not helpful in clarifying regularity of the dependence of the effect on the level of radiofrequency radiation. Obviously factors other than the level of exposure plays important role in the low-level RF EMF effects. An important factor is modulation frequency that is expected being close to the EEG frequencies (Hinrikus, Bachmann, Lass, Tomson, et al. 2008; Hinrikus et al. 2011). According to studies analyzed in the current review, the lowest electric field strength at which the effect was detected is 2.45 V/m (SAR = 0.003 W/kg) (Suhhova et al. 2013).

Possible consequences on health

The transformation of the biological effects of radiation into health consequences is a chaotic process (disrupted-line arrows in Figure 1). A very weak initial alteration on neuronal or molecular level can lead to unpredictable consequences on health – or not cause any remarkable health effect. Therefore, the threshold of RF EMF consequences on health cannot be determined.

Main attention in evaluation of the RF EMF health effects has been directed to risk of tumors (Carlberg et al. 2013; Miller et al. 2019; Choi et al. 2020). Due to long latent period, diverse exposure conditions and biological parameters, the causal relationship is difficult to reveal. The recent meta-analyses of case-control studies found that cellular phone use with cumulative call time more than 1000 h statistically significantly increased the risk of tumors (Choi et al. 2020).

Less attention in evaluation of the RF EMF health effects has been directed to neurological diseases and mental disorders. There is a possibility that the RF EMF neurophysiological effect can cause neurological and mental disorders not obligatory related to oxidative stress and genetic instability. The cohort study on cellular telephones and central nervous system diseases risks observed the excesses of migraine and vertigo and a possible association with dementia and Parkinson (Schuz et al. 2009). The recent cohort study concludes that people using mobile phones most extensively reported weekly headaches slightly more frequently than other users (Auvinen et al. 2019).

The analyses in the current review show that alteration in EEG are similar in the high majority of the studies: increase in EEG alpha, beta and gamma band levels as well as higher complexity of the signal (Table 1). Similar changes in EEG are characteristic in major depression disorder (Knott et al. 2001; Fingelkurts and Fingelkurts 2015). Based on these EEG parameters, the quantitative measures for the detection of symptoms of depression have been discussed (Ahmadlou et al. 2012; Hosseinifard et al. 2013).

The causality between the RF EMF and depression is not clear. The results of the study based on a special questionnaire indicated association between higher mobile phone use and symptoms of depression (Thomee et al. 2011). However, it is complicated to differentiate between the direct effect of RF EMF and psychological factors related to the high use of mobile phones leading sometimes even to addiction (Gutiérrez et al. 2016; Lapierre et al. 2019).

Depression has become a common mental disorder during last decades with the highest prevalence among individuals aged 18-25 (13.1%) (NIH 2021). The levels of RF EMF have increased and the use of mobile telecommunication technology has become more intense with prevalence in young people during the same period. Is this a coincidence or causality?

The results of some studies demonstrate that at the same level of RF EMF exposure and identical conditions, only a part of people are affected (Hinrikus, Bachmann, Lass, Karai, et al. 2008; Bachmann, Tomson, et al. 2007). The rate of sensitive people varies from 13% to 31% depending on modulation frequency (Hinrikus, Bachmann, Lass, Tomson, et al. 2008). It is not clear are some people 'immune' to the RF EMF permanently or occasionally. The connection between 'immunity' and hypersensitivity is important for interpretation of RF EMF health effects.

The results of some studies indicate that RF EMF-related changes in neuronal system (EEG signal) are much more frequent than in subjective behavior (Vecsei et al. 2018). The exposure-induced effects have been seen in objective indicators (EEG, glucose metabolism) but not in cognitive performance (Schmid, Murbach, et al. 2012; Kwon et al. 2011). Therefore, people would not mention existing health symptoms of the RF EMF effect. The situation that objective physiological symptoms appear earlier than the subjective feeling and symptoms is quite usual in the case of many diseases.

Conclusions

The analyses of the model of the non-thermal mechanism of RF EMF effect shows that the steps of the model contain no principal threshold for the effect. Therefore, the only way to estimate the possible threshold is analyses of experimental data. The review of experimental data of human RF EMF neurophysiological effects results in following main conclusions that indicated the directions of future research:

1. The lowest field strength that has caused the effect in EEG, according to the reviewed studies, is 2.45 V/m (SAR = 0.003 W/kg), close to the radio and TV broadcasting RF EMF field strength about 0.1 V/m. The future large-scale human, animal and in vitro studies are required to clarify the level and to increase the reliability of the experimentally determined threshold of RF EMF effect.
2. There is a preliminary indication that the intensity of the effect follows rather the field strength than SAR alteration. However, no sufficient data are available for clarifying regularity and linearity-nonlinearity of the relationship. The studies with systematic variations in exposure level (electric and magnetic field strengths, power density) would help to advance the field. The

research from cellular to humans is needed in this direction.

3. Very limited data are available about the repair and adaptive phenomena important in the interpretation of the RF EMF effects on health. Special studies are required to clarify the mechanisms and possibilities of the repair processes.
4. The finding that only part of people are sensitive to RF EMF exposure can be related to immunity to radiation or hypersensitivity. The variability of sensitivity between people and long-term stability of the status required large-scale long-term experimental studies.
5. The indication that the changes in EEG caused by RF EMF appeared similar to these in depression need a special attention. The fast increase of depression with the highest prevalence among young individuals and more intense use of mobile telecommunication technology with prevalence in young people during the same period needs attention. The possible causal relationship between RF EMF effect and depression among young people is the problem of high importance. The methodology and large-scale investigations in this direction are required.

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