*Int. J. Radiat. Biol.*, Vol. 86, No. 5, May 2010, pp. 358–366

informa healthcare

# The identification of an intensity 'window' on the bioeffects of mobile telephony radiation

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*(Received 10 June 2009; Revised 2 December 2009; Accepted 9 December 2009)*

**Abstract**

*Purpose:* The increased bioactivity 'windows' of GSM 900 and 1800 MHz radiations, (Global System for Mobile telecommunications) revealed recently by us and published in this issue, manifesting themselves as a maximum decrease in the reproductive capacity of the insect *Drosophila melanogaster*, were examined to discover whether they depend on the intensity of radiation-fields.

*Methods:* In each experiment, one group of insects were exposed to the GSM 900 or 1800 radiation at 30 or 20 cm distances, respectively, from the antenna of a mobile phone, where the bioactivity 'window' appears for each type of radiation and another group was exposed at 8 or 5 cm, respectively, behind a metal grid, shielding both microwave radiation and the extremely low frequency (ELF) electric and magnetic fields for both types of radiation in a way that radiation and field intensities were roughly equal between the two groups. Then the effect on reproductive capacity was compared between groups for each type of radiation.

*Results:* The decrease in the reproductive capacity did not differ significantly between the two groups.

*Conclusions:* The bioactivity window seems to be due to the intensity of radiation-field (10 $\mu$W/cm$^2$, 0.6–0.7 V/m) at 30 or 20 cm from the GSM 900 or 1800 mobile phone antenna, respectively.

**Keywords:** *GSM, DCS, distances, intensity, window effects, intensity windows*

## Introduction

The increased bioactivity of digital Mobile Telephony Radiation currently used widely is already confirmed by an increasing number of studies (Hyland 2000; Navarro et al. 2003; Salford et al. 2003; Kundi 2004; Panagopoulos et al. 2004, 2007a, 2007b, 2010; Aitken et al. 2005; Barteri et al. 2005; Belyaev et al. 2005, 2009; Caraglia et al. 2005; Diem et al. 2005; Markova et al. 2005; Hardell et al. 2006, 2007, 2009; Hardell and Hansson Mild 2006; Hutter et al. 2006; Nylund and Leszczynski 2006; Remondini et al. 2006; Eberhardt et al. 2008; Blettner et al. 2009; Garaj-Vrhovac and Orescanin 2009; Hardell and Carlberg 2009; Kundi and Hutter 2009; Lopez-Martin et al. 2009; Viel et al. 2009).

Recent experiments we have carried out (Panagopoulos and Margaritis 2008; Panagopoulos et al. 2009) have revealed the existence of increased bioactivity 'windows' of digital mobile telephony radiation. These bioactivity windows appeared for both types of digital mobile telephony radiation used in our experiments, GSM 900 MHz (Global System for Mobile telecommunications) and GSM 1800 MHz, (reported also as DCS 1800 MHz-Digital Cellular System). Under controlled conditions within our laboratory the bioactivity window of GSM 900 MHz appeared at the distance of 30 cm from the mobile phone antenna and the bioactivity window of GSM/DCS 1800 MHz at 20 cm distance from the antenna of the same handset. At these distances, the intensity of both types of radiation in the radio frequency (RF) range was about 10 $\mu$W/cm$^2$, the extremely low frequency (ELF) electric field intensity 0.6–0.7 V/m, the ELF magnetic field intensity 0.10–0.12 mG (also for both types of radiation), and the bioactivity of each type of radiation was maximum compared to smaller or larger distances.

The bioactivity of radiation was assessed by its effect on the reproductive capacity of the insect *Drosophila melanogaster*. The reproductive capacity of this insect, as this is defined by the number of $F_1$

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ISSN 0955-3002 print/ISSN 1362-3095 online © 2010 Informa UK Ltd.
DOI: 10.3109/09553000903567979

(first filial generation) pupae derived during the three days of the insect's maximum oviposition, is a valid estimate for the bioactivity of mobile telephony radiation, according to our previous experiments (Panagopoulos et al. 2000a, 2004, 2007a, 2007b, 2010; Panagopoulos and Margaritis 2002, 2003a, 2008). The maximum decrease in the reproductive capacity at 30 cm and 20 cm distance from the mobile phone antenna, for GSM 900 and 1800 MHz respectively, found in our recent experiments (Panagopoulos et al. 2010), compared to smaller or longer distances from the antenna, is reported here as 'increased bioactivity windows'. The decrease in reproductive capacity at these distances was as high or even higher than the corresponding decrease in contact with the mobile phone antenna where the intensity was higher than 250 $\mu$W/cm$^2$.

'Window effects' in regards to the bioactivity of electromagnetic radiation/fields (EMF), found to be dependent on the intensity or frequency of the radiation/field, have been reported since many years (Bawin et al. 1975, 1978; Bawin and Adey 1976; Oscar and Hawkins 1977; Blackman et al. 1980, 1989; Salford et al. 1994; Goodman et al. 1995; Persson et al. 1997; Shcheglov et al. 1997) and until today there is no definite explanation for their existence. The 'windows' represent the fact that increased bioactivity appears within certain values of a physical parameter of the field/radiation, like intensity or frequency, but not for lower or higher values of this parameter. Before our recent experiments (Panagopoulos and Margaritis 2008; Panagopoulos et al. 2010), no bioactivity windows regarding real signals of digital mobile telephony radiation were ever reported.

The aim of the present experiments was to identify whether the recorded windows of increased bioactivity are due to the RF ($\sim$10 $\mu$W/cm$^2$) or ELF (0.6–0.7 V/m, and 0.10–0.12 mG) radiation-field intensities within these windows (or to any combination of the three of them), or due to any other possible effects related to the distance from the antenna, like for example, the radiation wavelengths which happen to be close to the distances where the windows appeared for each type of radiation, i.e., 33 cm approximately for 900 MHz and 17 cm approximately for 1800 MHz.

Phenomena of wave interference can take place and become most evident between waves of the same polarisation and wavelength $\lambda$, emitted by different sources or between emitted and reflected waves from the same source. At certain location points where the difference in distances between the point and the two sources is an integer multiple of $\lambda$, these interfering waves can have an additive result increasing the amplitude of the resultant wave and consequently the wave intensity (Alonso and Finn 1967). Although we had only one source and no reflecting-metallic surfaces around the exposure area and additionally, radiation and field intensity measurements were performed and did not record any increase in RF or ELF intensities at the certain distances where the windows appear or at any other distance, possibilities of wave interference cannot be excluded. We note that these windows of increased bioactivity were recorded in the 'far field' of the mobile phone antenna at a distance of 20–30 cm from this (Panagopoulos et al. 2010). Therefore, the near field zone of the antenna does not interfere with the existence of the observed 'windows'.

## Materials and methods

Wild-type strain Oregon R *Drosophila melanogaster* flies were cultured according to standard methods and kept in glass vials with standard food. Culture methods and food composition were described previously (Panagopoulos et al. 2004).

A dual band cellular mobile phone that could be connected to either GSM 900 or 1800 networks was used as the exposure device (Panagopoulos et al. 2007a, 2007b, 2010). The highest Specific Absorption Rate (SAR), given by the manufacturer for the human head is 0.89 W/Kg. The basic exposure procedure was the same as in earlier experiments of ours (Panagopoulos et al. 2004, 2007a). The handset was fully charged during each set of exposures. The emitted GSM 900 or 1800 radiation during the exposures was 'modulated' by the human voice ('speaking emissions'). The experimenter spoke on the mobile phone during the exposures-same voice, reading the same text in every exposure session, as previously described (Panagopoulos et al. 2004). Radiation and field intensities were monitored constantly during the exposures. Measurements at 900 MHz and 1800 MHz were made with a RF Radiation Survey Meter, NARDA 8718 (Hauppauge, NY, USA). Measurements of electric and magnetic field intensities in the ELF range were made with a Holaday HI-3604 ELF Survey Meter (Eden Prairie, MN, USA). The exposures (and the measurements) were performed at the same place within our laboratory where the mobile phone had full perception of both GSM 900 and 1800 signals, as described before (Panagopoulos et al. 2004, 2007a). [The measured GSM radiation intensity within the lab, from the base stations in the area around the University was 0.1–0.2 $\mu$W/cm$^2$ both in 900 and 1800 MHz and the receiver of the handset showed constantly full perception of both signals-all bars were illuminated in the bar scale that measures the receiving signal].

After having recorded that the effect on reproductive capacity becomes a maximum at 30 and 20 cm distances from the mobile phone antenna for GSM 900 MHz and 1800 MHz radiations respectively, where the intensity of both radiations was found to be close to 10 $\mu$W/cm$^2$, as described (Panagopoulos et al. 2010), one group of insects (named as 'E1') was exposed at a distance of 30 cm for GSM 900 MHz, or 20 cm for GSM/DCS 1800 MHz, respectively. A second group (named as 'E2') was exposed right behind (and in contact with) a ferromagnetic metal grid shield (of appropriate total surface so as to hide the whole glass vial), made from galvanized iron wire (wire diameter 0.6 mm with square mesh opening 2.57 $\times$ 2.57 mm – Hebei Anping Hongruida Hardware Mesh Products Factory, Hengshui, Hebei, P.R. China), which diminishes both electromagnetic radiation and ELF electric and magnetic fields, at a distance of 8 or 5 cm, respectively, from the antenna where radiation and field intensities were measured and found to be roughly equal as in the corresponding first group. Average values of measurements $\pm$ standard deviation (SD) are given below. As explained before (Panagopoulos et al. 2007a, 2007b), the GSM 900 MHz intensity at the same distance from the antenna and with the same handset was higher than the corresponding GSM/DCS 1800 MHz. [The ferromagnetic metal grid shield placed at distances 8 or 5 cm from the antenna, was outside of the antenna's near field, which extends to a distance of 5.2 or 2.6 cm, for GSM 900 or 1800 mobile phone antenna respectively, according to the relation $r < \lambda/2\pi$, ($r$ the distance of near field far limit from the antenna for antennas smaller than the wavelength $\lambda$ of the emitted radiation, (World Health Organisation [WHO] 1993). Any metallic surfaces reflect electromagnetic radiation, therefore decreasing its intensity behind them and in their internal area if they are closed, without altering its frequency/wavelength. In addition metallic objects or closed surfaces, or metallic wirings-grids, diminish the electric field behind them and in their internal area, because of free electron cloud displacement within their mass on their surface. The displacement of the free electron cloud against the direction of the external electric field diminishes the electric field ('Faraday' cage). If in addition, the metallic surface or wiring-grid is made from ferromagnetic metal (Fe, Co, Ni), it also diminishes the magnetic field as it gets magnetized in the opposite direction than the external magnetic field (Alonso and Finn 1967; Reitz and Milford 1967; Jackson 1975). Finally a third group (named as SE) was the sham-exposed. The SE group was 'exposed' at 10 cm distance from the mobile phone antenna with the mobile phone turned off during the 6 min 'exposures'. During initial experiments we had already verified that there was no difference in what distance the SE group was 'exposed' or whether it was 'exposed' with or without the use of the ferromagnetic metal grid shield (see Appendix). After this, we were able to compare both exposed groups with the same sham-exposed group. The SE groups were otherwise treated exactly as the exposed ones (same voice applied during the sham-exposures as during the exposures). Each group consisted of 10 male and 10 female insects.

If the recorded effect was due to possible wave interference at distances 30 and 20 cm which are close to the wavelengths of 900 MHz and 1800 MHz, respectively, or to any other possible effect related to these distances, then the effect would be stronger in the E1 groups than in the E2 groups. If the effect was due to the intensity of the radiation-fields (i.e., intensity 'window'), then no important difference would be recorded between E1 and E2 groups.

The mean power density on the E1 group during the exposures was $10 \pm 3$ $\mu$W/cm$^2$ for GSM 900 MHz and $11 \pm 3$ $\mu$W/cm$^2$ for GSM/DCS 1800 MHz, and almost equal for E2 for both types of radiation, ($10.1 \pm 2.8$ $\mu$W/cm$^2$ and $10.8 \pm 3.2$ $\mu$W/cm$^2$, respectively). Although the RF radiation intensities were roughly equal between the E1 and E2 groups, there was a small difference in the ELF electric and magnetic field intensities between the two exposed groups, for both types of radiation. These intensities were a little higher in the E2 than in the E1 groups, suggesting that the ferromagnetic metal grid shield used to insulate E2 was not as effective in the ELF range as it was in the RF range of the electromagnetic spectrum. The measured ELF electric and magnetic field intensities, excluding the ambient electric and magnetic fields of 50 Hz were, $0.61 \pm 0.11$ V/m, $0.10 \pm 0.02$ mG for E1 and $0.65 \pm 0.10$ V/m, $0.12 \pm 0.03$ mG for E2, respectively; for the GSM 900 MHz signal and almost equal corresponding values for GSM 1800 MHz, ($0.6 \pm 0.13$ V/m, $0.09 \pm 0.03$ mG for E1 and $0.66 \pm 0.12$ V/m, $0.13 \pm 0.02$ mG for E2, respectively). The ELF survey meter used to measure the ELF fields cannot discriminate between the 217 Hz pulse repetition of the radiation and the fields in the handset. The measured ELF values given above include both contributions. The above-mentioned measured values of radiation/field intensities are averaged over six separate measurements of each kind $\pm$ SD. These values are typical for digital mobile telephony handsets under the above conditions and distances from the antenna and they are within the established current exposure criteria, (International Commission for Non-Ionising Radiation Protection [ICNIRP] 1998).

The total duration of exposure was 6 min per day in one dose and the exposures were started on the first day of each experiment (day of eclosion). In each experiment the two exposed groups were simultaneously exposed during the 6-min exposure sessions. After each exposure session, the corresponding SE group was sham-exposed. The exposures took place for five days in each experiment, as previously described (Panagopoulos et al. 2004, 2009). The daily exposure duration of 6 min, was chosen for reasons we have explained before (Panagopoulos et al. 2004, 2007a) and for keeping the same exposure conditions as in the previous experiments. The mobile phone during the exposures was parallel to the vials' axis.

In each experiment we kept the 10 males and the 10 females of each group in separate vials for the first 48 h, as before (Panagopoulos et al. 2004). After the first 48 h of each experiment, the males and females of each group were put together (10 pairs) in another glass vial with fresh food, allowed to mate and lay eggs for the next 72 h, during which, the daily egg production of *Drosophila* is at its maximum (Panagopoulos et al. 2004).

At the sixth day from the beginning of each experiment, the flies were removed from the glass vials, and the vials with the food and the laid eggs were maintained in the culture room for six additional days, without further exposure, in order to count the $F_1$ pupae as in previous experiments (Panagopoulos et al. 2000a, 2004, 2007b).

Following the same procedure of our earlier experiments, during the last six days we inspected the surface of the food within the glass vials under the stereo-microscope for any non-developed laid eggs or dead larvae, something that we have not observed in our experiments (whereas empty egg-shells can be seen after hatching). The number of observed exceptions (non-developed eggs or dead larvae), both in exposed and control groups (less than 4%) are within the Standard Deviation of progeny number. [The insignificant percentage of $F_1$ egg and larvae mortality is due to the fact that the paternal-maternal flies were newly emerged during the first 2–5 days of their adult lives]. Therefore, the number of pupae in our experiments corresponds to the number of laid eggs (oviposition). Furthermore, the counting of pupae can be done without any error at all, whereas the counting of laid eggs under a stereo-microscope is subject to considerable error.

The temperature during the exposures was monitored within the vials by a mercury thermometer with an accuracy of 0.05°C (Panagopoulos et al. 2004). The temperature was $25 \pm 0.5$°C within the room where the exposures (and sham-exposures) were performed (and within the vials with the insects).

The results were analysed by single factor Analysis of Variance test which calculates the probability (*P*), that the differences in the reproductive capacity between groups are due to random variations.

## Results

The mean values of reproductive capacity (number of $F_1$ pupae per maternal fly) from five identical experiments with each kind of radiation are shown in Table I and represented in Figure 1.

Table I. Effect of GSM 900 and 1800 radiation-fields on the reproductive capacity of groups exposed at 'window' intensity and sham-exposed groups.

| Experiment No. | Groups | Mean number of $F_1$ pupae per maternal fly, for GSM 900 MHz | Deviation from sham-exposed group | Mean number of $F_1$ pupae per maternal fly, for GSM 1800 MHz | Deviation from sham-exposed group |
|---|---|---|---|---|---|
| 1 | SE | 14.2 | | 13.8 | |
| | E1 | 8.3 | −41.55 % | 9.5 | −31.16 % |
| | E2 | 7.9 | −44.36 % | 8.9 | −35.51 % |
| 2 | SE | 13.4 | | 13.5 | |
| | E1 | 7.8 | −41.79 % | 8.5 | −37.04 % |
| | E2 | 8.2 | −38.81 % | 8.2 | −39.26 % |
| 3 | SE | 12.7 | | 14 | |
| | E1 | 7.3 | −42.52 % | 7.6 | −45.71 % |
| | E2 | 7.2 | − 43.31 % | 8.1 | −42.14 % |
| 4 | SE | 14.5 | | 14.3 | |
| | E1 | 9.2 | −36.55 % | 9 | −37.06 % |
| | E2 | 8.7 | −40 % | 9.3 | −34.97 % |
| 5 | SE | 13.7 | | 12.6 | |
| | E1 | 6.7 | −51.09 % | 7.3 | −42.06 % |
| | E2 | 7.2 | −47.45 % | 7.3 | −42.06 % |
| Average ± SD | SE | $13.7 \pm 0.70$ | | $13.64 \pm 0.65$ | |
| | E1 | $7.86 \pm 0.95$ | −42.63 % | $8.38 \pm 0.93$ | −38.56 % |
| | E2 | $7.84 \pm 0.65$ | −42.77 % | $8.36 \pm 0.77$ | −38.71 % |

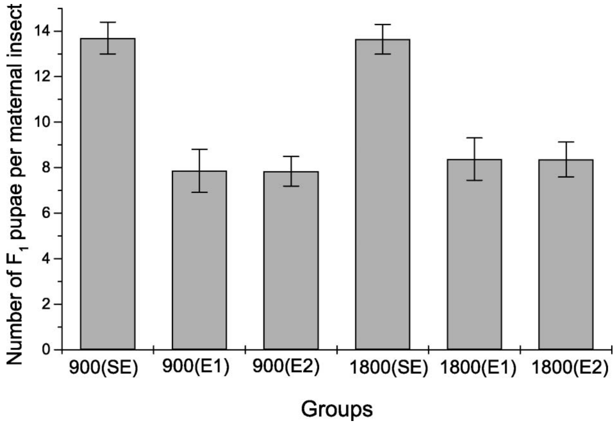


Figure 1. Reproductive capacity ± SD of exposed and sham-exposed groups to GSM 900 MHz and 1800 MHz radiation at 'window' intensity (10 $\mu$W/cm$^2$). The decrease in reproductive capacity of the exposed groups E1 and E2 for both types of radiation is significant in relation to the sham-exposed groups, but there is no significant difference between them.

The results show that the reproductive capacity between the two exposed groups did not differ significantly for both types of radiation, ($P > 0.97$ in both cases, meaning that differences between the two exposed groups have more than 97% probability to be due to random variations according to the statistical analysis). In contrast, the reproductive capacity of each exposed group was significantly decreased compared to the sham-exposed group as expected for both types of radiation, ($P < 10^{-5}$ in all cases).

Therefore, the reproductive capacity of both exposed groups was significantly decreased compared to the sham-exposed ones, as it was expected, but the difference in reduction was not statistically important between the two exposed groups, for both types of radiation. The decrease in reproductive capacity caused by GSM 900 in both exposed groups (−42.63% for E1, −42.77% for E2) was higher than the corresponding decrease caused by GSM/DCS 1800 (−38.56%, −38.71%, respectively) for the same radiation-field intensity, although differences were within the standard deviation (Table I). The results also show that for both types of mobile telephony radiation, the reproductive capacity of E2 was slightly more decreased than that of E1 (Table I), although these differences were again within the standard deviation.

No detectable temperature increase was found within the vials during the exposures, as measured by the sensitive mercury thermometer.

## Discussion and conclusion

In the present experiments we showed that the increased bioactivity 'window' of digital mobile telephony radiation revealed in our recent experiments (Panagopoulos and Margaritis 2008; Panagopoulos et al. 2010), is actually an 'intensity window' around the value of 10 $\mu$W/cm$^2$ (in regards to the RF intensity), [or around the values of 0.6–0.7 V/m and 0.10–0.12 mG (in regards to the ELF electric or magnetic field intensities, respectively), or to any combination of the three of them]. Within this 'window' the bioactivity of mobile telephony radiation becomes even more intense than at intensities higher than 250 $\mu$W/cm$^2$ (or higher than 13 V/m and 0.6 mG, respectively). Under normal conditions and without obstacles between the antenna and the exposed object, the intensity around 10 $\mu$W/cm$^2$ where the window appears exists at a distance of approximately 30 cm from a GSM 900 or 20 cm from a GSM/DCS 1800 mobile phone antenna, which corresponds to a distance of about 30 or 20 m, respectively, from a corresponding base station antenna, as base station antennas emit the same kind of radiation at about 100 times higher power than the corresponding mobile phones (Hyland 2000; Panagopoulos and Margaritis 2008; Panagopoulos et al. 2010).

We have shown that this window is only indirectly related with the distance from the antenna; therefore, it does not seem to be related with the wavelength (or the frequency) of the radiation. This window is directly dependent on the intensity of the radiation/field, no matter on what distance from the antenna this intensity exists. This conclusion comes from the results of our present experiments, that there is no significant difference between the E1- and E2-exposed groups for both types of radiation.

Our present results show that GSM 900 exposure decreases reproductive capacity a little more than DCS/GSM 1800 exposure for the same radiation/field intensity. This is in agreement with our previous results which showed that GSM 900 is slightly more bioactive than DCS/GSM 1800 even under the same radiation intensity (Panagopoulos et al. 2007a). This possibly means that the carrier frequency of the radiation, which is the only difference in this case, plays a small but statistically significant role in the bioactivity of mobile telephony radiation, implying that lower frequency fields are more bioactive than higher frequency ones with the same rest characteristics. This is explained by the mechanism we have proposed for the action of electromagnetic fields on cells (Panagopoulos et al. 2000b, 2002).

For both types of mobile telephony radiation, the reproductive capacity of E2 was slightly more decreased than that of E1, although differences were within standard deviation. This is possibly due to the fact that the ferromagnetic metal grid shield we used to diminish radiation and field intensities in the E2 groups was more effective in the RF than in the ELF region of the electromagnetic spectrum, resulting in slightly higher values of the ELF electric and magnetic field intensities in the E2 than in the corresponding E1 groups, although the RF intensity was roughly the same between the two groups. In other words, the slightly more decreased reproductive capacity of E2 groups in relation to the corresponding E1 ones is possibly due to the more increased values of the ELF fields. This might mean that not only the RF carrier wave intensity but also the pulsing ELF field intensities play an important role in the bioactivity of digital mobile telephony signals and in the existence of the recorded intensity windows.

We consider that the effect of the ferromagnetic metal grid shield on diminishing the effects on reproductive capacity was due to the decrease of the RF-ELF intensities and not to any possible near-far field structure alteration, because this grid was placed well outside of the near field zone (almost at double the distance from the antenna than the far limit of the near field zone) for both types of radiation. Although any conductive object (like the ferromagnetic metal grid shield that we used) within the near field of the antenna can alter the characteristics of the near field, (basically the local intensity and the pattern of radiation) as, especially in the reactive near field (the closest region to the antenna), conductive objects may practically become parts of the antenna, no considerable similar changes take place for conductive objects in the far field zone (Slater 1991). Even if the grid had caused an alteration in the zones, this alteration would basically reflect consequent alterations in radiation and field intensities which would have been measured. It is known that exposure in the near or far field of the same antenna can produce quantitatively different biological effects (Gapeyev et al. 1997) but in the present experiments both E1 and E2 groups were exposed in the far field of the antenna. Even if there were alterations in the structure of the zones caused hypothetically by the presence of the ferromagnetic metal grid shield that were not measured by the instrument, these alterations would influence equally both the exposed groups since both groups were within the same zone.

Since there was no detectable temperature increase during the exposures, the recorded effects are considered as non-thermal.

The intensity 'window' found in our experiments could possibly be correlated with the recent results of another experimental group reporting that GSM radiation caused increased permeability of the blood-brain barrier in rat nerve cells and the strongest effect was produced by the lowest SAR values corresponding to the weakest radiation intensity (Eberhardt et al. 2008).

As shown in previous experiments of ours (Panagopoulos et al. 2007b, 2010), the large decrease in the reproductive capacity of the insects exposed to mobile telephony radiation is due to the elimination of large numbers of egg chambers during early and mid oogenesis, either via stress-induced apoptosis or necrosis of their constituent cells.

We do not know whether the intensity window found is related exclusively to the specific experimental animal we used or if it concerns other organisms as well. Experiments with different experimental animals exposed to different intensities of mobile telephony radiation are necessary in order to answer this question. Since the effect of cell death induction especially within the above intensity window was observed in all kinds of female reproductive cells (nurse cells, follicle cells and the oocyte) (Panagopoulos et al. 2010) and since most cellular functions are identical in both insect and mammal cells, it is possible that this intensity window concerns a variety of cell types in different organisms and humans as well.

A possible explanation for the existence of bioactivity 'windows' may come from our proposed theory on the biophysical mechanism of action of electromagnetic fields (EMF) on cells (Panagopoulos et al. 2000b, 2002; Panagopoulos and Margaritis 2003b). According to this theory, the action of external EMF on cells is dependent on the irregular gating of membrane electrosensitive ion channels whenever a force on the channel sensors exceeds the force exerted on them by a change in the membrane potential of about 30 mV which is necessary to gate the channel normally. If in some kind of cells there is an upper limit for this value of membrane potential change, then the channel would be gated whenever the force exerted on its sensors is within this 'window'.

For example, the intensity window that we have recorded, in terms of the ELF electric field intensity, is around 0.6–0.7 V/m. Let us assume that it ranges from 0.5 to 1 V/m. According to our theory, these limits correspond to a single-valence, single ion displacement between $\partial r_1 = 1.3 \times 10^{-11}$ m and $\partial r_2 = 2.6 \times 10^{-11}$ m, in the vicinity of the channel's sensors, according to the equation (Panagopoulos et al. 2002):

$$\partial r = \frac{E_o z q_e}{\lambda \omega}$$

where: $E_o$ the amplitude of the external oscillating electric field which is equal to $E\sqrt{2}$ where $E$ the measured (root mean square) value of electric field intensity, $z$ the ion's valence (for example, $z = 1$ for $K^+$ ions), $q_e$ the unit charge ($= 1.6 \times 10^{-19}$ Cb), $\lambda \cong 6.4 \times 10^{-12}$ Kg/s the attenuation coefficient for the ion movement within a cation channel, $\omega = 2\pi\nu$ ($\nu$ the frequency of the external oscillating field, in our case let us take $\nu = 217$ Hz the pulse repetition frequency of the ELF pulses).

These displacements $\partial r_1$ and $\partial r_2$ would exert on each channel's sensor (S4 domain) corresponding forces $\partial F_1 = 2.5 \times 10^{-12}$ N and $\partial F_2 = 5 \times 10^{-12}$ N according to the equation

$$\partial r = -\frac{2\pi\varepsilon\varepsilon_o \partial F . r^3}{q . z q_e}$$

where $\varepsilon = 4$, the relative dielectric constant in the internal of a channel-protein, $\varepsilon_o = 8.854 \times 10^{-12}$ $N^{-1}$ $m^{-2}$ $Cb^{-2}$ the dielectric constant of vacuum, $r \cong 10^{-9}$ m the distance between the oscillating ion and the effective charge of the channel's sensor, and $q = 1.7\ q_e$ the effective charge of the channel's sensor (S4 domain) (Panagopoulos et al. 2002, 2000b).

A force between 2.5 and $5 \times 10^{-12}$ N on the channel's sensor, in turn, corresponds according to the equation

$$\partial F = \partial \Delta\Psi \frac{q}{s}$$

(Panagopoulos et al. 2000b) to a change $\partial\ \Delta\Psi$ in the membrane voltage between 90 and 180 mV, ($q = 1.7$ $q_e$ and $s \cong 10^{-8}$ m the membrane's width). Thus we have shown that the intensity window found in our present experiments corresponds to a gating voltage change between 90 and 180 mV in the membrane potential.

Channel gating is usually studied on nerve cells, and in these kind of cells possibly no upper limit exists, but the possibility of an upper limit (like the value of 180 mV that we found in our example), cannot be excluded for other kinds of cells which have not been studied until now in terms of their channel voltage gating. Our hypothesis for the explanation of the existence of bioactivity 'windows' is reported here for the first time. The above numerical example is just an indication that the bioactivity windows reported for many years in electromagnetic and radiation biology experiments but not explained so far, can possibly be theoretically explained according to our theory.

Our present results show that mobile telephony radiation at lower intensities might be even more bioactive than at higher ones. Since insects are found to be more resistant to radiations than mammals (Abrahamson et al. 1973; Koval et al. 1977), our results may indicate a danger for human health as well. The intensities of the increased bioactivity window found in our experiments are already much lower than those adopted by the current exposure criteria (ICNIRP 1998). The results of this and our other latest study (Panagopoulos et al. 2010), suggest that exposure limits should be restricted at values not higher than 1 $\mu W/cm^2$. Since in the case of base station mobile telephony antennas this intensity exists at about 100 m from the antennas (Panagopoulos et al. 2010), our latest results suggest that the base station antennas should be located at distances of at least a few hundred meters from residential and working areas.

**Declaration of interest:** The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

## References


Abrahamson S, Bender MA, Conger AD, Wolff S. 1973. Uniformity of radiation-induced mutation rates among different species. Nature 245:460–462.

Aitken RJ, Bennetts LE, Sawyer D, Wiklendt AM, King BV. 2005. Impact of radio frequency electromagnetic radiation on DNA integrity in the male germline. International Journal of Andrology 28(3):171–179.

Alonso M, Finn EJ. 1967. Fundamental university physics. Vol. 2. Fields and waves. Boston, MA: Addison-Wesley.

Barteri M, Pala A, Rotella S. 2005. Structural and kinetic effects of mobile phone microwaves on acetylcholinesterase activity. Biophysical Chemistry 113(3):245–253.

Bawin SM, Kaczmarek LK, Adey WR. 1975. Effects of modulated VMF fields, on the central nervous system. Annals of the New York Academy of Sciences 247:74–81.

Bawin SM, Adey WR. 1976. Sensitivity of calcium binding in cerebral tissue to weak environmental electric fields oscillating at low frequency. Proceedings of the National Academy of Sciences of the USA 73:1999–2003.

Bawin SM, Adey WR, Sabbot IM. 1978. Ionic factors in release of $^{45}Ca^{2+}$ from chick cerebral tissue by electromagnetic fields. Proceedings of the National Academy of Sciences of the USA 75:6314–6318.

Belyaev IY, Hillert L, Protopopova M, Tamm C, Malmgren LO, Persson BR, Selivanova G, Harms-Ringdahl M. 2005. 915 MHz microwaves and 50 Hz magnetic field affect chromatin conformation and 53BP1 foci in human lymphocytes from hypersensitive and healthy persons. Bioelectromagnetics 26(3):173–184.

Belyaev IY, Markova E, Hillert L, Malmgren LO, Persson BR. 2009. Microwaves from UMTS/GSM mobile phones induce long-lasting inhibition of 53BP1/gamma-H2AX DNA repair foci in human lymphocytes. Bioelectromagnetics 30:129–141.

Blackman CF, Benane SG, Elder JA, House DE, Lampe JA, Faulk JM. 1980. Induction of calcium-ion efflux from brain tissue by radiofrequency radiation: Effect of sample number and modulation frequency on the power-density window. Bioelectromagnetics (New York) 1:35–43.

Blackman CF, Kinney LS, House DE, Joines WT. 1989. Multiple power-density windows and their possible origin. Bioelectromagnetics 10(2):115–128.

Blettner M, Schlehofer B, Breckenkamp J, Kowall B, Schmiedel S, Reis U, Potthoff P, Schuz J, Berg-Beckhoff G. 2009. Mobile phone base stations and adverse health effects: Phase 1 of a population-based, cross-sectional study in Germany. Occupational and Environmental Medicine 66:118–123.

Caraglia M, Marra M, Mancinelli F, D'Ambrosio G, Massa R, Giordano A, Budillon A, Abbruzzese A, Bismuto E. 2005. Electromagnetic fields at mobile phone frequency induce apoptosis and inactivation of the multi-chaperone complex in human epidermoid cancer cells. Journal of Cellular Physiology 204(2):539–548.

Diem E, Schwarz C, Adlkofer F, Jahn O, Rudiger H. 2005. Non-thermal DNA breakage by mobile-phone radiation (1800 MHz) in human fibroblasts and in transformed GFSH-R17 rat granulosa cells in vitro. Mutation Research 583(2):178–183.

Eberhardt JL, Persson BRR, Brun AE, Salford LG, Malmgren LOG. 2008. Blood-brain barrier permeability and nerve cell damage in rat brain 14 and 28 days after exposure to microwaves from GSM mobile phones. Electromagnetic Biology and Medicine 27:215–229.

Gapeyev AB, Safronova VG, Chemeris NK, Fesenko EE. 1997. Inhibition of the production of reactive oxygen species in mouse peritoneal neutrophils by millimeter wave radiation in the near and far field zones of the radiator. Bioelectrochemistry and Bioenergetics 43:217–220.

Garaj-Vrhovac V, Orescanin V. 2009. Assessment of DNA sensitivity in peripheral blood leukocytes after occupational exposure to microwave radiation: The alkaline comet assay and chromatid breakage assay. Cell Biology and Toxicology 25:33–43.

Goodman EM, Greenebaum B, Marron MT. 1995. Effects of electro-magnetic fields on molecules and cells. International Review of Cytology 158:279–338.

Hardell L, Carlberg M, Hansson Mild K. 2006. Pooled analysis of two case-control studies on use of cellular and cordless telephones and the risk for malignant brain tumours diagnosed in 1997–2003. International Archives of Occupational and Environmental Health 79(8):630–639.

Hardell L, Carlberg M, Söderqvist F, Mild KH, Morgan LL. 2007. Long-term use of cellular phones and brain tumours: Increased risk associated with use for > or = 10 years. Occupational and Environmental Medicine 64(9):626–632 (Review).

Hardell L, Hansson Mild K. 2006. Mobile phone use and risk of acoustic neuroma: Results of the interphone case-control study in five North European countries. British Journal of Cancer 94(9):1348–1349.

Hardell L, Carlberg M, Hansson Mild K. 2009. Epidemiological evidence for an association between use of wireless phones and tumor diseases. Pathophysiology 16(2–3):113–122.

Hardell L, Carlberg M. 2009. Mobile phones, cordless phones and the risk for brain tumours. International Journal of Oncology 35:5–17.

Hutter H-P, Moshammer H, Wallner P Kundi M. 2006. Subjective symptoms, sleeping problems, and cognitive performance in subjects living near mobile phone base stations. Occupational and Environmental Medicine 63:307–313.

Hyland GJ. 2000. Physics and biology of mobile telephony. The Lancet 356:1833–1836.

International Commission for Non-Ionising Radiation Protection (ICNIRP). 1998. Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz). Health Physics 74:494–522.

Jackson JD. 1975. Classical electrodynamics. New York: John Wiley & Sons, Inc.

Koval TM, Hart RW, Myser WC, Hink WF. 1977. A comparison of survival and repair of UV-induced DNA damage in cultured insect versus mammalian cells. Genetics 87:513–518.

Kundi M. 2004. Mobile phone use and cancer. Occupational and Environmental Medicine 61:560–570.

Kundi M, Hutter HP. 2009. Mobile phone base stations – effects on wellbeing and health. Pathophysiology 16:123–135.

Lopez-Martin ME, Brogains J, Relova-Quinteiro JL, Cadarso-Suárez C, Jorge-Barreiro FJ, Ares-Pena FJ. 2009. The action of pulse-modulated GSM radiation increases regional changes in brain activity and c-Fos expression in cortical and subcortical areas in a rat model of picrotoxin-induced seizure proneness. Journal of Neuroscience Research 87:1484–1499.

Markova E, Hillert L, Malmgren L, Persson BR, Belyaev IY. 2005. Microwaves from GSM mobile telephones affect 53BP1 and gamma-H2AX foci in human lymphocytes from hypersensitive and healthy persons. Environmental Health Perspectives 113(9):1172–1177.

Navarro EA, Segura J, Portolés M, Gómez-Perretta de Mateo C. 2003. The microwave syndrome: A preliminary study in Spain. Electromagnetic Biology and Medicine 22(2–3):161–169.

Nylund R, Leszczynski D. 2006. Mobile phone radiation causes changes in gene and protein expression in human endothelial cell lines and the response seems to be genome- and proteome-dependent. Proteomics 6(17):4769–4780.

Oscar KJ, Hawkins TD. 1977. Microwave alteration of the blood-brain barrier system of rats. Brain Research 126:281–293.

Panagopoulos DJ, Karabarbounis A, Margaritis LH. 2004. Effect of GSM 900-MHz mobile phone radiation on the reproductive capacity of *Drosophila melanogaster*. Electromagnetic Biology and Medicine 23(1):29–43.

Panagopoulos DJ, Messini N, Karabarbounis A, Philippetis AL, Margaritis LH. 2000a. Radio frequency electromagnetic radiation within 'safety levels' alters the physiological function of insects. In: Kostarakis P, Stavroulakis P, editors. Millennium International Workshop on Biological Effects of Electromagnetic Fields. Proceedings; Heraklion, Crete, Greece, 17–20 October 2000. pp 169–175.

Panagopoulos DJ, Margaritis LH. 2002. Effects of different kinds of EMFs on the offspring production of insects. In: Kostarakis P, editors. 2nd International Workshop, Biological Effects of Electromagnetic Fields, Proceedings; Rhodes, Greece, 7–11 October 2002. pp 438–452.

Panagopoulos DJ, Messini N, Karabarbounis A, Filippetis AL, Margaritis LH. 2000b. A mechanism for action of oscillating electric fields on cells. Biochemical and Biophysical Research Communications 272(3):634–640.

Panagopoulos DJ, Karabarbounis A, Margaritis LH. 2002. Mechanism for action of electromagnetic fields on cells. Biochemical and Biophysical Research Communications 298(1):95–102.

Panagopoulos DJ, Margaritis LH. 2003a. Effects of electromagnetic fields on the reproductive capacity of *Drosophila melanogaster*. In: Stavroulakis P, editor. Biological effects of electromagnetic fields. Berlin: Springer. pp 545–578.

Panagopoulos DJ, Margaritis LH. 2003b. Theoretical considerations for the biological effects of electromagnetic fields. In: Stavroulakis P, editor. Biological effects of electromagnetic fields. Berlin: Springer pp 5–33.

Panagopoulos DJ, Chavdoula ED, Karabarbounis A, Margaritis LH. 2007a. Comparison of bioactivity between GSM 900 MHz and DCS 1800 MHz mobile telephony radiation. Electromagnetic Biology and Medicine 26(1).

Panagopoulos DJ, Chavdoula ED, Nezis IP, Margaritis LH. 2007b. Cell death induced by GSM 900MHz and DCS 1800MHz mobile telephony radiation. Mutation Research 626:69–78.

Panagopoulos DJ, Margaritis LH. 2008. Mobile telephony radiation effects on living organisms. In: Harper AC, Buress RV, editors. Mobile telephones, networks, applications and performance. New York: Nova Science Publishers. pp 107–149.

Panagopoulos DJ, Chavdoula ED, Margaritis LH. 2010. Bio effects of mobile telephony radiation in relation to its intensity or distance from the antenna, International Journal of Radiation Biology 86(5):00–00 [X-ref needed].

Persson BRR, Salford LG, Brun A. 1997. Blood-brain barrier permeability in rats exposed to electromagnetic fields used in wireless communication. Wireless Networks 3: 455–461.

Reitz JR, Milford FJ. 1967. Foundations of electromagnetic theory, Boston, MA: Addison-Wesley Publishing Company, Inc.

Remondini D, Nylund R, Reivinen J, Poulletier de Gannes F, Veyret B, Lagroye I, Haro E, Trillo MA, Capri M, Franceschi C, Schlatterer K, Gminski R, Fitzner R, Tauber R, Schuderer J, Kuster N, Leszczynski D, Bersani F, Maercker C. 2006. Gene expression changes in human cells after exposure to mobile phone microwaves. Proteomics 6(17):4745–4754.

Salford LG, Brun A, Sturesson K, Eberhardt JL, Persson BR. 1994. Permeability of the blood-brain barrier induced by 915 MHz electromagnetic radiation, continuous wave and modulated at 8, 16, 50, and 200 Hz. Microscopy Research and Technique 27:535–542.

Salford LG, Brun AE, Eberhardt JL, Marmgren L, Persson BR. 2003. Nerve cell damage in mammalian brain after exposure to microwaves from GSM mobile phones. Environmental Health Perspectives 111(7):881–883.

Shcheglov VS, Belyaev IY, Alipov YD, Ushakov VL. 1997. Power-dependent rearrangement in the spectrum of resonance effect of millimeter waves on the genome conformational state of E. coli cells. Electro- and Magnetobiology 16:69–82.

Slater D. 1991. Near-field antenna measurements. Boston, MA: Artech House, Inc.

Viel JF, Clerc S, Barrera C, Rymzhanova R, Moissonnier M, Hours M, Cardis E. 2009. Residential exposure to radiofrequency fields from mobile phone base stations, and broadcast transmitters: A population-based survey with personal meter. Occupational and Environmental Medicine 66:550–556.

World Health Organisation (WHO). 1993. World Health Organisation: Environmental Health Criteria 137. Electromagnetic fields 300 Hz to 300 GHz. Geneva: WHO.

## Appendix

Reproductive capacity of sham-exposed groups in four identical experiments.

| Experiment No. | Groups | Mean number of $F_1$ pupae per maternal fly, for GSM 900 MHz sham exposure | Mean number of $F_1$ pupae per maternal fly, for GSM 1800 MHz sham exposure |
|---|---|---|---|
| 1 | SE1 | 13.7 | 14.6 |
| | SE2 | 13.5 | 12.6 |
| | SE | 12.9 | 13.2 |
| 2 | SE1 | 12.7 | 11.8 |
| | SE2 | 14.8 | 15 |
| | SE | 14.4 | 10.9 |
| 3 | SE1 | 14.4 | 12.6 |
| | SE2 | 14.1 | 11.1 |
| | SE | 14.3 | 14.3 |
| 4 | SE1 | 14.7 | 13.4 |
| | SE2 | 13.2 | 12.9 |
| | SE | 13.5 | 13.8 |
| Average ± SD | SE1 | 13.87 ± 0.89 | 13.1 ± 1.19 |
| | SE2 | 13.9 ± 0.71 | 12.9 ± 1.61 |
| | SE | 13.77 ± 0.71 | 13.05 ± 1.5 |

The SE1 groups were sham-exposed at 30 and 20 cm from the GSM 900 or 1800 mobile phone antenna correspondingly, without use of any electromagnetic shielding. The SE2 groups were sham exposed at 8 or 5 cm correspondingly from the GSM 900 or 1800 mobile phone antenna behind the ferromagnetic metal grid shield. The SE groups were sham-exposed in both cases at 10 cm distance without any shield. Single factor Analysis of Variance test showed that the three different sham-exposed groups did not differ significantly in their reproductive capacity, ($P > 0.97$ both for GSM 900 and 1800 sham exposures). Therefore in our experiments we used only one sham-exposed group at 10 cm distance from the antenna without any shielding.