

# Reduced growth of soybean seedlings after exposure to weak microwave radiation from GSM 900 mobile phone and base station

Halgamuge, Malka N.; Yak, See Kye; Eberhardt, Jacob L.

2015

Halgamuge, M. N., Yak, S. K., & Eberhardt, J. L. (2015). Reduced growth of soybean seedlings after exposure to weak microwave radiation from GSM 900 mobile phone and base station. *Bioelectromagnetics*, 36(2), 87-95.

<https://hdl.handle.net/10356/96199>

<https://doi.org/10.1002/BEM.21890>

---

© 2015 Wiley Periodicals Inc. This is the author created version of a work that has been peer reviewed and accepted for publication by *Bioelectromagnetics*, Wiley Periodicals Inc. It incorporates referee's comments but changes resulting from the publishing process, such as copyediting, structural formatting, may not be reflected in this document. The published version is available at: [<http://dx.doi.org/10.1002/BEM.21890>].

*Downloaded on 13 Mar 2024 19:05:05 SGT*



# **Reduced Growth of Soybean Seedlings after Exposure to Weak Microwave Radiation from GSM 900 Mobile Phone and Base Station**

Journal:	<i>Bioelectromagnetics</i>
Manuscript ID:	BEM-13-0073.R4
Wiley - Manuscript type:	Research Article
Date Submitted by the Author:	29-Oct-2014
Complete List of Authors:	Halgamuge, Malka; The University of Melbourne, Civil & Environmental Engineering Eberhardt, Jacob; Lund University, Medical Radiation Physics
Keywords:	Mobile phones, base station, radiofrequency electromagnetic fields, soybean seedlings growth

SCHOLARONE™  
Manuscripts

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

**Reduced Growth of Soybean Seedlings after Exposure to Weak Microwave Radiation from GSM 900 Mobile Phone and Base Station**

<sup>1</sup>Malka N. Halgamuge <sup>2</sup>See Kye Yak and <sup>3</sup>Jacob L. Eberhardt

<sup>1</sup>Department of Electrical & Electronics Engineering, University of Melbourne, Victoria, Australia

<sup>2</sup>Electromagnetic Effects Research Laboratory, School of Electrical & Electronic Engineering, Nanyang Technological University, Nanyang, Singapore

<sup>3</sup>Department of Medical Radiation Physics, University of Lund, Lund, Sweden

*Running title:*

***Weak microwave radiation affects soybean growth***

Corresponding author: Malka N. Halgamuge, Department of Electrical & Electronics Engineering, University of Melbourne, Victoria 3010, Australia.

Tel. +61 3 8344 3933

Email: malka.nisha@unimelb.edu.au

## Abstract

The aim of this project was to study possible effects of environmental radiation pollution on plants. The association between cellular telephone (short duration, higher amplitude) and base station (long duration, very low amplitude) radiation exposure and the growth rate of soybean (*Glycine max*) seedlings was investigated. Soybean seedlings, pre-grown for 4 days, were exposed in a gigahertz transverse electromagnetic cell for 2 h to global system for mobile communication (GSM) mobile phone pulsed radiation or continuous wave (CW) radiation at 900 MHz with amplitudes of 5.7 and 41 V m<sup>-1</sup>, and outgrowth was studied one week after exposure. The exposure to higher amplitude (41 V m<sup>-1</sup>) GSM radiation resulted in diminished outgrowth of the epicotyl. The exposure to lower amplitude (5.7 V m<sup>-1</sup>) GSM radiation did not influence outgrowth of epicotyl, hypocotyls, or roots. The exposure to higher amplitude CW radiation resulted in reduced outgrowth of the roots whereas lower CW exposure resulted in a reduced outgrowth of the hypocotyl. Soybean seedlings were also exposed for 5 days to an extremely low level of radiation (GSM 900 MHz, 0.56 V m<sup>-1</sup>) and outgrowth was studied 2 days later. Growth of epicotyl and hypocotyl were found to be reduced, whereas the outgrowth of roots was stimulated. Our findings indicate that the observed effects were significantly dependent on field strength as well as amplitude modulation of the applied field.

**Keywords:** Mobile phones, base station, radiofrequency electromagnetic fields, soybean seedling growth.

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

**Introduction**

The use of mobile phones has evolved from a rare activity to 6 billion subscribers (87% of the world's population) worldwide, including both adults and children thereby creating an extremely strong mobile phone industry sector [International Telecommunication Union (ITU), 2011]. The World Health Organization (WHO) concluded in a review study that there is no epidemiological evidence that mobile phone usage causes brain tumors in adults [WHO, 2011]. However, radiofrequency (RF) radiation from mobile phones has been classified as a “Possible Human Carcinogen” (Group 2B) that might transform normal cells into cancer cells [WHO, 2011]. This classification was based on a review of previously published evidence including the Interphone study results published up to that date and the Swedish studies by Hardell et al. [2006]. Nonetheless, a recently published review suggests that most of these investigations led to inconclusive results partly due to a lack of a hypothetical mechanism to guide the experimental designs [Hore, 2012].

The exact mechanisms by which organisms react to exposure to electromagnetic fields and radiation are largely unknown. Increased production of reactive oxygen species (ROS) is a common response to many stressors, possibly including exposure to electromagnetic fields (EMFs), as stress situations interrupt cellular physiological processes between generation and neutralization of highly reactive molecules [Arora et al., 2002]. ROS can damage cell structures by oxidizing proteins, nucleic acids and membrane lipids. In a number of in vivo animal studies reviewed by Desai et al. [2009]

1  
2  
3 it was shown that oxidative stress develops in response to cell phone radiation. In  
4  
5 plants it was also reported that RF radiation increased ROS and induced oxidative  
6  
7 stress [Tkalec et al. 2007; Sharma et al. 2009]. Thus studies of simple plant systems  
8  
9 might reveal important information that could apply to animal and human biological  
10  
11 systems as well.  
12  
13  
14

15  
16 Possible biological effects from electromagnetic radiation from mobile  
17  
18 communication systems are known to depend on the carrier frequency, the mean power  
19  
20 level and the low frequency amplitude modulation of the power. Most studies in the  
21  
22 field of effects of RF EMFs and radiation have focused on animals and cell cultures.  
23  
24 Only a few studies of EMF effects on plants [Tkalec et al., 2005, 2007, 2009; Sharma  
25  
26 et al. 2009] have been reported. In early studies seeds were exposed to extremely low  
27  
28 frequency (ELF) magnetic fields or RF radiation in order to investigate biological  
29  
30 effects [Bigu-del-Blanco et al., 1977; Belova et al., 2001; Belova et al., 2007; Tkalec et  
31  
32 al., 2009; Shine et al., 2011], however, the results are inconsistent.  
33  
34  
35  
36  
37  
38  
39

40  
41 Large parts of the world are covered with sources of electromagnetic radiation  
42  
43 like radio and television transmitters and base stations for mobile communication, but  
44  
45 little is known about biological effects on plants. The aim of the present study is to  
46  
47 investigate the growth rate of 4-day-old soybean seedlings exposed to radiation from  
48  
49 global system for mobile communication (GSM) both as acute exposure to intermediate,  
50  
51 nonthermal exposure levels. This provides specific absorption rate (SAR) values  
52  
53 comparable to ones in the human head during mobile phone use and long term  
54  
55  
56  
57  
58  
59  
60

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

exposure at a very low exposure level, which give rise to SAR values as can be expected a few hundred meters from a base station. We also aim to study the importance of the amplitude modulation as used in GSM by comparing to the effects on growth rate of continuous wave radiation with the same carrier frequency and amplitude.

**Materials and Method**

**Exposure System**

GSM 900 mobile signals were considered in this experiment. GSM phones transmit data in bursts with a repetition rate of 217 Hz. Since, a number of papers indicated that the modulation pattern itself, in addition to carrier wave frequency and intensity, was an important parameter for causing biological effect, we chose to compare GSM 900 exposure with continuous wave exposure (CW). GSM 217 Hz fields were generated with 900 MHz center frequency, pulse period =  $1/217 = 4.6$  ms and pulse width = 0.576 ms. The exposure system contained: a signal generator (Agilent 4433B; Hewlett-Packard, Palo Alto, CA), a power amplifier (30W 1000A, 25A250A; Amplifier Research, San Diego, CA), a spectrum analyzer (Agilent 8891A; Hewlett-Packard, Palo Alto, CA), a power meter (PM2002; Amplifier Research, San Diego, CA) and a Gigahertz Transverse Electromagnetic (GTEM) cell (Model 5407; ESCO Technologies, St. Louis, MO) to create homogenous EMFs. The electric field

uniformity of the GTEM cell was measured according to the European Standard EN 61000-4-20 for testing and measurement techniques in transverse electromagnetic waveguides and found to be about 2 dB in a 633 x 250 mm vertical/transverse plane centered at an 80-cm septum height. The dimension of the testing region with highest accuracy of transverse wave was 400 x 400 mm (5407 model). The GSM 900 MHz mobile signals were generated by the signal generator and boosted by the power amplifier to field intensities (during the pulses) of 0.56-41 V m<sup>-1</sup> in the GTEM cell as measured with a near field probe (VM7000, ARWorldwide, Souderton, PA) in the middle of the testing region where the Petri dish with the soybeans was to be placed. Electric field values were measured with and without the Petri dishes present and were found to be identical.

At the beginning, during, and end of exposure, the temperature inside the GTEM cell was measured using a thermometer (Fluke-52, Auber Instruments, Alpharetta, GA). The temperature inside the GTEM cell as well as on seedling surface did not vary more than  $\pm 0.1$  °C.

### Soybean Seedlings

In this study, growth rate was investigated for soybean (*Glycine max*) seedlings. Seeds were pregrown in complete darkness for 4 days at 26 °C, as in Belova et al. [2007], on moist sterile filter paper in Petri dishes (90 mm in diameter) before exposure to radio frequency electromagnetic radiation in the GTEM cell. The temperature in the



1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

growing room was checked twice a day. After this period, exposure and sham exposure inside the GTEM cell was performed for 2 h at the ambient temperature of the air-conditioned room of 23 °C. Inside the GTEM cell, 10 seedlings (4 days old) were placed, evenly distributed, in a Petri dish (nearly 2.4 cm apart) in total darkness. The long axis of the *Allium Cepa* seeds was aligned along the propagation direction of the electromagnetic wave, as in Tkalec et al. [2009]. Filter paper was moistened with 2 ml of distilled water before RF exposure or sham exposure. The humidity level was 70% (MT6600 SWP hygrometer; Charm FaithAutosystem, Beijing, China). Immediately after exposure the dishes were transferred back to the growth chamber and watered, regularly. The length of the primary roots was measured after a week.

In another experiment, in order to mimic base station-like conditions, we exposed seedlings for 5 days (24 h/day) inside the GTEM cell at the very low field amplitude of 0.56 V m<sup>-1</sup>. After this exposure the seedlings were transferred to a growth chamber in total darkness for two days before stem and root outgrowth were determined.

The following parameters of outgrowth were studied: L<sub>1</sub> - epicotyl - length between leaves and cotyledon, L<sub>2</sub> – hypocotyl - length between cotyledon and start of root and branches L<sub>3</sub> – length of root and its branches (Fig. 1). Each segment measured was stretched out before measurement.

## Exposure

We performed 12 different experiments as shown in Table 1. To avoid thermal heating of the soybean seedlings, we kept the power density below  $5000 \text{ mW m}^{-2}$ . The soybean seedlings were exposed to RF fields of 900 MHz as continuous wave (CW) or pulse (pulse width 0.576 ms) modulated with 217 Hz repetition rate according to GSM 900. Three different field strengths were investigated: 0.56, 5.7 and  $41 \text{ V m}^{-1}$ , corresponding to (peak) power flux densities of 0.8, 86 and  $4400 \text{ mW m}^{-2}$  respectively. The time-averaged intensities of the pulsed signals are 1/8 of the intensities for the continuous wave signals with the same amplitudes (Table 1). The time averaged power density is the relevant parameter for determining SAR in the soybean seedlings.

Lin et al. [1973] showed that when wavelength of electromagnetic radiation is long compared to diameter of a sphere, analytic expressions can be derived for the electric field in the sphere and hence, for the absorbed power density. Durney et al. [1975] refined the model to include prolate spheroid objects. The long-wavelength condition is fulfilled for soybean seedlings in a 900 MHz electromagnetic plane wave field. In order to calculate SAR values according to this formalism, some assumptions have to be made. We calculated SAR values for a spheroid approximation of a soybean with a long axis of 1.5 cm and short axis of 0.75 cm. We assumed moisture content of 14% and a density of  $0.78 \text{ g/cm}^3$ . Data on the dielectric properties of soybeans at around 1 GHz could not be found in the available literature. For this reason, we used the empirical expressions given by Nelson [1991] and found values of 3.5 and 0.4 for

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

the relative permittivity and loss factor (real and complex part of the complex permittivity) respectively, for the density, moisture content and field frequency assumed. The loss factor corresponds to a conductivity of  $0.02 \text{ S m}^{-1}$ . The calculations were performed for a k-polarized plane wave (the long axis of the bean is along the propagation direction) according to Equation 6 of the Appendix. The SAR values we derived are  $2.6 \text{ mW kg}^{-1}$ ,  $0.049 \text{ mW kg}^{-1}$  and  $4.8 \times 10^{-4} \text{ mW kg}^{-1}$  for the signals of  $41 \text{ V m}^{-1}$ ,  $5.7 \text{ V m}^{-1}$  and  $0.56 \text{ V m}^{-1}$ , respectively (Table 1). As a comparison, the  $0.56 \text{ V m}^{-1}$  signal corresponds to a GSM mobile phone base station at a distance of approximately 500 m.

For the CW exposures, we chose to use the same electric field strengths as the peak values of the pulsed GSM signal. As a consequence, CW radiation will result in 8 times higher average power densities (and SAR) for the same electric field strength ( $\text{V m}^{-1}$ ):  $20 \text{ mW kg}^{-1}$  and  $0.39 \text{ mW kg}^{-1}$  for the signals of  $41 \text{ V m}^{-1}$  and  $5.7 \text{ V m}^{-1}$ , respectively (Table 1).

Lin et al. [1973] and Johnson et al. [1975] pointed out that in long-wavelength, quasi static approximation, the electric field in the irradiated object can be considered as the result of two components: first, a homogeneous internal field resulting from polarization of the medium by the external *electric* field component and second, a circular electric field caused by induction by the external *magnetic* field component. However, the approximation made by these authors that the real part of the permittivity is so much smaller than the complex part that it can be neglected, does not apply for

soybeans irradiated at 900 MHz. We have derived a more exact expression for the SAR distribution following the derivation described by Durney et al. [1975] (Equation 3 in Appendix). Under the assumption of the soybean being electrically homogeneous, the SAR distribution is calculated to be very homogeneous (Fig. 2).

## Statistical Analysis

We first computed the peakedness (Kurtosis) and Skewness of the probability distribution of the observed  $L_1$ ,  $L_2$  and  $L_3$  in order to test for the normality of the distribution. Since our data were not normally distributed, in this study we used non-parametric analyses (Mann-Whitney, Wilcoxon and Kruskal Wallis signed ranks tests). All analyses were carried out using SPSS statistical package for the Social Sciences, Version 21 (IBM Software, Armonk, NY), to compare the growth of soybean seedlings exposed to the RF EMFs with those grown concurrently under control conditions (sham exposed), using a 95% confidence level ( $p < 0.05$ ) to estimate statistical significance.

Crucial in experiments where growth rates are determined, is that all other factors except exposure are kept constant. Two tests for systematic errors were applied to the data sets. First, outgrowth for sham exposure was compared between the different experiments with the same exposure condition, thus testing for constant environmental conditions. Under constant conditions the results from different experiments can be pooled. Second, as a test for constant environmental conditions during a testing day, in five experiments sham exposures were applied both before and

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

after exposure during the same day. This allows us not only to compare exposed to shams, but also shams to shams (Fig. 3 a-d).

**RESULTS**

The data were analyzed with respect to  $L_1$ ,  $L_2$  and  $L_3$  as described above. Only if a simultaneous comparison between the three experimental conditions applied on the same day indicated a significant difference between the conditions, did we continue with pairwise comparisons. The reason was to avoid mass-significance effects due to multiple pairwise comparisons on the same material. Sham exposures during the same day never differed significantly as illustrated in Figure 3. The medians and interquartile range for  $L_2$  and  $L_3$  for CW exposure at  $5.7 \text{ V m}^{-1}$  are shown in Figure 3a, b). These parameters were significantly reduced as compared to the two sham exposures in this experiment. Similar results were found for  $L_1$  for GSM 900 exposure at  $41 \text{ V m}^{-1}$  (Fig. 3 c, d). In the fifth experiment ( $41 \text{ V m}^{-1}$ , GSM 900 MHz) with sham-exposure-sham design, no significant difference was found between the three parameters studied and the two sham exposures before and after exposure.

Comparing results from sham exposures obtained during different days gives confidence that data from identical exposure conditions can be pooled. Thus all 12 experiment occasions were used in the analysis. Results for pooled data (also sham exposures obtained on the same day were pooled) are shown in Table 2. For GSM exposure with signal strength of  $41 \text{ V m}^{-1}$ ,  $L_1$  was reduced by 1.7 mm ( $p = 0.002$ ),

whereas  $L_2$  and  $L_3$  did not change. GSM exposure with  $5.6 \text{ V m}^{-1}$  did not result in changes in outgrowth. For CW exposure with signal strength of  $41 \text{ V m}^{-1}$ , only  $L_3$  was reduced significantly, by 1.1 mm ( $p < 0.001$ ). CW exposure at the lower signal strength of  $5.7 \text{ V m}^{-1}$  only resulted in a reduction of  $L_2$  by 1.3 mm ( $p = 0.004$ ).

In the five-day experiment where a low power density of  $0.1 \text{ mW m}^{-2}$  was applied,  $L_1$  was reduced by 0.2 mm ( $p = 0.024$ ),  $L_2$  was reduced by 1 mm ( $p = 0.001$ ), whereas  $L_3$  increased by 1 mm ( $p < 0.001$ ) (Table 2).

## DISCUSSION

Most studies in the field of effects of RF EMFs and radiation have focused on animals and cell cultures. So far, however, there have been few experiments on plants. Our aim is to advance knowledge on the effects of EMFs on biological tissue. Studies on simple biological systems can add to our understanding of fundamental interaction mechanisms and which proteins in living matter are susceptible to electromagnetic radiation and fields. This knowledge is crucial to develop dose-response relationships on which guidelines for exposure limits can be built. It will also help the industry design safe communication systems.

Some trends can be discerned in results for the 2 h exposure experiments as below. When we consider  $L_1$  (length between leaves and cotyledon) we found that pulsed radiation with average power density of  $560 \text{ mW m}^{-2}$  reduces outgrowth more than CW with  $4400 \text{ mW m}^{-2}$ . This might indicate the importance of the low frequency

amplitude modulation of the RF-signal. When we consider  $L_2$  (length between cotyledon to start of root and its branches), no effect on outgrowth was observed except for CW radiation with power density of  $86 \text{ mW m}^{-2}$  where a reduction of outgrowth was seen. No effects were seen for GSM 900 with  $560 \text{ mW m}^{-2}$  or CW with  $4400 \text{ mW m}^{-2}$ . This gives an indication that CW with low SAR could be more effective than pulsed radiation with higher SAR for this parameter. Contrary to our findings, Juutilainen et al. [2011] published an extensive review of possible modulation-dependent biological effects of RF fields and concluded there is little evidence for modulation being important. One of the papers cited in this review, however, reported enhanced genotoxic effects of CW radiation as compared to GSM [Luukkonen et al., 2009]. Tkalec et al. found in studies on Axenic duckweed [2005, 2007] and *Allium cepa* [2009] that the extent of the biological effects depended on frequency, amplitude and modulation. The results for the  $L_2$  parameter might also implicate an “amplitude window” effect (a higher amplitude of exposure elicits a lower biological effect) as described by others for low frequency magnetic fields [Blackman et al., 1985; Lednev et al., 1991; Edmonds et al., 1993]. Finally, when we consider  $L_3$  (maximum length of root and its branches), we found no inhibiting effects on outgrowth except for CW at a power density of  $4400 \text{ mW m}^{-2}$ . As for the  $L_2$  parameter, CW seems to have more impact than GSM, but since in this case the power density is much higher than in any of the GSM exposures, no definite conclusions can be drawn.

Akbal et al. [2012] confirms our findings of a diminished root growth after



1  
2 exposure to high frequency electromagnetic radiation and discovered a decrease in root  
3 growth in lentil seedlings (*Lens Culinaris Medik*), exposed to mobile phone radiation at  
4  
5 1800 MHz.  
6  
7

8  
9  
10 Tkalec et al. [2005] reported decreased growth and reduced peroxidase activity  
11 in Axenic duckweed exposed to 400 MHz and 900 MHz CW and amplitude modulated  
12 microwaves for 2 and 14 h. The same author [Tkalec et al., 2007] found increased  
13 levels of peroxidation and H<sub>2</sub>O<sub>2</sub> and diminished anti-oxidative enzyme activity in  
14 Axenic duckweed and found mitotic aberrations [Tkalec et al., 2009] for a variety of  
15 exposure conditions at 400 and 900 MHz in *Allium cepa*. Also Sharma et al. [2009]  
16 found an inhibition of root growth and increased oxidative stress after exposure of  
17 mung beans (*Vigna radiata*) to radiation from mobile phones (900 MHz, 8.55  $\mu$ W cm<sup>-2</sup>,  
18 for ½, 1, 2, and 4 h).  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33

34  
35 Our results indicate that 900 MHz microwave exposure elicits a stress response  
36 that not only depends on strength of the exposure (SAR-value) but also on type of  
37 modulation.  
38  
39  
40  
41

42  
43 A stress response, similar to ones elicited by plant wounding, was reported by  
44 Beaubois et al. [2007] and Roux et al. [2008] who studied tomatoes at 900 MHz (5 V  
45 m<sup>-1</sup>, 10 min). They found a stress related accumulation of mRNA (calmodulin, calcium-  
46 dependent protein kinase and proteinase inhibitor) and an enhancement of the  
47 translation of encoded proteins. Several authors hypothesize membrane Ca<sup>++</sup> ions to be  
48 the primary target for stimulation of cells by electromagnetic radiation that alter the  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60



conformation of NADPH plasmic membrane oxidase, inducing increased formation of reactive oxygen species that may alter proteomic functions [Beauboiss et al., 2007; Ledoigt and Belpomme, 2013]

On the contrary, Schmutz et al. [1996] who investigated the effect of long-term exposure (2 years) of young spruce (4-year-old) and beech trees (3-year-old) to 2450 MHz with power flux densities 0.007 to 300 W m<sup>-2</sup> did not find any effect on crown transparency, growth, and photosynthesis. Nevertheless, they found changes in foliar calcium and sulfur concentration in beech trees.

Contrary to the findings of a diminished growth after exposure to high frequency electromagnetic radiation, several authors reported improved germination and growth parameters after exposure to static magnetic fields in the mT range [Aladjadjiyan, 2002; Atak et al., 2003; Yaycili and Alikamanoglu, 2005]. It is not unreasonable to assume that totally different interaction mechanisms are responsible for biological effects observed at different exposure frequencies.

Rather surprisingly, one-week exposure for very weak GSM 900 radiation with very low power density (0.1 mW m<sup>-2</sup>) influenced all three outgrowth parameters significantly. In this case L<sub>1</sub> and L<sub>2</sub> were influenced in the same way as for short-term exposure, the outgrowth being inhibited, whereas L<sub>3</sub> was stimulated by radiation. To our knowledge, no long-term studies of exposure of plants to very weak microwave radiation from mobile phone base stations have been published.

No generally accepted interaction model exists that explains how very weak high

frequency magnetic fields interact with biological molecules. Neither is it known whether it is the electrical or magnetic component of radiation that is responsible for the observed effects. Electric fields influence all electric dipoles and electrical charges in the biological system. Sernelius [2004] argued that van der Waals forces in biological matter can be altered dramatically by the presence of microwave fields. For bio effects where amplitude modulation of the carrier wave was found to be important, the theory developed by Lednev [1991] could be applicable. In this ion parametric resonance model, a combination of a time-varying magnetic field and the static earth magnetic field causes the bio effects. The field strength of  $41 \text{ V m}^{-1}$  corresponds to strength of the magnetic component of the signal of  $0.14 \text{ }\mu\text{T}$ . Earth's magnetic field at the site of the experiment (Singapore) is about  $40 \text{ }\mu\text{T}$ . The frequency of  $217 \text{ Hz}$  would correspond with the resonance frequency of an ion with charge one and mass three. No such ion comes to mind. However, the third harmonic of the square wave of the signal corresponds to the resonance frequency of hydrogen ions. The strongest biological effects according to the IPR model are expected when time varying and static magnetic fields have comparable strengths, and it is doubtful if the very weak AC magnetic field in this experiment could elicit a biological effect. Later Lednev [Belova et al., 2007] developed a promising interaction model based on polarization of hydrogen nuclei in biological matter. In this model, biological effects are expected, and seen for AC-magnetic fields below  $1 \text{ }\mu\text{T}$ . This model is not dependent on resonance frequency conditions and applies to any time-varying magnetic fields with a frequency well below

the Larmor frequency of hydrogen nuclei in the local Earth magnetic field (1700 Hz in Singapore).

**CONCLUSION**

In this paper, the possible effects of environmental radiation on plants (growth rate of soybean seedlings) using the association between cellular telephone-like (short duration, higher amplitude) and base station-like (long duration, very low amplitude) radiation exposure have been investigated. Evidence has been presented that nonthermal exposure levels for 900 MHz radiation mostly decreases the outgrowth of soybeans. Establishing a dose-response relationship is complicated by the fact that different parameters studied behave differently, with epicotyl outgrowth reduced more by modulated radiation than CW, and hypocotyl outgrowth only reduced by CW at low intensity ( $5.7 \text{ V m}^{-1}$ ), suggesting an amplitude-window effect. It was also observed that long-term exposure for extremely low-level ( $0.56 \text{ V m}^{-1}$ ) GSM 900 radiation significantly affected all response parameters.

**ACKNOWLEDGMENTS**

The authors would like to express their sincere thanks to Mr. W. S. Khoon from Electronic System Measurements Lab, Nanyang Technological University, Singapore, for the excellent technical assistance.

## References

- Akbal A, Kiran Y, Sahin A. 2012. Effects of electromagnetic waves emitted by mobile phones on germination, root growth, and root tip cell mitotic division of *lens culinaris medic*. *Polish Journal of Environmental Studies* 21: 23-29.
- Aladjadjiyan A. 2002. Study of the influence of magnetic field on some biological characteristics of *Zea mais*. *Journal of Central European Agriculture* 3:89-94.
- Arora A, Sairam RK, Srivastava GC. 2002. Oxidative stress and antioxidative system in plants. *Current Science* 82:1227-38.
- Atak C, Emiroglu O, Aklimanoglu S, Rzakoulieva A. 2003. Stimulation of regeneration by magnetic field in soybean (*Glycine max* L. Merrill) tissue cultures. *J Cell Mol. Biol.* 2:113-119.
- Beaubois E, Girard S, Lallechere S, Davies E, Paladian F, Bonnet P, Ledoigt G, Vian A. 2007. Intercellular communication in plants: Evidence for two rapidly transmitted systemic signals generated in response to electromagnetic field stimulation in tomato. *Plant, Cell and Environment* 30:834-44.
- Belova NA, Ermakova ON, Ermakov AM, Rojdestvenskaya ZY, Lednev VV. 2007. The bioeffects of extremely weak power-frequency alternating magnetic fields. *Environmentalist* 27:411-416.
- Belova NA, Lednev VV. 2001. Extremely weak alternating magnetic fields affect the gravitropic response in plants. *Biophysics* 46:121-124.

- Bigu-Del-Blanco J, Bristo JM and Romero-Sierra C. 1977. Effects of low-level microwave radiation on germination and growth rate in corn seeds. *Proceedings of the IEEE* 65:1086-1088.
- Blackman CF, Benane SG, House DE, Joines WT. 1985. Effects of ELF (1-120 Hz) and modulated (50 Hz) RF fields on the efflux of calcium ions from brain tissue in vitro. *Bioelectromagnetics* 6:1-11.
- Desai NR, Kesari KK and Agarwal A. 2009. Pathophysiology of cell phone radiation: Oxidative stress and carcinogenesis with focus on male reproductive system. *Reproductive Biology and Endocrinology* 7: 114.
- Durney CH, Johnson CC, Massoudi H. Long-wavelength analysis of plane wave irradiation of a prolate spheroid model of man. 1975. *IEEE Transactions on Microwave Theory and Techniques* 23:246-253.
- Edmonds DT. 1993. Larmor precession as a mechanism for the detection of static and alternating magnetic fields. *Bioelectrochemistry and Bioenergetics* 30: 3–12.
- Hardell L, Carlberg M, Mild KH. 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* 79:630–639.
- Hore PJ. 2012. Are biochemical reactions affected by weak magnetic fields? *Proceedings Of The National Academy of Sciences of the United States of America* 109:1357-1358.

- 1  
2  
3 International Telecommunication Union. 2011. The world in 2011, ICT facts and  
4  
5 figures. Available: <http://www.itu.int/ITU->  
6  
7 [D/ict/facts/2011/material/ICTFactsFigures2011.pdf](http://www.itu.int/ITU-D/ict/facts/2011/material/ICTFactsFigures2011.pdf), [last accessed, 17 July 2013].  
8  
9  
10 Johnson CC, Durney CH, Massoudi H. 1975. Long-wavelength electromagnetic power  
11  
12 absorption in prolate spheroidal models of man and animals. *IEEE Transactions on*  
13  
14 *Microwave Theory and Techniques* 23:739-747.  
15  
16  
17 Juutilainen J, Höytö A, Kumlin T, Naarala J. 2011. Review of possible modulation-  
18  
19 dependent biological effects of radiofrequency fields. *Bioelectromagnetics* 32:511-  
20  
21 534.  
22  
23  
24  
25  
26 Lednev VV. 1991. Possible mechanism for the influence of weak magnetic fields on  
27  
28 biological systems. *Bioelectromagnetics* 12:71-75.  
29  
30  
31 Ledoigt G, Belpomme D. 2013. Cancer induction molecular pathways and HF-EMF  
32  
33 irradiation. *Advances in Biological Chemistry* 3:177-186.  
34  
35  
36  
37 Lin JC, Guy AW, Johoson CC. 1973. Power deposition in a spherical model of man  
38  
39 exposed to 1-20-MHz electromagnetic fields. *IEEE Transactions on Microwave*  
40  
41 *Theory and Techniques* 21:791-797.  
42  
43  
44  
45 Luukkonen J, Hakulinen P, Mäki-Paakkanen J, Juutilainen J, Naarala J. 2009.  
46  
47 Enhancement of chemically induced reactive oxygen species production and DNA  
48  
49 damage in human SH-SY5Y neuroblastoma cells by 872 MHz radiofrequency  
50  
51 radiation. *Mutation Research/Fundamental and Molecular Mechanisms of*  
52  
53 *Mutagenesis* 662:54-58.  
54  
55  
56  
57  
58  
59  
60

- Nelson SO. 1991. Dielectric properties of agricultural products: measurements and applications. *IEEE Transactions on Electrical Insulation* 26:845-869.
- Roux D, Vian A, Girard S, Paladian F, Davies E, Ledoigt G. 2008. High frequency (900 MHz) low amplitude (5 V m<sup>-1</sup>) electromagnetic field: A genuine environmental stimulus that affects transcription, translation, calcium and energy charge in tomato. *Planta* 227:883-891.
- Schmutz P, Siegenthaler J, Stäger C, Tarjan D, Bucher JB. 1996. Long-term exposure of young spruce and beech trees to 2450-MHz microwave radiation. *Science of The Total Environment* 180:43-48.
- Sernelius BE. 2004. Possible induced enhancement of dispersion forces by cellular phones. Presented at the 17th Conference of the European Colloid & Interface Science Society, Firenze, Italy, September 21-26, 2003. *Physical Chemistry Chemical Physics* 6:1363.
- Sharma VP, Singh HP, Kohlic RK, Batish DR. 2009. Mobile phone radiation inhibits vigna radiata (mung bean) root growth by inducing oxidative stress. *Science of The Total Environment* 407:5543-5547.
- Shine MB, Guruprasad KN, Anand A. 2011. Enhancement of germination, growth, and photosynthesis in soybean by pre-treatment of seeds with magnetic field. *Bioelectromagnetics* 32:474-484.
- Tkalec M, Malarić, K. Pevalek-Kozlina B. 2005. Influence of 400, 900 and 1900 MHz electromagnetic fields on *Lemna minor* growth and peroxidase activity.

1  
2 Bioelectromagnetics 26:185-93.  
3

4  
5 Tkalec M, Malarić, K. Pevalek-Kozlina B. 2007. Exposure to radiofrequency radiation  
6 induces oxidative stress in duckweed *lemna minor* l. *Science of The Total*  
7  
8  
9  
10  
11  
12 Environment 388:78-89.

13 Tkalec M, Malarić K, Pavlica M, Pevalek-Kozlina B, Vidaković-Cifrek Z. 2009.  
14  
15 Effects of radiofrequency electromagnetic fields on seed germination and root  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
meristematic cells of *allium cepa* l. *Mutation Research* 672:76-81.

WHO. 2011. IARC classifies radiofrequency electromagnetic fields as possibly  
carcinogenic to humans. World Health Organization, Press Release No: 208, Lyon,  
France.

Yaycili O, Alikamanoglu S. 2005. The effect of magnetic field on *Paulownia* tissue  
cultures. *Plant Cell, Tissue and Organ Culture* 83:109-114.



## APPENDIX

Expressions for SAR distribution, as given by Durney et al. [1975] for homogeneous prolate spherical cylindrical objects in a long-wavelength approximation were used in this paper. However, the Equations derived by Durney et al. [1975] assume that the magnitude of the real part of the complex permittivity can be neglected compared to the complex (lossy) part of the permittivity. Since this condition is not met for soybeans irradiated at 900 Mhz, we used more general expressions.

For electric, magnetic and cross (k)-polarization of the incident electromagnetic field, the following Equations for the SAR distributions were derived:

$$SAR_E(x, y, z) = \sigma E_0^2 \frac{\left[ \frac{B_e^2}{\epsilon_r^2 + e_i^2} - \frac{2B_e a^2 k y \epsilon_i}{(a^2 + b^2)(\epsilon_r^2 + e_i^2)} + \frac{k^2(a^4 y^2 + b^4 z^2)}{(a^2 + b^2)^2} \right]}{2\rho} \quad (1)$$

$$SAR_H(x, y, z) = \sigma E_0^2 \frac{\left[ \frac{B_h^2}{\epsilon_r^2 + e_i^2} - \frac{k B_h y \epsilon_i}{2(\epsilon_r^2 + e_i^2)} + \frac{k^2(x^2 + y^2)}{4} \right]}{2\rho} \quad (2)$$

$$SAR_k(x, y, z) = \sigma E_0^2 \frac{\left[ \frac{B_h^2}{\epsilon_r^2 + e_i^2} - \frac{2B_h b^2 k z \epsilon_i}{(a^2 + b^2)(\epsilon_r^2 + e_i^2)} + \frac{k^2(a^4 x^2 + b^4 z^2)}{(a^2 + b^2)^2} \right]}{2\rho} \quad (3)$$

Where the expressions have been written in Cartesian coordinates, and where

$\epsilon_r$  and  $\epsilon_i$  are the real and imaginary part of the relative permittivity;

$2a$  and  $2b$  are the lengths of the long and short axis of the spherical cylinder;

$\sigma$  = conductivity of the material;

$\rho$  = density of the material;

$E_0$  = amplitude of the electric field component of the RF radiation;

$k = \omega(\mu_0\epsilon_0)^{1/2}$  with  $\omega$  the circular frequency of the radiation and  $\mu_0$  the magnetic susceptibility and  $\epsilon_0$  the permittivity of vacuum;

$$B_e = [(u_{10})^2 - 1]^{-1} \left[ -1 + \left[ \frac{u_{10}}{2} \ln \left( \frac{u_{10} + 1}{u_{10} - 1} \right) \right] \right]^{-1}$$

$$B_h = 2[(u_{10})^2 - 1]^{-1} \left[ \frac{-u_{10} \ln \left[ \frac{u_{10} + 1}{u_{10} - 1} \right]}{2} + \frac{(u_{10})^2}{(u_{10})^2 - 1} \right]^{-1}$$

$$u_{10} = a/(a^2 - b^2)^{1/2}$$

Integration over the volume of the spheroid gives the average SAR for the volume under study:

$$SAR_E = \sigma E_0^2 \frac{\left[ \frac{B_e^2}{\epsilon_r^2 + e_i^2} - \frac{2B_e a^2 k y \epsilon_i}{(a^2 + b^2)(\epsilon_r^2 + e_i^2)} + \frac{k^2 a^2 b^4}{5(a^2 + b^2)} \right]}{2\rho} \quad (4)$$

$$SAR_E = \sigma E_0^2 \frac{\left[ \frac{B_h^2}{\epsilon_r^2 + e_i^2} + \frac{k^2 b^2}{10} \right]}{2\rho} \quad (5)$$

$$SAR_k = \sigma E_0^2 \frac{\left[ \frac{B_h^2}{\epsilon_r^2 + e_i^2} + \frac{k^2 a^2 b^2}{5(a^2 + b^2)} \right]}{2\rho} \quad (6)$$

## Figure captions

Fig. 1. One week old soybean seedling:  $L_1$  – epicotyl – length between leaves and cotyledon ,  $L_2$  – hypocotyl – length between cotyledon and root and branches,  $L_3$  – maximum length of root and its branches.

Fig. 2. Distribution of Specific Absorption Rate (SAR) in a soybean of 15 mm long oriented with the

long (z-) axis along the propagation direction of the RF radiation (k-polarization) according to the long wavelength approximation (see text). The soybean is approximated as a prolate spheroid with a diameter of 7.5 mm.

Fig. 3. Box plots with median and interquartile range for a)  $L_2$  for CW exposure at  $5.7 \text{ V m}^{-1}$ , b)  $L_3$  for CW exposure at  $5.7 \text{ V m}^{-1}$ , c)  $L_1$  for GSM 900 exposure at  $41 \text{ V m}^{-1}$  and d)  $L_1$  for GSM 900 exposure at  $41 \text{ V m}^{-1}$ . The T-bars (whiskers) extend to 1.5 times the height of the box (inter quartile range, IQR).

Table 1. *Exposure scheme for 900 MHz exposure. The GSM exposures consist of 0.5 ms pulses with a repetition rate of 217 Hz.*

Table 2. *Medians in mm (p-values in brackets) for the difference between exposed and sham exposed, pooled data (n.s. is denoted as non significant difference).*

## FIGURES

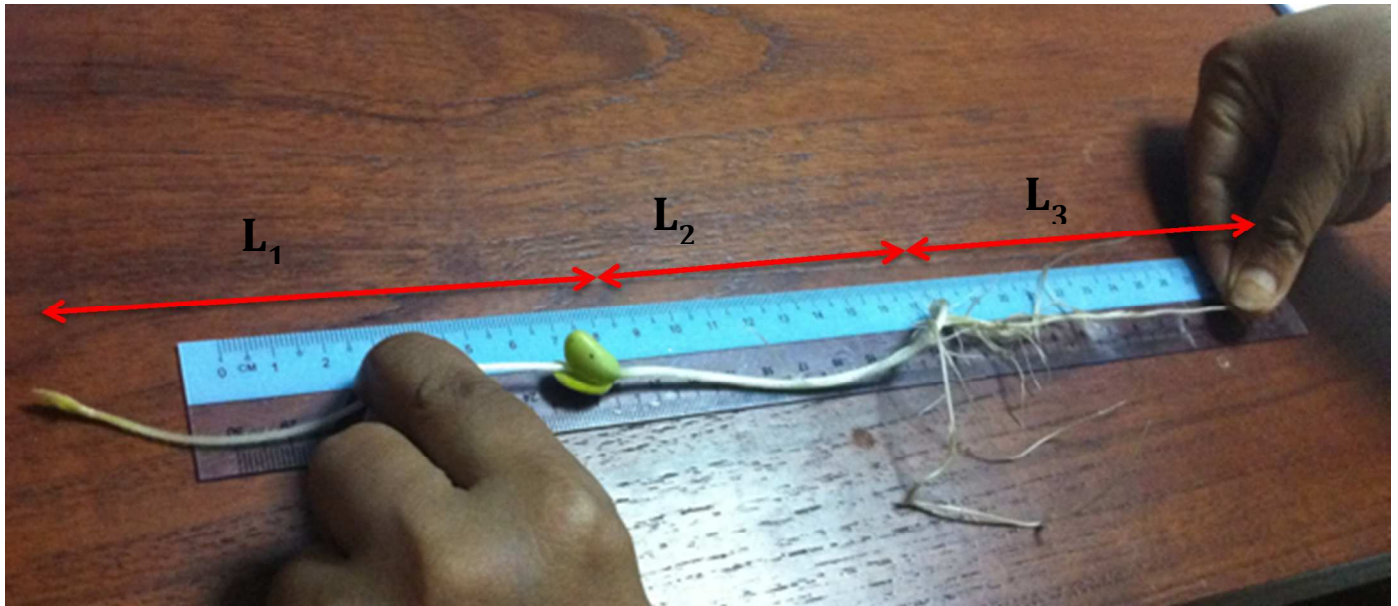


Fig. 1. One week old soybean seedling:  $L_1$  – epicotyl – length between leaves and cotyledon ,  $L_2$  – hypocotyl – length between cotyledon and root and branches,  $L_3$  – maximum length of root and its branches.

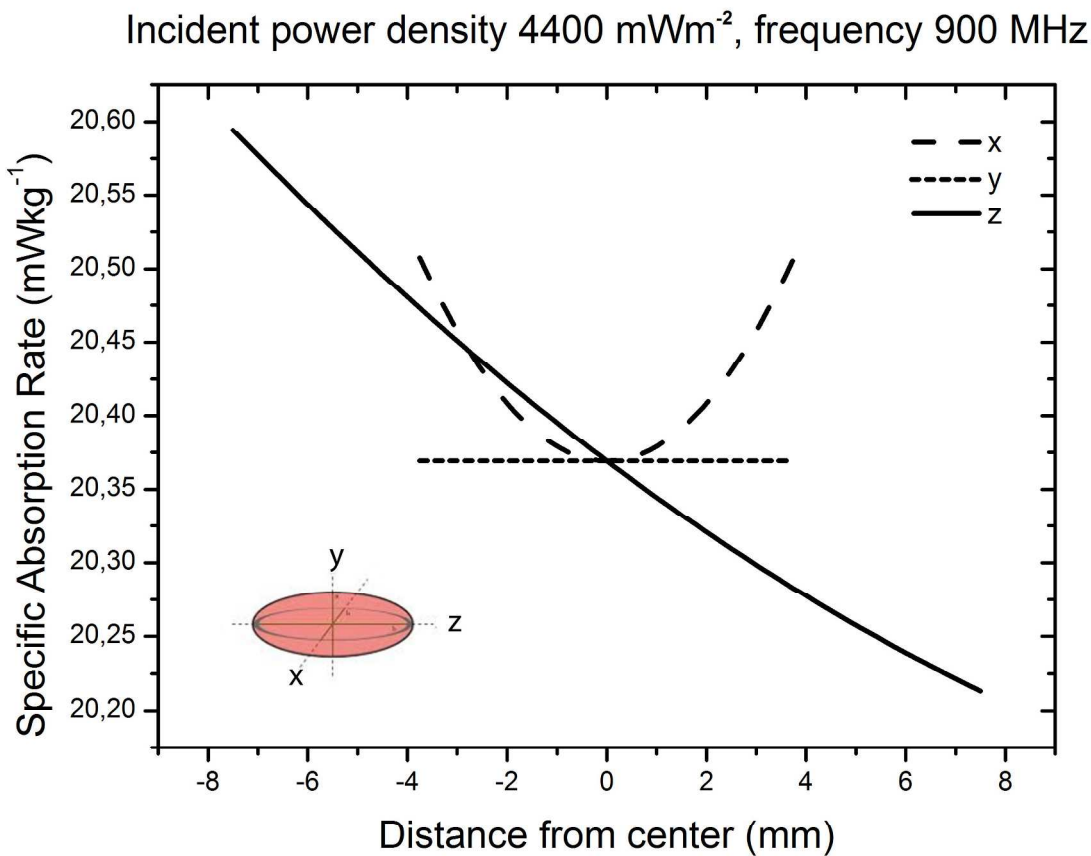


Fig. 2 Distribution of Specific Absorption Rate (SAR) in a soybean of 15 mm long oriented with the long (z-) axis along the propagation direction of the RF radiation (k-polarization) according to the long wavelength approximation (see text). The soybean is approximated as a prolate spheroid with a diameter of 7.5 mm.

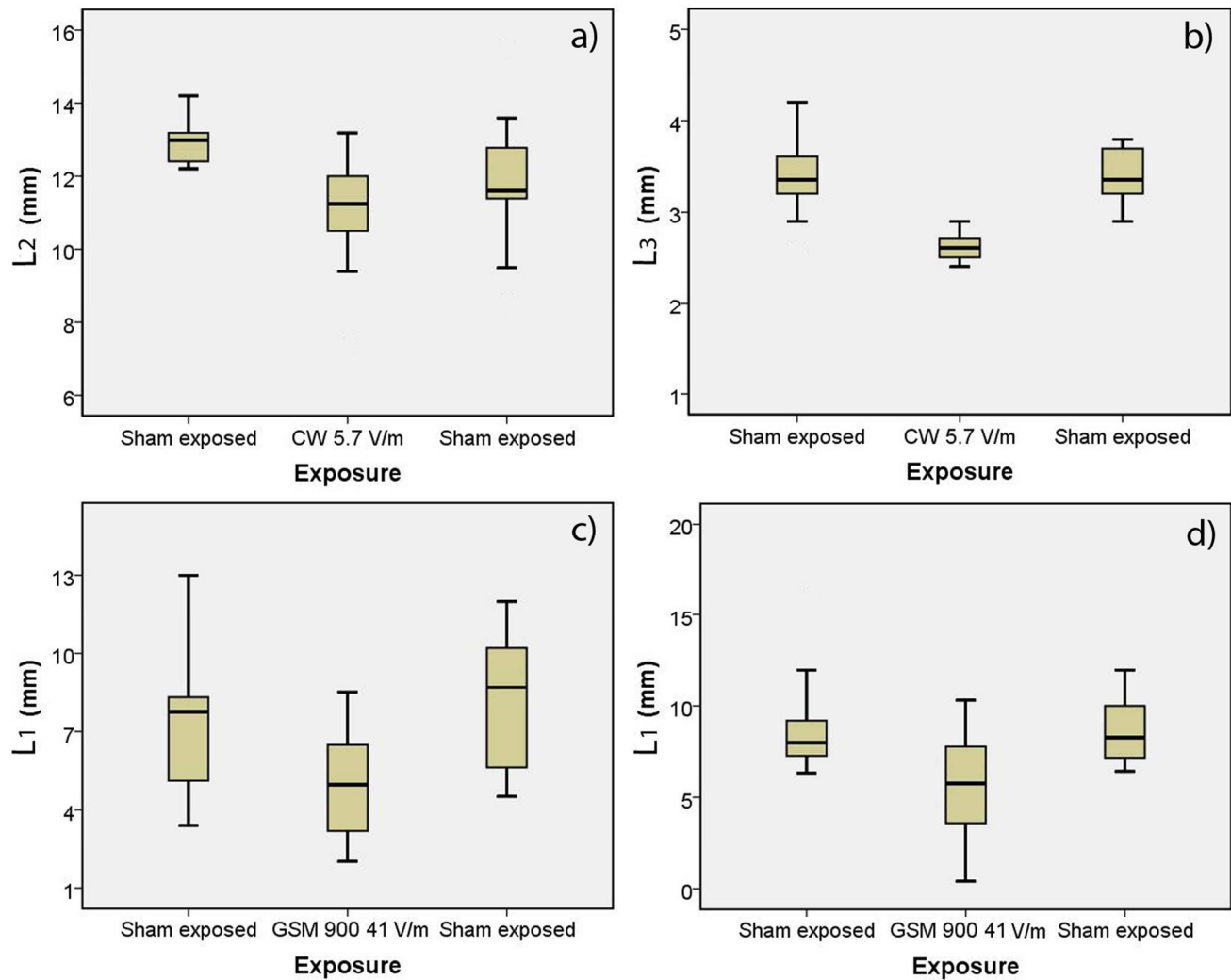


Fig. 3. Box plots with median and interquartile range for a)  $L_2$  for CW exposure at  $5.7 \text{ V m}^{-1}$ , b)  $L_3$  for CW exposure at  $5.7 \text{ V m}^{-1}$ , c)  $L_1$  for GSM 900 exposure at  $41 \text{ V m}^{-1}$  and d)  $L_1$  for GSM 900 exposure at  $41 \text{ V m}^{-1}$ . The T-bars (whiskers) extend to 1.5 times the height of the box (inter quartile range, IQR).

TABLES

Table 1. Exposure scheme for 900 MHz exposure. The GSM exposures consist of 0.5 ms pulses with a repetition rate of 217 Hz

Number of Experiments	Exposure Type	Signal Strength (V m <sup>-1</sup> )	Time Averaged Power Density (mW m <sup>-2</sup> )	SAR (mWkg <sup>-1</sup> )	Exposure Time
2	GSM	41	560	2.6	2 + 2 h (sham + exposure)
1	GSM	5.7	11	0.049	2 + 2 h (sham + exposure)
2	GSM	41	560	2.6	2 + 2 + 2 h (sham + exposure + sham)
1	GSM	5.7	11	0.049	2 + 2 + 2 h (sham + exposure + sham)
2	GSM	0.56	0.10	4.8x10 <sup>-4</sup>	5 days + 5 days (sham + exposure)
2	CW	41	4400	20	2 + 2 h (sham + exposure)
2	CW	5.7	86	0.39	2 + 2 + 2 h (sham + exposure + sham)

Table 2. Medians in mm (*p*-values in brackets) for the difference between exposed and sham exposed, pooled data (*n.s.* is denoted as non significant difference).

Exposure	Signal Strength ( $\text{V m}^{-1}$ )	Avg. Power Density ( $\text{mW m}^{-2}$ )	L <sub>1</sub>	L <sub>2</sub>	L <sub>3</sub>
GSM (2 h)	41	560	-1.7 ( $p = 0.002$ )	n.s.	n.s.
GSM (2 h)	5.7	11	n.s.	n.s.	n.s.
GSM (5 days)	0,56	0.1	-0.2 ( $p = 0.024$ )	-1.0 ( $p = 0.001$ )	+1.0 ( $p < 0.001$ )
CW (2 h)	41	4400	n.s.	n.s.	-1.1 ( $p < 0.001$ )
CW (2 h)	5,7	86	n.s.	-1.3 ( $p = 0.004$ )	n.s.