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Review

Comparing DNA damage induced by mobile telephony and other types of man-made electromagnetic fields

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ABSTRACT

The number of studies showing adverse effects on living organisms induced by different types of man-made Electromagnetic Fields (EMFs) has increased tremendously. Hundreds of peer reviewed published studies show a variety of effects, the most important being DNA damage which is linked to cancer, neurodegenerative diseases, reproductive declines etc. Those studies that are far more effective in showing effects employ real-life Mobile Telephony (MT) exposures emitted by commercially available mobile phones. The present review - of results published by my group from 2006 until 2016 - compares DNA fragmentation induced by six different EMFs on the same biological system - the oogenesis of Drosophila melanogaster - under identical conditions and procedures. Such a direct comparison between different EMFs - especially those employed in daily life - on the same biological endpoint, is very useful for drawing conclusions on their bioactivity, and novel. It shows that real MT EMFs are far more damaging than 50 Hz alternating magnetic field (MF) - similar or much stronger to those of power lines - or a pulsed electric field (PEF) found before to increase fertility. The MT EMFs were significantly more bioactive even for much shorter exposure durations than the other EMFs. Moreover, they were more damaging than previously tested cytotoxic agents like certain chemicals, starvation, dehydration. Individual parameters of the real MT EMFs like intensity, frequency, exposure duration, polarization, pulsing, modulation, are discussed in terms of their role in bioactivity. The crucial parameter for the intense bioactivity seems to be the extreme variability of the polarized MT signals, mainly due to the large unpredictable intensity changes.

1. Introduction

1.1. Microwave EMFs, DNA damage and related effects

The number of published peer review studies showing DNA damage and related effects induced by Radio Frequency (RF)/microwave Electromagnetic Fields (EMFs), especially by Mobile Telephony (MT) EMFs, on a variety of organisms/cell types under different experimental conditions is increased considerably in recent years [1–36], in spite of attempts to dispute some of them [37–39].

Specifically, the damage on reproductive cells of different animals found in several of the above studies explains other findings connecting microwave EMF exposure with insect, bird, and mammalian (including human) infertility [40–48], or reduction in bird and insect (especially bees) populations during the past 10–15 years [49–53].

The effects on DNA and reproduction reported by different labs on a variety of animals demonstrate a remarkable similarity. For example, Sharma and Kumar [47] found a large decrease in reproduction (egg laying) of bees after exposure to mobile phone radiation, which was identically observed before in fruit flies [15,16,41,42] and birds [49–51]. The recorded decreased reproduction is strongly corroborated by very similar effects in amphibians [54,55], rats [17,46], and human sperm [44]. This unique similarity of effects in different organisms found by different research groups can be explained by the observed cell death induction in reproductive cells due to DNA damage found for Drosophila ovarian cells [15,16], human sperm cells [22], mice and rat sperm cells [10,17], and chick embryos [36]. It is evident that such a similarity of findings is not a coincidence.

It is important to note that the exposure levels in the majority of the above studies were below the officially accepted exposure limits [56] and only in a few of them [4–6,13] they were slightly exceeding these limits.

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1.2. Microwave EMFs, electro-hypersensitivity, and cancer

During the past 15 years several statistical studies indicate a connection between residential exposure to radiation of MT base station antennas (which emit similar radiation with that of mobile phones), and reported symptoms of unwellness usually referred to as "microwave syndrome", or "electro-hypersensitivity" (EHS). These include headaches, fatigue, sleep disorders, etc. [57–63]. Similar effects that were previously categorized as medically unexplained symptoms (MUS) are recently attributed to chronic stress and inflammation [64]. Recently, in an effort to find objective methods for EHS evaluation, ~80% of EHS self-reporting patients were found to present oxidative stress biomarkers in their peripheral blood [65] which is strongly related to DNA damage.

At the same time, more and more epidemiological studies indicate an increasing connection between mobile phone use and brain tumors in humans, [66–75]. The time length of cancer development after cellular damage may be many years depending on the animal and the type of cancer. It is called latency period and is defined as the time between the initial causative event and the development of clinically recognizable cancer. The latency period for gliomas (type of brain cancer) is more than 20 years in humans [76]. This probably explains why epidemiological studies only recently have started showing a connection between mobile phone use and cancer.

Tumor promotion in experimental animals after long-term RF exposure at levels below the officially accepted limits is also reported [77,78]. In a recent study of the USA National Toxicology Program (NTP) rats were exposed for 2 years, 9 h per day, in a simulated near field of a mobile phone antenna emitting 2nd generation (Global System for Mobile telecommunications - GSM) or 3rd generation (Code Division Multiple Access - CDMA) EMFs. [The CDMA is part of the Universal Mobile Telecommunication System – UMTS]. Exposed rats developed brain cancer (glioma) and heart cancer (malignant schwannoma) for both lower (1.5 W/kg) and higher (3, and 6 W/kg) Specific Absorption Rate (SAR) levels than the current exposure limit (2 W/kg) for the human head [56,79]. An Italian life-span exposure study of rats in a simulated GSM 1800 far field, also found induction of heart schwannomas and brain glial tumors, in agreement with the results of the NTP study [80].

These findings are in agreement with the above reported DNA damage findings, since DNA damage is a main cause of cancer [81,82]. Alternatively, DNA damage may result in cell death, reproductive declines, or neurodegenerative diseases [83,84].

1.3. Combination of frequency bands in telecommunication microwave EMFs

It is important to note that except for the RF/microwave carrier frequency, Extremely Low Frequencies - ELFs (0–3000 Hz) are always present in all telecommunication EMFs in the form of pulsing and modulation. There is significant evidence indicating that the effects of telecommunication EMFs on living organisms are mainly due to the included ELFs [29,30,85–91]. For example, Frei et al [87] found that a 2.8 GHz RF EMF pulsed on 500 Hz was significantly more effective in increasing heart rate in rats than the corresponding continuous wave (CW) (un-pulsed) RF 2.8 GHz EMF with the same average intensity and exposure duration. Huber et al [90] found exposure to 900 MHz RF EMF pulse modulated on GSM MT ELFs, to induce changes in the human electro-encephalogram (EEG), while the corresponding CW signal (same RF frequency un-pulsed) with the same exposure duration did not. Similarly, Franzellitti et al [29] found that a 1.8 GHz RF signal amplitude-modulated by GSM pulsing ELFs induced DNA damage in cultured human trophoblast cells, while the same signal un-modulated (CW), with the same exposure duration, was ineffective. Moreover, ELF EMFs alone are found independently to be bioactive, as are RF EMFs modulated or pulsed by ELFs [92–94]. Bawin and Adey [92] found that the ELF sinusoidal signals used previously to modulate a RF carrier CW EMF [85,86] induced alone (without the RF carrier) alterations in Ca^{2+} concentration in chicken and cat brain cells as did the modulated RF EMF, while the RF carrier alone (un-modulated) was ineffective.

These experimental results are in agreement with the "ion forced-oscillation mechanism" for irregular gating of electro-sensitive ion channels on cell membranes which predicts that pulsing EMFs are more bioactive than CW EMFs of the same other parameters, and that the biological activity of any specific type of EMF is inversely proportional to its frequency and proportional to its intensity [95–97]. The International Agency for Research on Cancer (IARC) has classified both ELF and RF EMFs as possibly carcinogenic to humans [98,99].

1.4. Conflict between experimental studies due to unrealistic exposures

An extremely important observation is the intense opposition between the results of experimental studies that employ real exposures from commercially available devices (mobile phones or other telecommunication devices), and studies employing simulated exposures from generators or "test" phones with similar but invariant parameters such as intensity, frequency etc. While ~50% of the studies employing simulated exposures do not find any effects, studies employing real-life exposures from commercially available devices display an almost 100% consistency in showing adverse effects [34–36,84,100–118]. A wide variety of biological and clinical effects are already found to be induced by real-life exposures on a similarly wide variety of animals/biological samples including human volunteers exposed in vivo (19 studies) [19,34,35,100,104,106–109,114,116], human sperm in vitro (2 studies) [23,100], mice or rats or guinea pigs or rabbits in vivo (24 studies) [100,102,103,105,110,111,115,117], Drosophila (11 studies) [15,16,26,31,41,42,100,101,140,141], bees (4 studies) [47,100,118], ants (1 study) [100], chick embryos (3 studies) [36,45,100], quails (1 study) [100], human cells in vitro (2 studies) [100,112], cow brain tissue in vitro (1 study) [113], mouse cells in vitro (1 study), protozoa (1 study), and even purified proteins in vitro (1 study) [100]. From a total of 71 studies reviewed above that employed real exposures 68 recorded significant adverse effects (95.8%) ranging from loss of orientation, kinetic, behavioural, or EEG changes, heart rate changes, effect on cognitive function and memory impairment, effect on cell growth and proliferation, temperature increases in brain tissue, to decrease in male and female reproductive capacity, reproductive declines, molecular changes, changes in enzymatic activity, biochemical changes in the pregnant women and their embryos, DNA damage and cell death, protein damage, and histopathological changes in the brain [34–36,84,100–118]. From the remaining three studies, two reported no effect and one reported an increase in short-term memory of children which we did not count as an adverse effect although it may be [100,106]. Nineteen of the above 71 studies were published within the last three years [35,36,102–118] after the publication of the observation that real exposures induce stronger effects than simulated ones [100]. (For real exposure studies published up to 2015, see Refs. [34,101], and reviews [84,100]. For real exposure studies published from 2016 up to today references are [35,36,102–118]).

The only difference between real and simulated electromagnetic signals emitted by modern telecommunication devices/antennas (and corresponding exposures) is that real ones are highly and unpredictably variable each moment (especially in their intensity), while simulated ones have fixed parameters, and thus are invariable and totally predictable.

Although experimental studies employing real-life microwave telecommunication exposures are obviously much more effective in showing effects, there also seems to be an overall predominance (~60%) of studies showing effects. In a recent review of in vitro studies investigating a variety of microwave effects in many different cultured cell types regardless of real-life or simulated exposure, from a total of 161 studies, 98 found effects (60.87% of the studies), and 63 did not [119].

1.5. Comparison of bioactivity between MT and other types of man-made EMFs

Comparison studies between different EMFs on the same biological model/endpoint under the same conditions and procedures are rare in the scientific literature, in spite of the fact that they can be very useful in drawing conclusions on the bioactivity of the different physical parameters between EMFs. Such studies are those already discussed above [29,30,85–91] which suggested that the ELF pulsing and modulation is mainly responsible for the biological effects of the modulated (information carrying) RF EMFs and not the RF carrier itself. This observation is of great importance in terms of protection/safety especially in the case of modern types of microwave/RF telecommunication EMFs all of which increasingly employ ELF pulsing (and modulation) in order to increase the density/amount of transmitted information (see 4.3). A recent study by D'Silva et al [36] compared bioactivity between 2nd (GSM) and 3rd (UMTS) generation MT EMFs emitted by real mobile phones on chick embryo development and found that both induced DNA damage and structural changes, with the UMTS being even more bioactive than the GSM.

There are a few studies comparing power frequency (50–60 Hz) EMFs with CW RF EMFs. These RF fields bear no similarity with real modern telecommunication RF EMFs basically due to the absence of ELF pulsing and modulation. Marchionni et al [120] found a 50 Hz alternating Magnetic Field (MF) to be able to stimulate ion channels in rat sensory neurons while a 900 MHz CW EMF was not. Lin et al [121] found that a 50 Hz EMF (60 G, 205 V/m) or a 2 GHz CW RF EMF 20 V/m, could both upregulate gene transcription in yeast.

Two studies were found comparing 50–60 Hz fields with simulated MT EMFs. These studies are closer to reality than the CW RF studies, but not close enough since they did not employ real MT EMFs. Simulated MT EMFs include ELF pulsing at the same average frequencies and intensities as the real ones, but this pulsing is totally invariant and thus predictable, in contrast to the real fields in which ELFs (and RFs) vary unpredictably each moment [84,99,100]. Therefore, simulated MT EMFs are certainly expected to be more bioactive than CW RF EMFs, but not as bioactive as real MT EMFs. A study by Belyaev et al [8] reported that GSM 900 simulated exposure by a "test" phone (with SAR = 0.037 W/kg), or exposure of equal duration (2 h) to 50 Hz alternating MF (with intensity 0.15 G), induced chromatin condensation (a sign of cell death) in human lymphocytes at similar degrees. A more recent study by Duan et al [122] compared a 50 Hz alternating MF (10, 20, or 30 G) with a simulated GSM 1800 MHz EMF (1, 2, or 4 W/kg) with the same exposure duration, and found only the strongest fields of both types (both exceeding ICNIRP limits) to be able to induce DNA damage at more or less comparable degrees, although of different patterns.

The direct comparison of effects on the same biological model under identical conditions and procedures between MT EMFs, and a 50 Hz alternating MF is important, since 50 Hz alternating MFs are those of power lines which are accused for carcinogenicity long before the MT EMFs [123–126], and both types of EMFs are classified as possible carcinogens [98,99].

A specific aim of the present review (apart from reviewing other related studies), is the direct comparison of DNA fragmentation recorded in our previous studies on Drosophila ovarian cells, under identical conditions and experimental procedures, induced by six different man-made EMFs: GSM 900, GSM 1800 [15,16], 50 Hz alternating MF 1, 11, 21 G [94], and 8 kHz (44.4 Hz pulse repetition rate), 400 kV/m, pulsed electric field (PEF) [127]. Moreover, to draw conclusions on which specific physical parameters of the EMFs are most responsible for the recorded bioactivity. In this case the MT EMFs are real ones and thus this comparison is novel.

1.6. Drosophila oogenesis as a detector for EMF-induced DNA fragmentation

Each ovary of an adult female Drosophila consists of 16 to 20 ovarioles. Each ovariole is an individual egg assembly line, with new egg chambers produced in the most anterior cyst called germarium (g). During oogenesis, new egg chambers produced by specific stem cells bud off the germaria and develop through 14 successive developmental stages (S1-S14) moving toward the posterior end to be fertilized and laid through the oviduct. Each egg chamber consists of a cluster of 16 germ cells, surrounded by an epithelial monolayer of somatic follicle cells (FCs) responsible for building the egg shell. In the germarium, the germline cyst originates from a single cell, (cystoblast), which undergoes four mitotic divisions to form the 16-cell cluster. Among the 16 germ cells, one differentiates as the oocyte (OC) - the single cell which after fertilization will give the embryo - and the rest become nurse cells (NCs) which will serve as nutrients for the OC. Therefore, each egg chamber in the ovaries of female Drosophila consists of three different types of cells; a single OC, 15 NCs, and up to ~1200 FCs [128–132].

NCs and FCs, undergo Programmed Cell Death (PCD) during the late oogenesis stages 11–14 after they have completed their role and are no longer needed, exhibiting DNA fragmentation, actin cytoskeleton disorganization, chromatin condensation, and phagocytosis of the cellular remnants by the adjacent follicle and epithelial cells [128–130].

In addition to PCD during late oogenesis, Stress-Induced Cell Death (SICD) may take place during the early- and mid-stages (from germarium up to stage 10) in cases that certain egg chambers do not develop normally due to starvation or other stress factors, [128–130]. Both PCD and SICD occur after DNA fragmentation. The most sensitive developmental stages during oogenesis for SICD, are the germarium referred to as the "germarium checkpoint" or "early oogenesis checkpoint", and stages 7–8 just before the onset of vitellogenesis (stages 8–10), referred to as the "mid-oogenesis checkpoint" [129,130]. Both checkpoints were found to be very sensitive to stress factors such as poor nutrition [129], or exposure to cytotoxic chemicals like etoposide or staurosporine [128]. In all cases, the stress-induced DNA fragmentation at the two checkpoints was observed only in the NCs and FCs, not in the OC. Moreover, apart from the two checkpoints, egg chambers were not observed before our experiments [15] to degenerate during other stages of early- or mid-oogenesis [15,128–132].

In our experiments we studied DNA fragmentation induced by different types of man-made EMFs, not PCD. For this reason, late oogenesis egg chambers (stages 11–14) were excluded, and we only examined egg chambers from germarium up to stage 10.

2. Exposure details and experimental methods

In each experiment with all six different EMFs, newly emerged adult *Drosophila melanogaster* flies from the stock were collected; anesthetized very lightly with diethyl ether and separated males from females. The collected flies were then put in groups of ten males and ten females in standard laboratory glass vials, with standard food forming a smooth plane surface 1 cm thick at the bottom of the vials. The glass vials were closed with cotton plugs. Detailed descriptions were given before [15,16,41,42,94,127].

The exposures to the EMFs started on the first day of each experiment (day of eclosion), 1 h after all flies were fully awaken from the anesthesia, and lasted for a total of 120 h (5 days). The net duration of exposure/sham-exposure to each individual EMF, and the field/radiation intensities ± standard deviation (SD) were as follows: a) Exposure/Sham-Exposure to the GSM 900 or 1800 EMFs for 6 min every 24 h (36 min total) with the handset in "talk" mode and in contact with the vials (RF radiation intensity ~0.378 ± 0.059 mW/cm^2, ELF E-field

~19 ± 2.5 V/m, ELF B-field ~0.9 ± 0.15 mG for GSM 900 and ~30% lower corresponding values for GSM 1800, highest SAR for human head of the handset used in our experiments given by the manufacturer 0.89 W/kg) [15,16]. b) Exposure/Sham-Exposure to the 50 Hz alternating MF (1 or 11 or 21 G) continuously for the 5 days (120 h total) within especially designed and constructed coils [94]. c) Exposure/Sham-Exposure to the 8 kHz (44.4 Hz pulse repetition rate), 400 kV/m PEF for 30 min every 2 h during the 5 days (30 h total) in especially designed and constructed capacitors [127]. [This PEF roughly resembles the atmospheric EMFs (sferics) produced by lightning during thunderstorms. These have a ~10 kHz carrier frequency (instead of 8 kHz) with a ~20 Hz pulse repetition (instead of 44.4 Hz). The shape of the pulses is in both EMFs bipolar damping) [127,133]].

Then, 120 h after the beginning of exposure/sham-exposure, the flies were removed from the glass vials, the females were collected, anesthetized, and dissected. Egg chambers from germarium up to stage 10 were collected from both ovaries, and fixed for the TUNEL (Terminal deoxynucleotide transferase dUTP Nick End Labeling) assay, as described before [15,16,94,127].

The TUNEL assay is a known marker for DNA fragmentation (severe DNA damage including single and double strand breaks). According to this assay, fluorescein dUTP (a fluorescent substance) binds through the action of terminal transferase (an enzyme that catalyzes the specific biochemical reaction), onto fragmented genomic DNA which then becomes labelled by characteristic fluorescence. The label incorporated at the damaged sites of DNA is visualized by fluorescence microscopy [134].

3. Comparing DNA damage from the different EMFs

The comparison of DNA fragmentation in Drosophila ovarian cells (sum ratio of TUNEL-positive to total number of egg chambers) between GSM 900, GSM 1800, 50 Hz MF 1 G (MF1), 11 G (MF2), 21 G (MF3), and PEF 400 kV/m, is presented in Table 1, and Fig. 1.

MT EMFs were found to be significantly more hazardous than the other types of EMFs inducing DNA fragmentation in a much higher degree even though the durations of daily exposure to the other EMFs were significantly longer than the 6 min daily exposure to MT EMFs.

More specifically: GSM 900 or GSM 1800 mobile phone radiation with total exposure duration 36 min induced DNA fragmentation to up to 50.16% of the egg chambers in the ovaries of the exposed females (with the GSM 900 being more bioactive than GSM 1800 basically due to its higher intensity) [15,16] (Table 1, Fig. 1). The corresponding percentages for 1, 11, and 21 G, 50 Hz MF exposure were up to 7.52% with total exposure duration 120 h [94] (Table 1, Fig. 1). Finally, the corresponding percentage for the PEF was 2.74% with total exposure duration 30 h [127], (Table 1, Fig. 1). [The above percentages (as in Table 1) refer to the difference in the percentage of egg chambers with fragmented DNA between exposed and sham-exposed animals. If we referred to % deviation (increase) in DNA damage of the exposed in regards to the sham-exposed, the corresponding percentages would be much greater (669.6% for the GSM EMFs, 114.8% for the MF, and 47.7% for the PEF)].

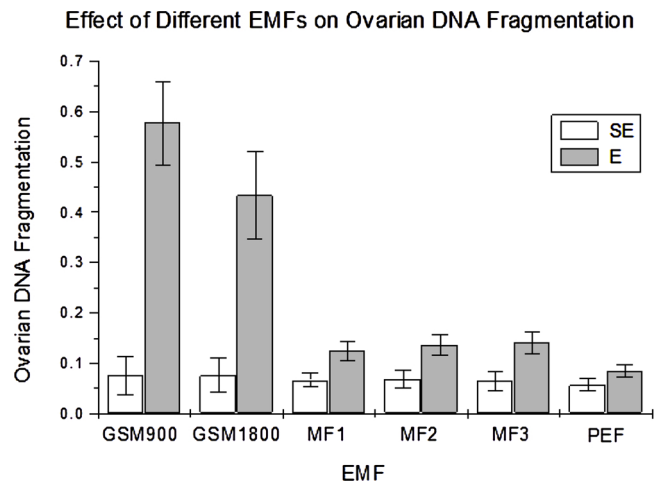

Fig. 1. Ovarian DNA Fragmentation (ratio of TUNEL-positive to total number of egg chambers), induced by six different EMFs [GSM 900, GSM 1800, 1 G MF (MF1), 11 G MF (MF2), 21 G MF (MF3), and 400 kV/m PEF], under identical conditions/procedures. E: exposed groups, SE: sham-exposed groups.

It should be emphasized that while the mobile phone EMFs/radiation exposed the samples at the very same intensity levels as users are daily exposed by mobile phones, the intensities of the other EMFs were significantly higher than the environmentally accounted ones: 1) The strongest MF intensity accounted at the closest proximity to the most powerful power lines is usually significantly less than 1 G or 0.1 m T [94]. In our experiments exposure to 1 G caused 5.72% increase in ovarian DNA fragmentation, while 11 G caused 6.71%, and 21 G caused 7.52% DNA fragmentation [94] (Table 1, Fig. 1). 2) The PEF similar to those of atmospheric discharges (sferics) exposed the animals at 400 kV/m, while sferics are sensed by sensitive individuals at (totally polarized) intensities down to ~0.35 V/m (approximately ~1000 km from a thunderstorm) [127,133].

From the above comparison, it follows that (real) MT EMFs are much more bioactive than the other EMFs, and - most important - much more bioactive than the 50 Hz alternating MF which was (and is still) accused for carcinogenicity, long before the MT EMFs.

Previously examined stressors like cytotoxic chemicals such as etoposide or staurosporine, or poor nutrition were only observed to induce DNA fragmentation, exclusively in the NCs and the FCs, and exclusively at either one of the two checkpoints (germarium and stages 7–8) during early and mid-oogenesis [128–130,132]. Thus, they were not found to induce DNA fragmentation in the OC, neither at developmental stages other than the two checkpoints. Later it was found that the absence of water (dehydration) can induce DNA fragmentation at more developmental stages in addition to the two checkpoints, but again not in the OC [135].

Fig. 2 shows an ovariole of an unexposed female with TUNEL-

Table 1
Effect of Different EMFs on Ovarian DNA Fragmentation.

EMF	Ratio of TUNEL-positive to total number of egg-chambers (**Exposed**) ± SD	Ratio of TUNEL-positive to total number of egg-chambers (**Sham-Exposed**) ± SD	**Difference** in DNA fragmentation between Exposed and Sham-Exposed Groups	*P*-value, between Exposed and Sham-Exposed groups
GSM 900	0.5772 ± 0.083	0.075 ± 0.038	+ 50.16 %	< 0.0002
GSM 1800	0.4339 ± 0.087	0.062 ± 0.034	+ 35.77%	< 0.0005
MF 1	0.1243 ± 0.019	0.0671 ± 0.014	+ 5.72%	< 0.001
MF 2	0.1367 ± 0.02	0.0696 ± 0.018	+ 6.71%	< 0.001
MF 3	0.1407 ± 0.021	0.0655 ± 0.019	+ 7.52%	< 0.001
PEF	0.0848 ± 0.012	0.0574 ± 0.012	+ 2.74%	< 0.05

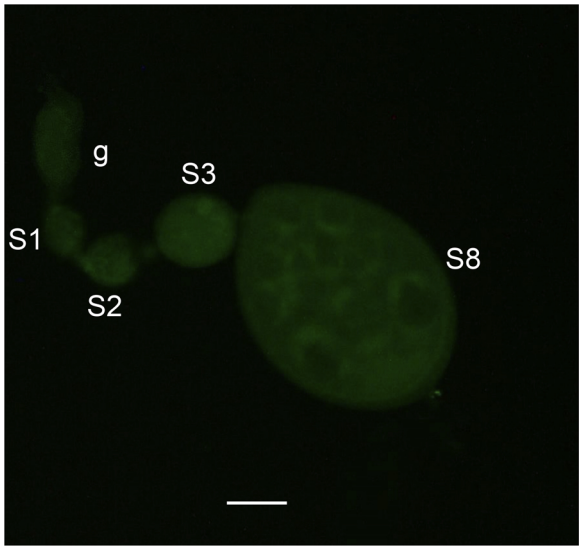

Fig. 2. Normally developed ovariole of an unexposed female Drosophila, containing egg chambers from germarium (g) up to stage 8 (S8), all TUNEL-negative. Bar: 10 µm.

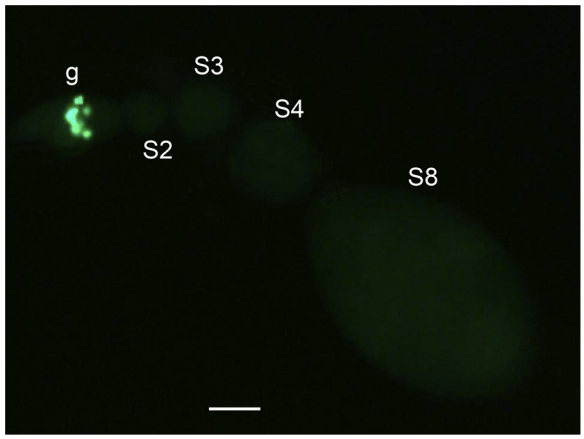

Fig. 3. Ovariole of an exposed to 1 G (0.1 mT) MF female Drosophila, containing egg chambers from germarium (g) up to stage 8 (S8), with fragmented DNA only at the germarium and TUNEL-negative at all other developmental stages. Bar: 10 µm.

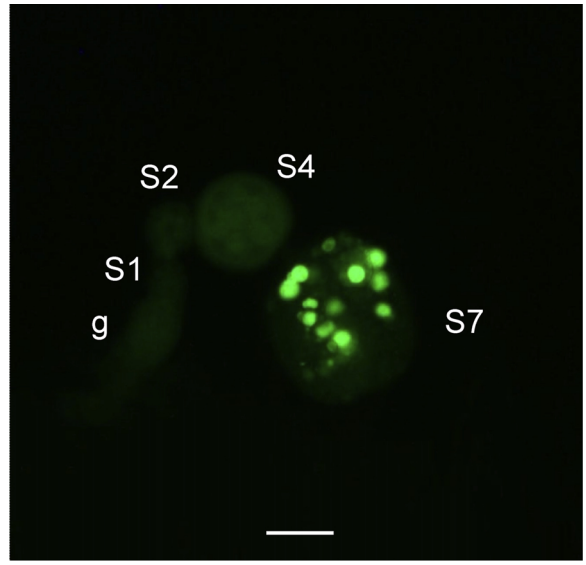

Fig. 4. Ovariole of an exposed to PEF female Drosophila, containing egg chambers from germarium (g) up to stage 7 (S7), with fragmented DNA only at the stage 7 egg chamber and TUNEL-negative at all other developmental stages. Bar: 10 µm.

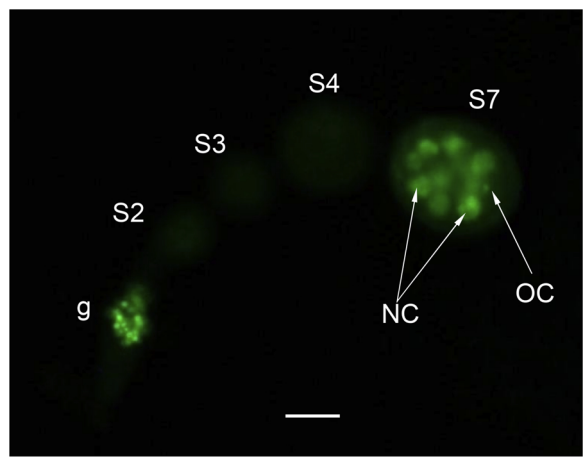

Fig. 5. Ovariole of an exposed to 21 G (2.1 mT) MF female Drosophila, containing egg chambers from germarium (g) up to stage 7 (S7), with fragmented DNA in the nurse cells (NC) at both checkpoints, germarium and stage 7, and TUNEL-negative at all other developmental stages. In the stage 7 egg chamber, the TUNEL-positive signal is evident also in the oocyte (OC). Bar: 10 µm.

negative egg chambers at all stages. Figs. 3–5 show ovarioles of females exposed to MF (Fig. 3,5), or exposed to PEF (Fig. 4). The degree of damage induced by the PEF or the MF is more or less comparable with that from other cytotoxic agents (except for dehydration) examined before [94,127–129] and smaller than the damage caused by dehydration [135]. Only in a few cases, exposure to the strongest MF (21 G or 2.1 m T) caused DNA damage also in the OC (Fig. 5), something that was not observed with any other examined cytotoxic agent [94,128,129,135]. [The nucleus of the OC is distinct as is smaller than the nuclei of the NCs (Fig. 5, 7)].

Mobile phone EMF/radiation exposure during normal "talk" mode was found to induce DNA fragmentation, not only at the two checkpoints, but at all developmental stages during early- and mid-oogenesis (from germarium up to stage 10), and moreover to all three types of egg chamber cells, i.e. NCs, FCs and the OC [15,16].

Figs. 6 and 7 show ovarioles of females exposed to MT EMFs exhibiting a TUNEL-positive signal at all developmental stages during early and mid-oogenesis and in all three types of egg chamber cells (NCs, FCs, OC). Thus, MT EMFs were found to be significantly more bioactive than all other previously examined stress factors (etoposide, staurosporine, starvation, dehydration), although a direct comparison is not possible.

4. Discussion

4.1. What does the comparison of effect of different EMFs on Drosophila ovarian DNA show?

We compared results from previous studies in which we used the Drosophila oogenesis as a sensitive biological system, and the TUNEL assay to record DNA fragmentation in the ovarian cells induced by six different man-made EMFs under identical conditions and procedures. The six different EMFs: were 1) GSM 900 mobile phone radiation, 2) GSM 1800 mobile phone radiation [15,16], 3) 1 G, 50 Hz alternating MF (MF1), 4) 11 G, 50 Hz alternating MF (MF2), 5) 21 G, 50 Hz alternating MF (MF3) [94], and 6) PEF (8 kHz, 44.4 Hz, 400 kV/m) found before to increase fertility [127], similar to EMFs of atmospheric

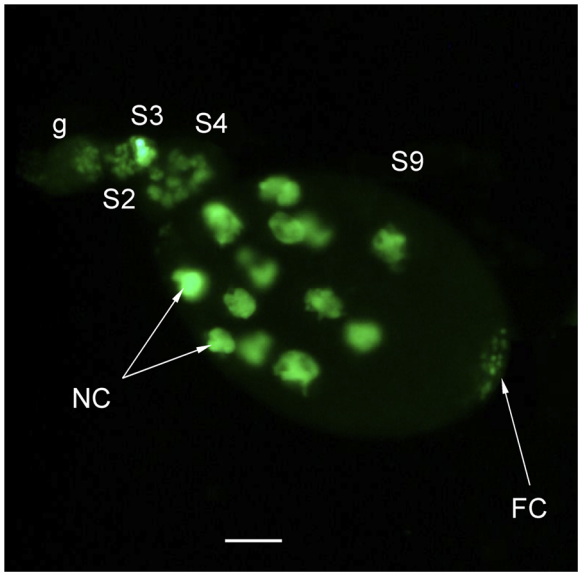

Fig. 6. Ovariole of an exposed to MT EMF (GSM 1800) female Drosophila, containing egg chambers from germarium (g) up to stage 9 (S9), with fragmented DNA in the nurse cells (NC) at all developmental stages from germarium up to stage 9. At the stage 9 egg chamber the TUNEL-positive signal is evident also in the follicle cells (FC). Bar: 10 µm.

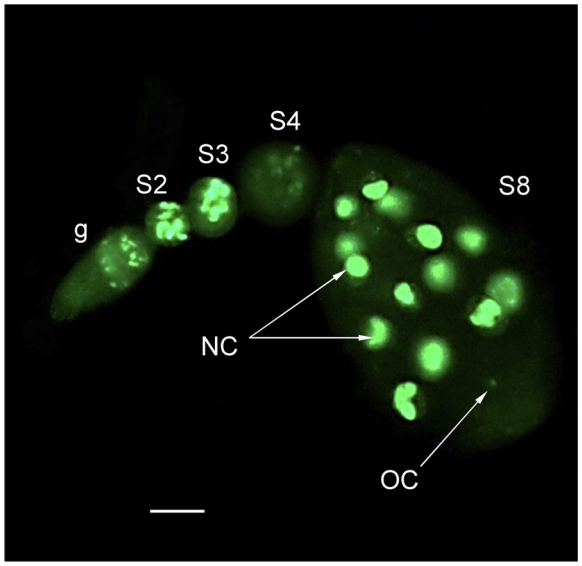

Fig. 7. Ovariole of an exposed to MT EMF (GSM 900) female Drosophila, with fragmented DNA in the nurse cells (NC) at all developmental stages from germarium (g) up to stage 8 (S8). At the stage 8 egg chamber the TUNEL-positive signal is evident also in the oocyte (OC). Bar: 10 µm.

discharges [133].

From the comparison it becomes obvious that the MT EMFs (GSM 900, GSM 1800) are far more damaging than the 50 Hz MFs, or the PEF (Table 1, Fig. 1). Moreover, MT EMF exposure was found to induce DNA fragmentation in Drosophila ovarian cells more than other types of external stress examined before like certain chemicals (etoposide or staurosporine), starvation, or dehydration. The MT EMFs were found to induce DNA fragmentation not only at the two most sensitive developmental stages (checkpoints) but at all developmental stages during early- and mid-oogenesis (from germarium up to stage 10), and in all three kinds of egg chamber cells (i.e. not only in the NC and FC but also in the OC). DNA fragmentation in the OC may result, if not in cell death, in heritable mutations transferred to the next generations. Such a possibility can be far more dangerous than a reduction in the offspring, since it may lead to cancerous or mutated organisms. The 50 Hz alternating MF or the PEF were found to induce DNA fragmentation at more or less comparable degrees with the non-electromagnetic agents.

The observed DNA fragmentation is an indirect effect, since EMFs compared in the present study are non-ionizing, meaning they do not cause direct ionization. The indirect effect on DNA can be induced by irregular release within the cell of oxidative free radicals or hydrolytic enzymes like DNases, which may occur after irregular gating of voltage-gated ion channels on the cell membranes caused by ELF EMFs, such as the ELF pulses and modulation always present in MT EMFs/radiation. Irregular gating of ion channels in cell membranes by EMFs is described by the "ion forced-oscillation mechanism" [95–97], and may lead to disruption of the cell's electrochemical balance and function [136,137]. The validity of this mechanism has been verified by computer numerical test. Other mechanisms suggested before failed to pass the same test [138]. The same mechanism was recently applied successfully to explain health symptoms caused by atmospheric discharges (lightning) reported for decades but never explained before [133].

Despite many other studies that report no effects [93,94,98–100,106,119], the consistency and remarkable similarity of many of the reported effects - including the most detrimental DNA damage - and the rapidly increasing number of the studies reporting effects during the recent years is alarming. All studies from different research groups and on different biological models/endpoints cited in the Introduction of the present study exhibit mutually supportive results and this makes unlikely the possibility that these results could be wrong or due to randomness.

In addition to remarkable gene similarities, the basic cellular processes are identical in insect and mammalian cells. All cells in both insects (including *Drosophila*) and mammals (including humans) have the same type of cell membranes, are full with billions of identical free ions like calcium (Ca^{+2}), potassium (K^{+}), sodium (Na^{+}) etc, initiating and accompanying all cellular events, and have the same intracellular organelles like mitochondria, ribosomes, endoplasmic reticulum, nucleus containing the cell's genomic DNA with the same basic structure, chemical elements and bonds in all organisms, etc. [139]. These similarities at the cellular level between all animals are more fundamental than differences in volume, mass, shape, macroscopic functions, intelligence, etc, since all health effects are initiated at the cellular level. Thus, it is reasonable to assume that a cellular effect caused by EMFs on *Drosophila* (e.g. DNA damage) can be expected to occur also in the human organism. The great advantage in studying the effect on Drosophila is - among others - the much shorter life-cycle due to which, an effect can be observed within a few hours or days, while in mammals it would take much longer.

4.2. Examination of physical parameters responsible for the intense bioactivity of MT EMFs

It is evident that real-life microwave telecommunication EMFs are very bioactive. The question arising is, which specific parameter(s) of this type of EMFs is mainly responsible for this intense bioactivity?

Plea of experimental data in combination with theoretical calculations [16,97,100,140,141] point that the most important physical parameters of EMFs in terms of bioactivity, are: 1) polarization (in combination with coherence), 2) ELF components (pulsing, modulation, etc.), 3) field/radiation intensity, 4) exposure duration, 5) field variability.

Let us now examine the individual parameters of the specific EMFs compared in the present study: 1) All six EMFs were totally (linearly) polarized (and coherent), therefore we must exclude polarization/coherence as the critical parameter. 2) All six of them include ELFs, three of them (GSM 900, GSM 1800, PEF) were pulsed on ELF, and still the PEF did not cause significant DNA fragmentation, therefore we must also exclude ELF and pulsing. 3) Although a direct comparison in

intensity is not possible due to the different frequencies and waveforms among the MT, MF, and PEF EMFs, the MT EMFs were at environmentally accounted intensities, while the other EMFs were at significantly higher intensities than environmentally accounted ones, and still the effect induced by the MT EMFs was much stronger. Therefore, we must also exclude field/radiation intensity. 4) The MT EMFs were the most bioactive despite the shortest exposure duration, therefore we must also exclude exposure duration.

What else was different in the MT EMFs than in the other four EMFs? Obviously the answer is the *variability* of the exposure. The parameters of the (real) MT fields (and especially intensity and waveform) change tremendously and unpredictably each moment during the exposure (even though average intensity values over a few min or more may not change very much), while the parameters of the MFs and the PEF are invariable (apart from the constant alternation or the constant pulsing of the carrier wave which are absolutely predictable).

Now is time to go back to the previous studies in which they also compared the action of GSM and 50 Hz alternating MF exposures. In the Belyaev et al study [8] the effects induced by the two EMFs were of similar degrees. The intensities of both types of EMFs were smaller in that study than in our studies. More specifically, the intensity (SAR) of the GSM EMF was ~10 times smaller, and the intensity of the MF 140 times (21/0.15) smaller than the strongest one in our studies. That means the balance between the two EMFs in our studies favored the (strongest) MF by ~14 times than in [8], and in addition the exposure to the MF was much longer (120 h) in our studies than the exposure to the GSM EMFs (36 min), while in [8] the exposures were of equal durations. And still, in our studies the effect of the GSM EMF was much stronger than the corresponding effect of the 50 Hz MF. What was different? Obviously, the difference was that we employed real-life highly variable GSM EMFs emitted by commercially available mobile phones [15,16], while Belyaev et al [8] employed simulated GSM EMFs with invariable parameters emitted by "test" mobile phones.

Similarly, in the Duan et al study [122] the effects induced by the 50 Hz MF (30 G) and by the simulated GSM EMF (4 W/kg) were of similar degrees. Their intensities in both fields were stronger than in our studies [15,16]. More specifically, the intensity (SAR) of the GSM EMF was ~4.5 times bigger (4/0.89), and the intensity of the MF 1.43 times bigger (30/21) than the strongest one in our studies. That means the balance between the two EMFs in their study favoured the GSM EMF by ~3 times than in our studies, and in addition their exposures were of equal durations, while in our studies the exposure to the GSM EMFs was much shorter than the exposure to the MF. And still, in their study the effect of the GSM field was much smaller than in our studies (of similar degree with that of the MF), since in our studies the effect of the GSM EMF was much stronger than the corresponding effect of the 50 Hz MF. Again, the crucial difference was obviously the real GSM exposure employed in our studies [15,16] being much more bioactive than the simulated invariable exposure by a generator employed in the Duan et al study [122].

4.3. The inherent variability of the real MT EMFs and its role in bioactivity

All types of modern microwave telecommunication EMFs such as MT, domestic cordless phones (DECT), wireless internet (Wi-Fi), combine RF fields (with frequency on the order of ~1 GHz) as the carrier signals, with ELF fields (0–3000 Hz) to modulate the carrier and for increasing the capacity of transmitted information by pulsing the signal. GSM EMFs, emitted by mobile phones and base antennas, except for their RF carrier signal, (900, 1800, 1900 MHz) include a pulse repetition frequency 217 Hz, plus other ELFs such as the multi-frame repetition frequency of 8.34 Hz. UMTS (3rd generation) mobile phones and base station antennas emit an RF carrier signal at 1900–2100 MHz, with two pulsing ELFs, at 100 Hz ("Time Division Duplex"), and 1500 Hz ("Adaptive Power Control"). During any conversation with either GSM or UMTS mobile phones, there are constant unpredictable changes related with the varying information transmitted each moment. Moreover there are continuous sudden unexpected changes in intensity, due to changes in location, number of subscribers using the network each moment, atmospheric conductivity changes, etc. which may exceed 100% of average intensity. Finally, for energy saving reasons, when GSM handsets operate in "listening" mode, the average emitted power is much less (about one tenth) than when they operate in "speaking" mode [32,41,100,142–145]. Thus, real digital microwave telecommunication EMFs change constantly and unpredictably, being impossible to simulate them by EMFs of fixed parameters.

Why exposure variability is so important for bioactivity? Living organisms have been constantly exposed throughout biological evolution to terrestrial static electric and magnetic fields of average intensities ~130 V/m and ~0.5 G respectively. While no adverse health effects are connected with normal exposure to these natural ambient fields, variations in their intensities on the order of ~20% during "magnetic storms" or "geomagnetic pulsations" due to changes in solar activity with an average periodicity of about 11 years are connected with increased rates of animal/human health incidents, including nervous and psychic diseases, hypertensive crises, heart attacks, cerebral accidents, and mortality [146,147].

Voltage-gated ion channels in all cell membranes switch between open and close state whenever a change exceeding ~30% in the membrane voltage takes place [139,148], and all physiological cellular effects are initiated by changes in ionic concentrations mediated by ion channel gating [139]. It is known that ~30 mV changes in the normal ~100 mV transmembrane voltage is able to gate voltage-gated ion channels in cell membranes [95–97,139,148].

Living organisms perceive EMFs as environmental stressors [93,100,146]. It is reasonable to assume that cells/organisms adapt more easily when EMFs are not significantly and unexpectedly varying, in other words when their parameters are kept constant or vary only slightly, or when the variation is predictable (as e.g. with the alternating 50 Hz MFs, or the PEF in the present study, or the simulated MT EMFs employed in many other studies). Since living organisms do not have defense against variations on the order of ~20% of natural EMFs as reported, it is realistic to expect that they do not have defense against EMFs, which vary unpredictably and at ~100% or even more from average intensity (and in addition are totally polarized, coherent, pulsed, modulated, including simultaneously several different frequencies, etc. as are the microwave EMFs employed in all modern telecommunications). Similarly, since cells respond to changes on the order of ~30% of the physiological membrane fields, it is realistic to expect that they will - irregularly - respond to changes in externally applied polarized EMFs of adequate intensity.

What is the difference between the natural EMFs in the terrestrial environment, the physiological EMFs of cell membranes, and the man-made EMFs employed in the studies? Terrestrial and cell membrane fields are static and significantly (almost totally) polarized. They normally do not vary considerably in their intensities, but variations on the order of 20–30% induce cellular/health effects. Man-made EMFs used in the studies are totally polarized, and at the same time (especially the microwave telecommunication EMFs) highly variable (alternating, pulsed) with unexpected changes exceeding 100% of their normal average intensities.

4.4. Conclusions

It comes that variability in the EMF exposure is an extremely important factor in order for the specific type of polarized EMF to be able to induce biological/health effects.

It seems that the bioactive parameters of EMFs are: 1) Polarization (combined with coherence), 2) ELFs, 3) Intensity, 4) Variability (unexpected changes exceeding 20–30 % of average/normal intensity). Once the EMF is polarized, includes ELFs, and has adequate intensity, the parameter that makes the difference is variability.

The extreme and unpredictable variability of the real-life MT signals that apparently seems to be the reason for the corresponding intense bioactivity, does not concern only the 2nd generation (GSM) MT signals tested in our experiments and in the present review, but all existing types of digital MT signals (2nd, 3rd, 4th generation), and all types of modern digital microwave telecommunication signals/EMFs (DECT phones, Wi-Fi routers, etc.), since they all operate under the same principles combining RF carrier signals with ELF pulsing and modulation of similar frequency bands, emitting variable information each moment which in turn makes the emission variable in intensity, frequency, waveform etc. In fact, with every new generation of telecommunication devices (e.g. 3rd, 4th, 5th generation mobile phones or base antennas) the amount of information transmitted each moment (speech, text, images, video, internet, etc.) is increased, resulting in higher variability and complexity of the signals with the living cells/organisms even more unable to adapt. The result of the recent study that found a real 3rd generation (UMTS) MT EMF to be more bioactive than real 2nd generation (GSM) MT EMF emitted by the same device [36] is in line with this fact.

Thus, the present study makes the point that once a specific EMF is polarized (and coherent), includes ELFs, and has adequate intensity, then variability in its parameters (especially in its intensity) is of decisive importance in terms of its bioactivity. In the present study this was shown, a) by the direct comparison between six different EMFs in terms of their ability to induce DNA fragmentation in my studies, b) by indirect comparison between the effects of real MT EMFs in my studies and simulated MT EMFs in other studies, both directly compared with corresponding effects of a 50 Hz alternating MF, and c) by the large difference in bioactivity between simulated MT signals with invariable parameters and real MT (highly variable) ones from a great number of reviewed studies. This important point in terms of biological activity and public health protection should be further confirmed experimentally by direct comparison of effects between simulated and real MT EMFs of the same average parameters.

The importance of exposure variability shown in the present study implies the need to define EMF-exposures not only by frequency components and average intensity values, but by reporting maximum and minimum intensity as well, frequency variations, pulsing or continuous wave, modulation, and - of course - polarization. Moreover, in published reviews of experimental studies employing MT and other types of microwave telecommunication EMFs such as DECT phones, Wi-Fi etc, it must be explicitly reported whether the exposures were real from commercially available devices or simulated from generators, test phones, etc.

The present study further confirms my previous results and conclusions that experiments should employ real-life and not simulated EMFs, and human/animal exposure to microwave telecommunication EMFs should be drastically reduced by prudent use, and establishment of much stringer exposure limits by the responsible health authorities.

Declarations of interest

None.

Appendix 1 List of frequently used Abbreviations in the text

CW: continuous wave
ELF: extremely low frequency (0–3000 Hz)
EMF: electromagnetic field
FC: follicle cell
G: Gauss (magnetic field unit)
g: germarium
GSM: Global System for Mobile telecommunications
MF: magnetic field
MT: mobile telephony
NC: nurse cell
OC: oocyte
PEF: pulsed electric field
RF: radio frequency
S: stages of oogenesis
SAR: Specific Absorption Rate
SD: Standard Deviation
TUNEL: Terminal deoxynucleotide transferase dUTP Nick End Labeling
UMTS: Universal Mobile Telecommunication System

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