

A radio-frequency system for *in vivo* pilot experiments aimed at the studies on biological effects of electromagnetic fields

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

2005 Phys. Med. Biol. 50 3643

(<http://iopscience.iop.org/0031-9155/50/15/011>)

View [the table of contents for this issue](#), or go to the [journal homepage](#) for more

Download details:

IP Address: 129.21.35.191

The article was downloaded on 23/05/2012 at 03:08

Please note that [terms and conditions apply](#).

A radio-frequency system for *in vivo* pilot experiments aimed at the studies on biological effects of electromagnetic fields

Lucia Ardoino, Vanni Lopresto, Sergio Mancini, Carmela Marino,
Rosanna Pinto and Giorgio A Lovisolo

Section of Toxicology and Biomedical Sciences, ENEA (Ente Nuove tecnologie,
Energia e Ambiente), 00060 Rome, Italy

E-mail: rosanna.pinto@casaccia.enea.it

Received 15 March 2005, in final form 26 May 2005

Published 20 July 2005

Online at stacks.iop.org/PMB/50/3643

Abstract

An exposure system consisting of two long transversal electromagnetic (TEM) cells, operating at a frequency of 900 MHz, is presented and discussed. The set-up allows simultaneous exposure of a significant number of animals (up to 12 mice per cell) in a blind way to a uniform plane wave at a frequency of 900 MHz, for investigating possible biological effects of exposure to electromagnetic fields produced by wireless communication systems. A heating/refrigerating system has also been designed for maintaining comfortable environmental conditions within the TEM cells during experiments. An accurate dosimetric study has been performed both numerically and by means of direct measurements on phantoms and living mice. The results have shown that good homogeneity of exposure and adequate power efficiency, in terms of whole-body specific absorption rate (SAR) per 1 W of input power, are achievable for the biological target.

1. Introduction

A large number of animal experiments have been performed over the past 40 years, using various frequencies and modulations (Adey *et al* 1999, Imaida *et al* 1998a, 1998b, Heikkinen *et al* 2001, 2003).

Most of the major ongoing studies have dealt with cancer models. All of the long-term bioassays or sensitized studies gave negative results, except for one using transgenic mice—genetically modified to increase the background incidence of lymphomas; an increased tumour incidence was found following global system mobile (GSM) exposure (Repacholi *et al* 1997). Yet, such a finding did not emerge from a recent confirmation study, using a different design (Utteridge *et al* 2002). While awaiting the results of a further replication study, adopting

various tests to analyse the tumour induction and the tumour promotion, there is no convincing evidence—from animal investigations—that the incidence of lymphomas and other types of tumours is influenced by lifetime daily exposure to mobile telephony radio-frequency (RF) radiation.

Nevertheless, the World Health Organization (WHO) has also recommended some short-term projects (Repacholi 1998) on animals: follow-up studies to immune system studies; studies to assess the accuracy and reproducibility of published RF effects on the permeability of the blood–brain barrier and other neuropathologies (e.g. dura mater inflammation, dark neurones).

Therefore, besides systems adopted for long-term experiments with several animals (Moros *et al* 1998, 1999, Hansen *et al* 1999, Wilson *et al* 2002), devices for few animals (mice) are necessary for performing both short- and long-term experiments with different end-points.

To this end, a set-up for the simultaneous exposure of a significant number of animals, to be used for pilot studies, is presented and discussed in this paper. The system is constituted by two identical transverse electro-magnetic (TEM) cells of long length for the exposure of mice, to a uniform TEM plane wave at a frequency of 900 MHz, with high values of power per unity of mass (specific absorption rate (SAR), measured in W kg^{-1}) induced in the biological target. The TEM cell allows the generation of well-known and characterized field distributions within the structure, and of exposure conditions (Crawford 1974, VanHese *et al* 1992). The set-up of two long TEM cells (Ardoino *et al* 2002, Gatta *et al* 2003) allows the simultaneous exposure of up to 12 mice per cell in blind way, i.e. the group of mice contained in one cell can be RF-exposed whereas the group in the other cell can be sham-exposed. Each cell is 120 cm long (that is 4λ at the frequency of 900 MHz, λ being the wavelength) and presents a cut-off frequency of 1.2 GHz.

An accurate dosimetric study has been performed according to WHO's guidelines for quality EMF experiments and to an international scientific discussion on quality assurance (Chou *et al* 1996, WHO 1997, Kuster and Schonborn 2000). The study has been developed with the following methodology: (1) evaluation of the power efficiency of the system (in terms of whole-body SAR induced in each mouse) by means of power balance measurements on living animals; (2) analysis of the homogeneity of exposure (in terms of average SAR) among different groups of mice by means of numerical simulations; (3) validation of the results achieved from numerical simulations by means of thermal SAR measurements in homogeneous phantoms.

Particular attention has been paid to the control of temperature during experimental sessions. It is apparent, from former studies, that the vast majority of the reported biological effects are related to heating. These effects result either from a rise in tissue temperature or in physiological and behavioural responses, aimed at minimizing the total heat load. To prevent temperature increase in the RF-exposed animals with respect to the sham-exposed ones, and to maintain comfortable and well-known environmental conditions within the cells, a temperature control system has been implemented for the two TEM cells.

The exposure system has been used for exposure of both adult and newborn mice, according to the scheduled biological protocol.

2. Materials and methods

The exposure frequency of 900 MHz and the basic GSM modulation signal have been chosen to investigate possible bio-effects of a far field exposure (e.g. radio base station source).

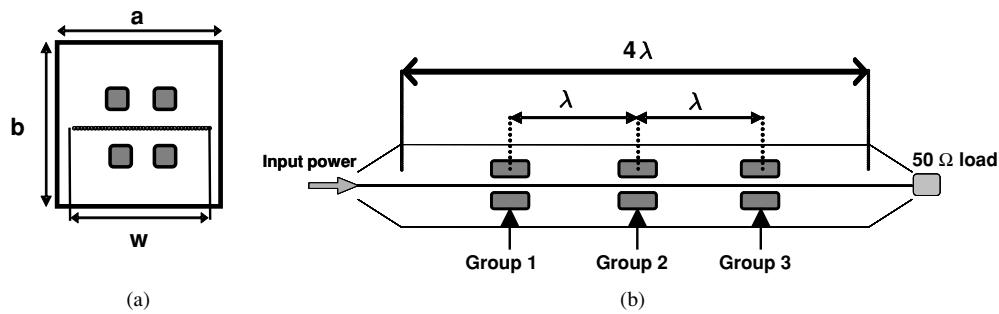


Figure 1. Transversal section—front view (a), and longitudinal section—side view (b) of the TEM cell; the positioning of mice within the cell is also shown.

2.1. TEM cell design

The device has been designed according to the electromagnetic restraints about cut-off frequency (higher order modes), minimization of voltage standing wave ratio (VSWR) and optimization of the uniform field volume.

The TEM cell has equal transversal dimensions $a = b$ (figure 1(a)) with a broad and thin inner conductor, to obtain a large electric (E) field uniform region. Transversal dimension of 12 cm and inner septum, 10 cm wide, have been defined to ensure a pure TEM mode propagation up to 1.25 GHz, and to allow 50 Ω matching at the cell ports. The length of the transmitting part of the cell has been fixed to 120 cm (i.e. 4λ at the frequency of 900 MHz), for the simultaneous exposure of several animals in the same conditions due to TEM mode reconstruction.

In order to allow air flowing within the cell and easy access for animal positioning, a removable grid-wall on one side of the outer conductor was built.

The analysis of the electric field distribution within the TEM cell has been numerically performed by using a finite integration technique (FIT) code (Computer Simulation Technology Microwave Studio). Numerical simulations have shown that, in the transversal section of the cell, a region of uniform electric field exists, large enough for positioning a couple of mice on each side with respect to the cell inner septum, as illustrated in figure 1(a). At the centre of this area, the simulated electric field has yielded to values confirming the theoretical values calculated analytically by means of the following equation:

$$E = \frac{\sqrt{P Z_c}}{\frac{b}{2}} \quad (1)$$

where E (V m^{-1}) is the amplitude of the electric field within the TEM cell, P (W) is the net input power, Z_c (Ω) is the characteristic impedance (50 Ω), and b (m) is the size of the cell (figure 1(a)).

Thanks to the length of the cell, up to 12 mice can be placed within the device, in groups of four as shown in figure 1(b), with the caudal axis parallel to field propagation direction, in order to have the best condition for homogeneity of exposure. The computed electric field distributions, both on the empty cell and containing 12 phantoms (representing adult mice, about 24 g each), are shown in figure 2. It is apparent that both the length of the cell and the particular placement of mice guarantee the reconstruction of fields among each group of animals. Field reconstruction has been experimentally checked by means of measurements, performed with an E -field probe inserted into the cell through a slit wall.

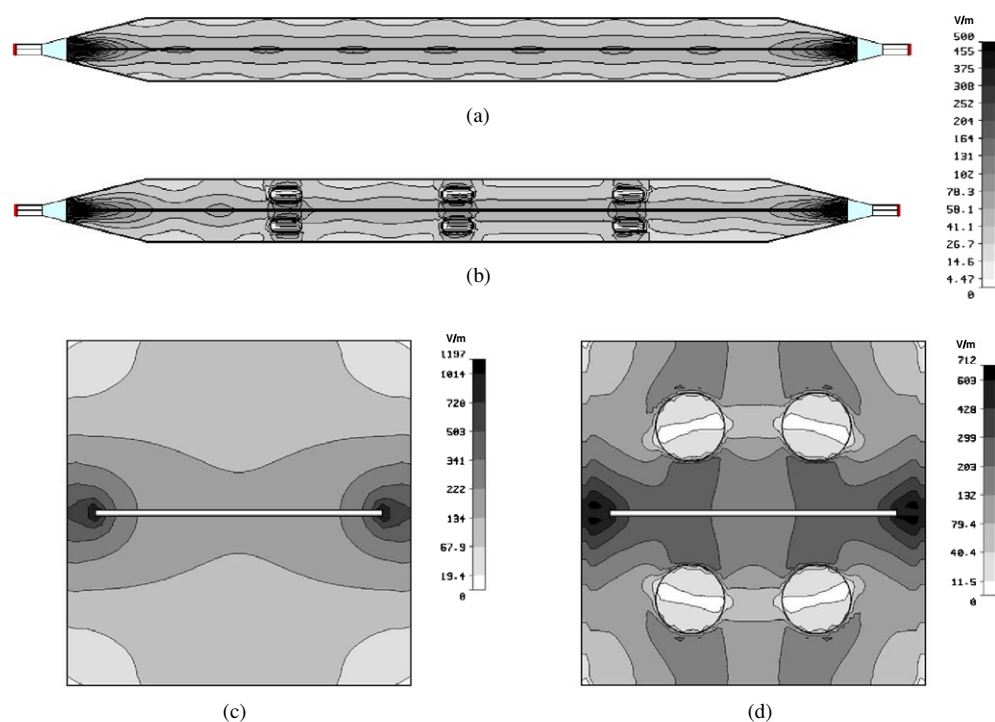


Figure 2. Computed electric field amplitude distribution within the TEM cell empty (a) and (c), and containing 12 adult mice (b) and (d), for 1 W peak input power. The longitudinal (a) and (b), and transversal (c) and (d) sections, as well as the positioning of mice, are those indicated in figure 1.

2.2. Dosimetry in TEM cell

Exposure conditions have been precisely determined by means of an accurate dosimetric analysis, performed both numerically and experimentally.

Numerical dosimetry has been performed on an homogeneous model of adult mouse using the above-mentioned FIT code. The SAR distribution in an homogeneous model can be quite different from that obtained when an inhomogeneous model is taken into account (Van de Kramer *et al* 2001). Nevertheless, the use of homogeneous phantoms allows, in a first approach, the dosimetric characterization of the exposure system in reference conditions; moreover it can give useful information when whole-body exposure is considered and no particular target (tissue or organ) has to be examined by biological protocols.

In this case, numerical dosimetry has allowed us to compare the power efficiency (i.e. SAR per 1 W of input power) predicted by numerical simulations with the power efficiency experimentally assessed by means of power balance method and thermal measurements, in order to check the reliability of the considered experimental procedures. Numerical dosimetry was also used to verify that there were not significant differences, in terms of dose, among the three different groups of mice placed into the cell (figure 2).

Experimental dosimetry has been performed on both phantoms and living animals. The phantoms have been used for the characterization of the TEM cell, by using thermal measures and the power balance method. The two experimental techniques have been validated by means of both a cross-comparison of the results of measurements and a comparison with the

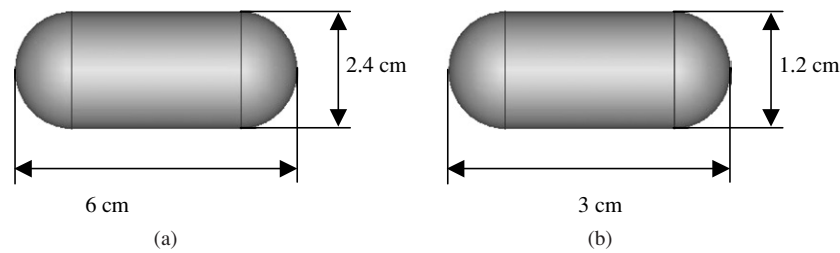


Figure 3. Numerical models of adult (a) and newborn mouse (b).

results of numerical simulations. The power balance method has been used also on living animals, since it is particularly suitable for *in vivo* measurements of whole-body average SAR, induced in animals exposed in an enclosed system (Balzano *et al* 2000), whereas thermal SAR measurements cannot easily be performed on living animals.

The numerical model of adult mouse has a weight of about 24 g and length of 6 cm (figure 3(a)); it is constituted by a material that can be considered a representative of a weighted average upon all body tissues: specific heat $c = 4102 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$, electric conductivity ($\sigma = 1.02 \text{ S m}^{-1}$, relative permittivity ($\epsilon_r = 55.03$ (these parameters are referred to the frequency of 900 MHz) and density $\rho = 0.96 \text{ g cm}^{-3}$. In numerical simulations, the positioning of mice within the cell is as illustrated in figure 1. The homogeneous phantoms used for experimental dosimetry have the same characteristics of the numerical model.

For thermal measurements a small percentage (0.7%) of agar, which does not affect the electrical parameters, was added to the phantom's medium to prevent convective motions related to heating.

The SAR is related to temperature according to the following relation (Bowman 1982, Weinbaum and Jiji 1985, Chan 1992):

$$\text{SAR} = c \frac{\Delta T}{\Delta t} \quad (2)$$

where c is the specific heat ($\text{J kg}^{-1} \text{ }^\circ\text{C}^{-1}$), ΔT is the temperature increment measured within the phantom after a high RF power pulse of duration Δt . Relation (2) is derived from the bio-heat equation, where both convective and conductive contributes have been neglected, as their rise is slower than the temperature increment produced by RF irradiation. To measure temperature increments within phantoms, a fluoroptic thermometer (Luxtron 712) with two channels has been employed. The two optical probes have an accuracy of $0.1 \text{ }^\circ\text{C}$. The probes have been placed in correspondence of the middle and of the back of one phantom (figure 4(a)). In this way, local measurements have been performed, thus allowing the assessment of the power dissipated inside the phantom, which has been compared with the results obtained from numerical simulations. Data acquisition from the thermometer has been remotely controlled, via general purpose interface bus (GPIB), by dedicated software developed in Labview, running on a personal computer.

Afterwards, experimental dosimetry on both phantoms and living mice has been performed using the power balance method. In order to allow a correct and repeatable positioning within the TEM cell, as in numerical simulations, living mice have been put inside cylindrical plastic jigs, with small holes for transpiration; the jigs have been placed upon suitably sized polystyrene supports, for the positioning of mice at the same distance from the septum (figure 4(b)). The jigs and the supports were made of materials transparent to RF radiation.

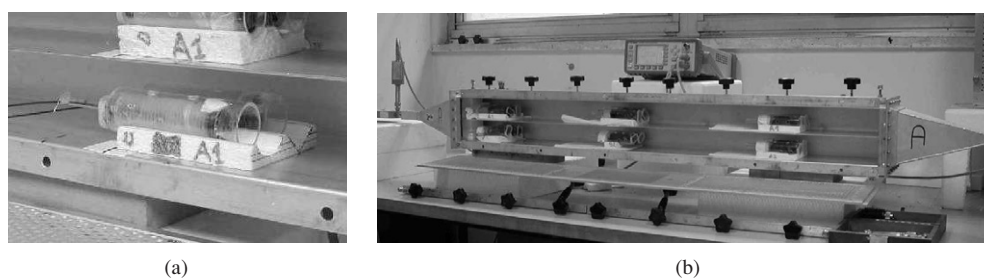


Figure 4. Mouse phantoms employed for thermal SAR measurements (a), and TEM cell containing jigs with mice (b).

The average RF power absorbed by each mouse has been assessed by using the following equation:

$$P_{\text{abs per mouse}} = 1/n\{P_{\text{in}} - P_{\text{out}} - (P_{\text{refl}} + P_{\text{loss}})\} \quad (3)$$

where n is the number of mice within the cell, P_{abs} is the RF power absorbed in one mouse, P_{in} the input power of the cell, P_{out} the power dissipated in the 50Ω terminal load, P_{refl} the power reflected at the input port, and P_{loss} is the power dissipated in the cell structure, including jigs and supports.

The same procedures have been followed when newborn mice were employed (two days old mice exposed for five days, 1 h per day). The numerical model of newborn mouse has been assumed to be homogeneous, with a weight of about 3 g and length of 3 cm (figure 3(b)). For the positioning of newborn mice within the TEM cell, the jigs have been substituted by polystyrene blocks, with two holes each, where mice have been placed wrapped in gauze, in order to allow better transpiration and to prevent little mice from injuring with plastic corner.

2.3. Exposure system

Two non-standard TEM cells ($12 \times 12 \times 120 \text{ cm}^3$), operating at a frequency of 900 MHz, have been constructed to investigate the biological effects of exposure at different levels of power density and, consequently, of SAR, which is considered a suitable parameter for comparing effects observed under various exposure conditions.

RF-exposed and sham-exposed mice have been put inside two identical TEM cells, placed in the same room. The positioning of mice within the TEM cell is as illustrated in figure 1, with a reciprocal distance from each group of about 33 cm (i.e. λ at 900 MHz). A black box has been installed to perform the experimental procedure in a blind way (figure 5).

In order to maintain comfortable environmental conditions within the TEM cell during experiments, a heating/refrigerating system has been designed. The system consists of two external metallic jackets filled with circulating water, fed by a thermostatic bath, and placed in contact with the top and bottom walls of the cell (figure 6). The temperature of the circulating water is controlled by the thermostatic bath. In this way, during experiments, it is possible either to refrigerate or to heat the internal environment of the TEM cell, according to the needs.

The temperature in the TEM cell cavity and on the biological target (i.e. phantoms and living mice, both sham- and RF-exposed) has been monitored during experiments, by using Luxtron 712 fluoroptic thermometer. A temperature increase of about $2 \text{ }^\circ\text{C}$ was observed inside the phantoms when they were exposed to a dose of 2 W kg^{-1} for 2 h. On living mice, placed into jigs, the probe was positioned externally under the abdomen. In this case, an initial increment of more than $1 \text{ }^\circ\text{C}$, mostly due to stress, was observed both in sham- and RF-exposed

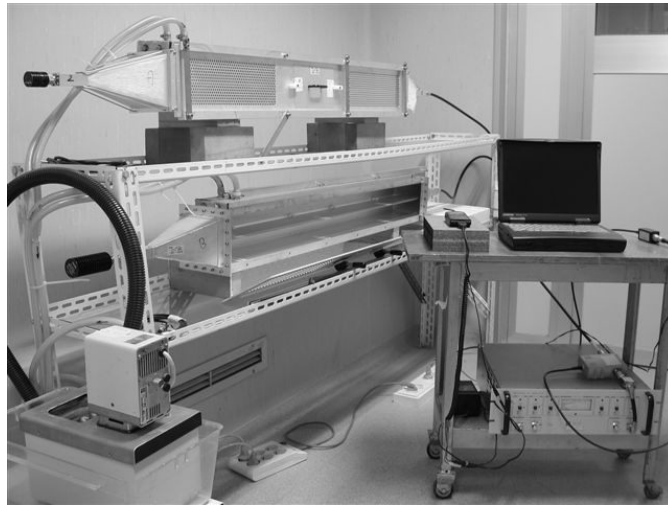


Figure 5. Set-up of TEM cell exposure system with blind control.

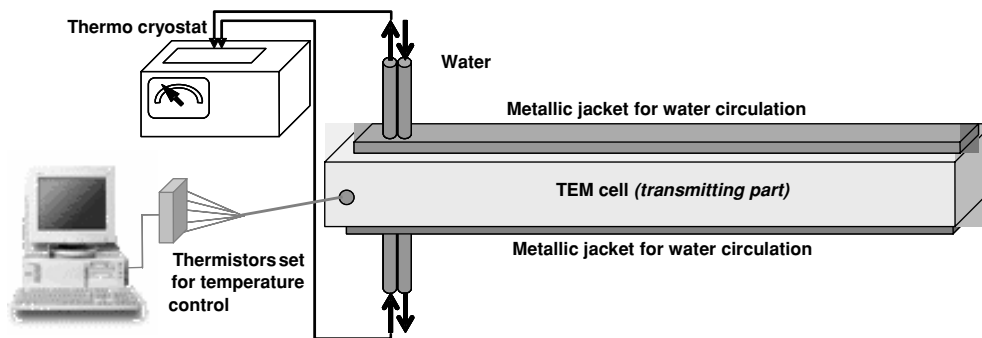


Figure 6. Heating/refrigerating system for controlling the environmental conditions within the TEM cell.

animals. Such a temperature increment can be compensated by the thermoregulatory system of an adult mouse; nevertheless exposed animals showed a slightly higher temperature than sham-exposed ones. Therefore, a refrigeration system was necessary in order to eliminate any possible stress factor and to prevent from eventual body temperature increment during exposures at high SAR levels. The refrigeration system was turned on 1 h before the beginning of the exposure; in this way, animals were placed in an environment at a temperature of about 20 °C, where they could compensate, in around 20 min, the initial increase of body temperature due to the stress of manipulation and restriction in jigs. By means of this system, the maximum temperature difference between RF-exposed group and sham-exposed group of adult mice has been maintained lower than 0.5 °C, a physiological difference among individuals.

When newborn mice have been employed, there was a necessity to maintain the air temperature within the TEM cell around 30 °C, in order to create suitable environmental conditions for the survival of the newborn animals. In this case, the thermostatic bath of the system has been set to allow the correct heating of the cell.

The whole exposure system was completely monitored by a dedicated software, developed in Labview. A commercial cellular phone, operating in test mode, has been used as GSM basic

Table 1. Computed power efficiency ($\text{W kg}^{-1} \text{W}_{\text{in}}^{-1}$) referred to an adult mouse phantom of 24 g.

	Group 1	Group 2	Group 3
Mean	0.473	0.453	0.443
Minimum	0.016	0.013	0.011
Maximum	5.335	4.791	4.383

Table 2. Computed power efficiency ($\text{W kg}^{-1} \text{W}_{\text{in}}^{-1}$) referred to a newborn mouse phantom of 3 g.

	Group 1	Group 2	Group 3
Mean	0.149	0.149	0.149
Minimum	0.032	0.033	0.033
Maximum	2.440	2.404	2.393

signal generator. The signal was led to the input of a RF amplifier (50 W, 400–1000 MHz bandwidth, Kalmus 707FC), and real time monitored by a bidirectional power sensor (Rohde & Schwarz NRT Z43) connected to the personal computer by an interface adapter (Rohde & Schwarz RS232).

3. Results

Average and peak SAR values, together with the indication of a standard deviation (SD) on the whole distribution, are commonly used to report the dose induced in the biological target. In particular, by assessing the power efficiency it is possible to characterize the exposure system from the dosimetric point of view, and therefore determine the power input to feed the TEM cell to obtain the SAR levels required by experimental protocols.

Numerical dosimetry allows performing a detailed analysis of the SAR distribution, calculating not only the whole-body SAR in the biological target, and the homogeneity of exposure of different groups of mice, but also local SAR values, thus allowing recognizing possible hot-spots. Simulations have been performed on one TEM cell containing both 12 adult mice, with a weight of about 24 g each, and 12 newborn mice, with a weight of about 3 g each. Mice have been placed with the caudal axis parallel to field propagation direction and radiated from the bottom. Calculated power loss density distributions (W m^{-3}) for 1 W input power are shown in figures 7(a) and (b) for adult mice, and (c) and (d) for newborn mice; transversal section distributions are referred to mice of group 2.

Computed average power efficiencies ($\text{W kg}^{-1} \text{W}_{\text{in}}^{-1}$) and descriptive statistics of SAR distributions for adult and newborn mice are reported in tables 1 and 2, respectively. Due to the symmetry of the configuration and of the field distribution within the TEM cell, each group of mice is homogeneously exposed; therefore SAR values reported in the tables are referred to one mouse per group. As can be seen, there are slight differences of average SAR among the three groups of mice: those belonging to the group closer to the source of radiation absorb more power. Moreover, highest SAR values are located in the back part of the body (figure 7), as mice were irradiated from the bottom. Anyway, differences in terms of average SAR among the three groups are lower than 10% in the case of adult mice, whereas in the case of newborn mice, differences may be considered negligible (see tables 1 and 2). These differences have been compensated by the daily rotation of animals' positioning during the exposures.

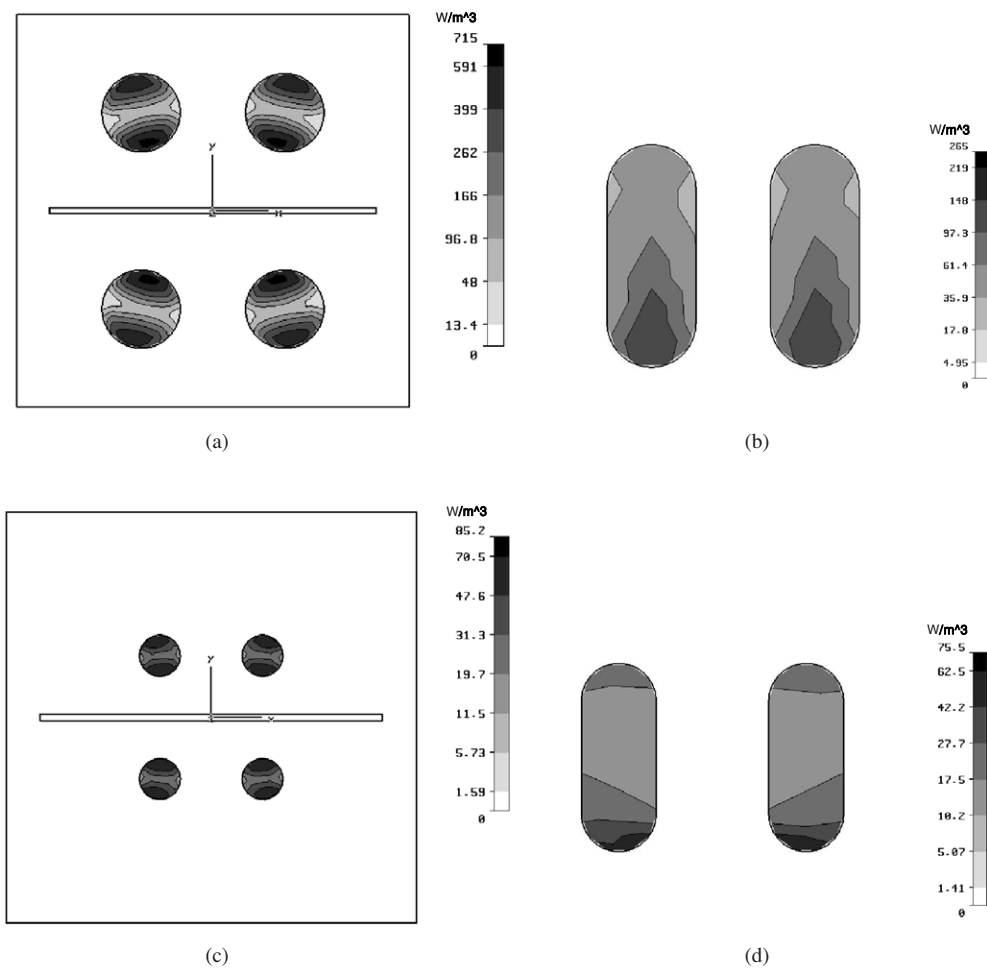


Figure 7. Power loss density distributions calculated at 900 MHz, within adult mice (a) and (b), and newborn mice (c) and (d), for 1 W peak input power, on a transversal section (a) and (b), and on a longitudinal section (c) and (d) of the TEM cell.

The calculated average power efficiency of group 2 adult mouse phantoms (figure 1(b)), equal to $0.45 \text{ W kg}^{-1} \text{ W}_{\text{in}}^{-1}$, has been considered the reference value for comparison with experimental measures, performed by means of power pulse method (thermal SAR) in mouse phantoms.

Thermal SAR measurements have been performed on 24 g adult mice phantoms, with the characteristics described in section 2, by applying a high RF-power pulse and by measuring the increment of temperature within the phantom. Two small holes (2 mm of diameter) have been made in one phantom of the group closer to the source of radiation, through which two cannulas have been inserted to allow the correct positioning, within the phantom, of the thermometer's fibre optic probes. Due to their small dimensions, the probes allow performing local measures; therefore they have been positioned in two different points along the caudal axis: one close to the bottom, and the other in the middle. In this way, it is possible to evaluate differences of temperature increments, and then of SAR, in different points within the

phantom, as was evidenced by numerical simulations. The outcome of these measurements was an average efficiency of $0.59 \text{ W kg}^{-1} \text{ W}_{\text{in}}^{-1}$ (with a SD of 0.12) near the bottom of the phantom, whereas in the middle an average efficiency of $0.43 \text{ W kg}^{-1} \text{ W}_{\text{in}}^{-1}$ (with a SD of 0.1) was found.

With reference to whole-body measurements, performed by means of the power balance method on both phantoms and living mice, the power dissipated at different levels of input power has been measured with jigs and their supports positioned within the TEM cell as illustrated in figure 1, with and without the biological target: the difference between the power losses in these two conditions indicates the power absorbed by the biological samples.

Measures with living mice have been performed using different weighted animals. Difference of efficiency has been found among different groups of mice (from 20 g to 26 g), with a slightly higher absorption, and therefore higher efficiency values, related to the more weighted mice. Variations among the different results of measures can be linked also to the possibility of a partial movement of mice within the jigs, and to small variations in the positioning of supports in the different experimental sessions. From the analysis of these outcomes, an average efficiency of 0.38 W kg^{-1} per 1 W input power, with a SD of about 0.09, has been assessed. The power efficiency assessed on phantoms has shown good agreement with this result, even though the phantom is a homogeneous model, whereas mice are of course non-homogeneous and can partially move within the jigs.

The efficiency of $0.38 \text{ W kg}^{-1} \text{ W}_{\text{in}}^{-1}$ (SD = 0.09) has been assumed as the reference value to determine the SAR levels planned for the experiments, i.e. the power input to feed the TEM cell for inducing in mice the required dose.

4. Conclusions

A model of the long TEM cell designed to operate at the up-link band of GSM 900 MHz has been presented and discussed in this paper. By means of both direct experimental measurements and numerical simulations, it has been shown that good homogeneity of exposure and adequate power efficiency values (in terms of SAR per 1 W input power) are obtainable in the biological target. In particular, experimental evaluations performed in one TEM cell containing 12 adult mice, have provided a whole-body average SAR of 0.38 W kg^{-1} (SD = 0.09) per 1 W input power.

Cylindrical plastic jigs, with small holes for transpiration, have been used to allow the correct positioning of mice within the TEM cells, thus achieving repeatability of exposure conditions. Moreover, daily rotation of animals' positioning allowed improving the homogeneity of exposure.

The temperature within the cell cavity and on the mice has been monitored during experiments; this has evidenced the possibility of body temperature increment during exposures at the considered SAR levels. Therefore, a system for the control of environmental temperature within the TEM cell has been implemented, which allowed us to significantly reduce differences between RF- and sham-exposed groups of animals. The system for the control of temperature has already been used in an experiment where different groups of animals were examined, in order to assess the role of temperature on possible biological effects related to RF exposure: a sham-exposed group, a non-refrigerated RF-exposed group and a refrigerated RF-exposed group.

The exposure system is equipped with a black box that allows performing exposures in a blind way, thus reducing researchers' subjectivity in the interpretation of results. The device is particularly suitable for *in vivo* pilot experiments, aimed at investigating possible biological effects of EM radiation associated with cellular phones. Ongoing studies are devoted to

realizing a numerical model of a mouse from scans obtained by a real mouse, in order to perform numerical dosimetry on specific biological targets (tissues or organs).

Acknowledgments

The authors wish to thank Professor Guglielmo d'Inzeo of the Department of Electronic Engineering, University of Rome 'La Sapienza', for his helpful suggestions and constructive criticism, and Dr Claudio Pioli for the accurate definition of exposure conditions. This work was partially supported by the national research project of the Ministry of Education and University Research MIUR/CNR-ENEA (2001-2004) on 'The protection of the human being and environment from the electromagnetic emissions'.

References

- Adey W R *et al* 1999 Spontaneous and nitrosourea-induced primary tumors of the central nervous system in Fischer 344 rats chronically exposed to 836 MHz modulated microwaves *Radiat. Res.* **152** 293–302
- Ardoino L, Pinto R, Mancini S, Marino C, Lovisolo G A, Apollonio F and d'Inzeo G 2002 Exposure systems and dosimetry in biological experiments *Proc. 2nd Int. Workshop on Biological Effects of Electromagnetic Fields* Rodhes, 7th Nov pp 266–71
- Balzano Q, Chou C K, Cicchetti R, Faraone A and Tay R 2000 An efficient RF exposure system with precise whole body average SAR determination for *in vivo* animal studies at 900 MHz *IEEE Trans. Microw. Theory Tech.* **48** 2040–9
- Bowman H F 1982 Heat transfer mechanisms and thermal dosimetry *Natl Cancer Inst. Monogr.* **61** 437–5
- Chan C L 1992 Boundary element method analysis for the bioheat transfer equation *J. Biomech. Eng.* **114** 358–65
- Chou C K, Bassen H, Osepchuk J, Balzano Q, Petersen R, Meltz M, Cleveland R, Lin J C and Heynick L 1996 Radio frequency electromagnetic exposure: tutorial review on experimental dosimetry *Bioelectromagnetics* **17** 195–208
- Crawford M L 1974 Generation of standard EM fields using TEM transmission cells *IEEE Trans. Electromagn. Compat.* **16** 189–95
- Gatta L, Pinto R, Ubaldi V, Pace L, Galloni P, Lovisolo G A, Marino C and Pioli C 2003 Effects of *in vivo* exposure to GSM-modulated 900 MHz on mouse peripheral lymphocytes *Radiat. Res.* **160** 600–5
- Hansen V W, Bitz A K and Streckert J R 1999 RF exposure of biological systems in radial waveguides. *IEEE Trans. Electromagn. Compat.* **41** 487–93
- Heikkinen P, Kosma V M, Hongisto T, Huuskonen H, Hyysalo P, Komulainen H, Kumlin T, Lahtinen T, Lang S, Puranen L and Juutilainen J 2001 Effects of mobile phone radiation on x-ray-induced tumorigenesis in mice *Radiat. Res.* **156** 775–85
- Heikkinen P, Kosma V M, Alhonen L, Huuskonen H, Komulainen H, Kumlin T, Laitinen J T, Lang S, Puranen L and Juutilainen J 2003 Effects of mobile phone radiation on UV-induced skin tumourigenesis in ornithine decarboxylase transgenic and non-transgenic mice *Int. J. Radiat. Biol.* **79** 221–33
- Imaida K, Taki M, Yamaguchi T, Ito T, Watanabe S, Wake K, Aimoto A, Kamimura Y and Shirai T 1998a Lack of promoting effects of the electromagnetic near-field used for cellular phones (929 MHz) on rat liver carcinogenesis in medium-term bioassay *Carcinogenesis* **19** 311–4
- Imaida K, Taki M, Watanabe S, Kamimura Y, Ito T and Shirai T 1998b The 1.5 GHz electromagnetic near-field used for cellular phones does not promote rat liver carcinogenesis in a medium term liver bioassay *Japan J. Cancer Res.* **89** 995–1002
- Kuster N and Schonborn F 2000 Recommended minimal requirements and development guidelines for exposure setups of bio-experiments addressing the health risk concern of wireless communications *Bioelectromagnetics* **21** 372–84
- Moros E G, Straube W L and Pickard W F 1998 A compact shielded exposure system for the simultaneous long-term UHF irradiation of forty small mammals. I. Electromagnetic and environmental design *Bioelectromagnetics* **19** 459–68
- Moros E G, Straube W L and Pickard W F 1999 Compact shielded exposure system for the simultaneous long-term UHF irradiation of forty small mammals. II. Dosimetry *Bioelectromagnetics* **20** 81–93
- Repacholi M H 1998 Low-level exposure to radiofrequency electromagnetic fields: health effects and research needs *Bioelectromagnetics* **19** 1–19

- Repacholi M, Basten A, GebSKI V, Noonan D, Finnie J and Harris A 1997 Lymphoma incidence in E μ -pim1 transgenic mice exposed to pulsed 900-MHz fields *Radiat. Res* **147** 631–40
- Utteridge T D, GebSKI V, Finnie J W, Vernon-Roberts B and Kuchel T R 2002 Long term exposure of Em-pim1 transgenic mice to 898.4 MHz microwaves does not increase lymphoma incidence *Radiat. Res.* **158** 357–64
- Van de Kramer J B, Van Wieringen N, De Leeuw A A and Lagendijk J J 2001 The significance of accurate dielectric tissue data for hyperthermia treatment planning *Int. J. Hyperthermia* **17** 123–42
- VanHese J, Martens L, DeZutter D, DeVagter C, Persson B R R, Malmgren L and Salford L G 1992 Simulation of the effect of inhomogeneities in TEM transmission cells using FDTD-method *IEEE Trans. Electromagn. Compat.* **34** 292–8
- Weinbaum S and Jiji L M 1985 A new simplified bioheat equation for the effect of blood flow on local average tissue temperature *J. Biomech. Eng.* **107** 131–9
- WHO 1997 *EMF Project: Guidelines for Quality Research* <http://www.who.int/peh-emf/>
- Wilson B W, Faraone A, Sheen D, Swicord M, Park W, Morrissey J, Creim J and Anderson L E 2002 Space efficient system for small animal, whole body microwave exposure at 1.6 GHz *Bioelectromagnetics* **23** 127–31