Progress In Electromagnetics Research, PIER 94, 133–152, 2009

A REVERBERATION CHAMBER TO INVESTIGATE THE POSSIBLE EFFECTS OF "IN VIVO" EXPOSURE OF RATS TO 1.8 GHz ELECTROMAGNETIC FIELDS: A PRELIMINARY STUDY

P. F. Biagi, L. Castellana, T. Maggipinto, G. Maggipinto
T. Ligonzo, L. Schiavulli, and D. Loiacono

Department of Physics
University of Bari
Via Amendola, 173, Bari 70126, Italy

A. Ermini

Department of Mechanical Engineering
University of Roma Tor Vergata
Via di Tor Vergata, Rome 00133, Italy

M. Lasalvia

Department of Medical and Occupational Science
University of Foggia
Via L. Pinto, Foggia 71100, Italy

G. Perna and V. Capozzi

Department of Biomedical Sciences
University of Foggia
Via L. Pinto, Foggia 71100, Italy

Abstract—A system generating 1.8 GHz electromagnetic fields for bio-medical and behavioral study on laboratory animals was designed and implemented. The system is based on a reverberation chamber. An input power up to 5 W can be sent to an indoor transmitting antenna and an electric field strength (E) more than 90 V/m can be reached inside the chamber. The system was characterized at different input powers measuring E in different points by means of a miniature sensor. Then, boxes with 300 cc of physiological liquid inside were realized as simple phantoms simulating laboratory animals (rats)

Corresponding author: P. F. Biagi (biagi@fisica.uniba.it).

and E inside the liquid was measured, performing several simulations by moving the phantoms $(1,2)$ in the chamber and/or putting them still in different positions. On the basis of these measurements, the SAR (Specific Absorption Rate) and the Pe (power efficiency = SAR/input power) were determined at different powers. The actual system is characterized by a low power efficiency with respect to the "in vivo" exposition systems based on transversal electromagnetic (TEM) cells. Its advantage is to have inside the chamber a habitat similar to the usual one for the laboratory animals.

1. INTRODUCTION

In the last years, several experiments have been carried out in many worldwide laboratories in order to study the possible health effects of electromagnetic exposure. The results often have been contradictory among them and are still object of scientific debate [1–14]. The problem cannot be considered definitely clarified and further experiments are necessary in order to increase the experimental results.

Generally "in vivo" investigations are carried out on animals immobilized in narrow cells [1–6]. The main drawback of such a procedure is the existence of other stressing agents on the animals in addition to the electromagnetic exposure. Therefore, the development of more suitable systems should be promoted. In particular, the exposure equipment should be devoid of collateral perturbations (noise, temperature and humidity variations, etc.); the laboratory animals should live in a habitat similar to their usual one and the electromagnetic field should have a well defined and accurately set frequency and intensity. The use of a reverberation chamber, that is a metallic cavity whose dimensions are large with respect to the wavelength of the indoor electromagnetic field, can give a solution to the mentioned requirements. The internal electromagnetic field is characterized by stochastic values, but it is (on the average) uniform and isotropic one [14–17]. Particularly, the reverberation chambers are able to simulate usual habitat of the animals so that the problems related to the use of immobilized animals can be overcome.

In this study, a preliminary set up of an exposure system based on a reverberation chamber is presented.

2. EXPOSURE SYSTEM AT 1.8 GHz AND ELECTRIC FIELD MEASUREMENT

A system for electromagnetic exposure of laboratory animals was designed and built by an Italian research Team (Department of Physics, University of Bari; Department of Biomedical Sciences, University of Foggia). The system consists of: a) a cage used as habitat for the animals; b) a reverberation chamber to be used either as an exposure or not exposure environment; c) a rack with the instrumentation. The cage, with dimensions $(60 \times 40 \times 42)\,\mathrm{cm}^3$, is built in Plexiglas (1 cm thick) and it is provided with a Plexiglas manger and a plastics watering system for feeding the animals (Figure 1(a)). Many holes on the walls need to increase the airing inside the cage. The reverberation chamber, with dimensions $(150 \times 85 \times 85)\,\mathrm{cm}^3$, is made (ITEL-Telecomunicazioni Company, Italy) in aluminum and it has an electric field tight door (Figure 1(b)); inside the chamber, the cage for the animals can be inserted (Figure 1(c)). A reverberation chamber works correctly at a frequency f if the number of eigen-mode N is larger than 60 [15]; N is given by:

$$N = \frac{8}{3\pi} abd \left(\frac{f}{c}\right)^3 - (a + b + d)\frac{f}{c} + \frac{1}{2} \tag{1}$$

where a, b and d represent the size of the chamber and c is the wave velocity in free space. In our reverberation chamber for $f = 1.8\,\mathrm{GHz}$, that is the frequency we used in this study, the previous calculation gives $N \sim 180$.

The reverberating chamber includes: a) one transmitting antenna; b) illumination lamps for day-like (white) and night-like (red) light; c) two electric tight filters dedicated to the air exchange, one on the roof (Figure 1(b)) and the other one on the right lateral wall; d) one humidity-temperature sensor; e) one screened video camera; f) a stirrer consisting of two metallic paddles (Figure 1(d)) connected by a drive belt to an external motor which controls the rotation of the stirrer without making noises and vibrations inside the chamber. Different antennae can be installed in the chamber. In this study, a stick antenna 4.15 cm long (the length is $\lambda/4$ for 1.8 GHz) fixed orthogonally on the right lateral wall of the chamber, below the air filter, was used. The previous filter is arranged to be connected to a suction pump for better airing the inside environment and for avoiding bad smells produced by the animals. The instrumentation in the rack consists of: a) one clock for controlling and alternating (day-night) illumination inside the chamber; b) one RF generator (f = 100 kHz–2112 MHz) with an output amplitude ranging, for frequencies 1056 MHz and above, from $-140\,\mathrm{dB}_m$ to $+10\,\mathrm{dB}_m$; c) one power amplifier (up to 5 W in the frequency range 1.5–2.0 GHz) connected to the transmitting antenna; d) a milliwatt-meter (100 kHz–20000 MHz) in order to measure the input power to the transmitting antenna; e) one viewer for the video camera; f) one personal computer with a video-recording card for vid

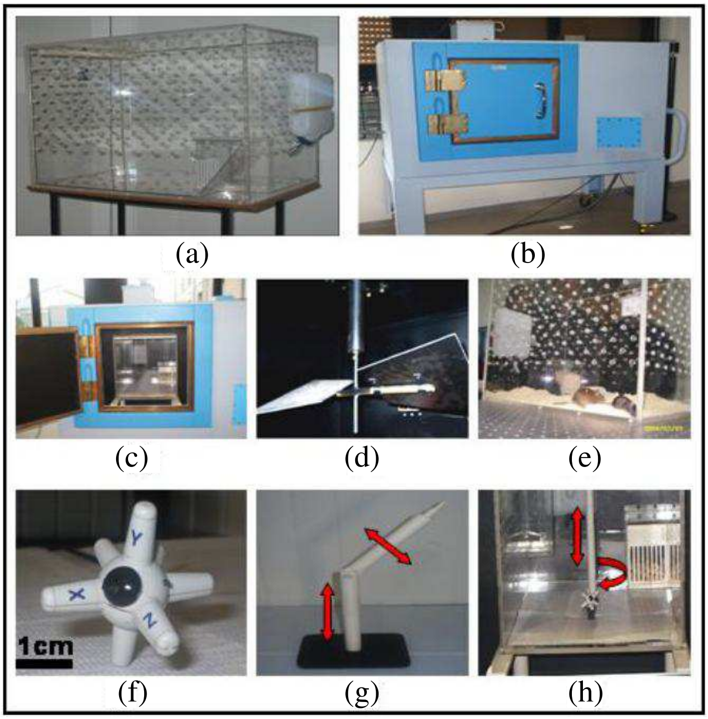

Figure 1. (a) Cage $(60 \times 40 \times 42)\,\mathrm{cm}^3$ in Plexiglas with a manger and a plastics watering system for laboratory animals. The holes on the walls are for the airing inside the cage. (b) Reverberation chamber $(150 \times 85 \times 85)\,\mathrm{cm}^3$, made of aluminium and having an electric field tight door. The lump at the top is one of the electric tight filters. (c) Cage inside the chamber. Two tracks allow the insertion of the cage and constitute its building. (d) Stirrer, i.e., two rotating metallic shovels, located inside the chamber on its right hand side. (e) Two laboratory animals inside the cage. (f) Electric field probe PMM EP-600 suitable for small rooms. The probe is formed by 6 monopoles. The dimensions are: 17 mm — sphere; 17 mm — sensor; 53 mm — overall. (g) Mobile bearing EB for the use outside the cage zone. The possibility of tilting and raising in every point is shown in the Figure. (h) Mobile bearing IB for the use in the cage zone, with or without the cage itself. In Figure the possible rotation and raising of the system for every position (three, every 5 cm) of the probe on the horizontal pole are shown.

data acquisition (up to 900 hours continuous recording); g) one digital instrument, to be connected to the humidity-temperature sensor for the data recording with an adjustable sampling rate ranging from 1 s to 3600 s.

The video camera with the viewer is used for controlling the inside situation. Besides, behavioral studies on the laboratory animals can be performed.

The electric field strength (E) inside the chamber was measured by a Field Meter (NARDA STS Company, Segrate (MI), Italy, PMM 8053B) connected with an optical fiber to an Electric Field Probe (NARDA STS Company, Segrate (MI), Italy, EP-600). The probe is shown in Figure 1(f); the whole dimension is 53 mm and the weight is 90 g. The sensitivity and frequency ranges are 0.15–90 V/m and 100 kHz–9.25 GHz, respectively. The probe was calibrated in air at the PMM Manufacturing Plant and EMC Laboratory. The Portable Field Meter has various measurement options such as the measurement of E averaged on a fixed time interval, that is the option we used in this paper choosing a 6 min range time. The probe was located in different points inside the chamber using the mobile external bearing EB Figure 1(g) far from the cage zone and the mobile internal bearing IB Figure 1(h) inside the cage zone, with or without the cage itself. Both the bearings are made in PVC and can be tilted and extended as shown in Figures 1(g) and 1(h). As an advantage with respect to the EB bearing, the IB can be moved in several different positions without having to stop the exposure and opening the chamber door. In any case the measurements were made at a minimum distance of 20 cm from the chamber halls (metal) in order for their readings to be minimally affected by coupling with the shields [18].

3. PRELIMINARY TESTS AND SETTING UP

The first problem to solve was carrying out a good habitat for the laboratory animals. The main characteristics of such a habitat are: a) intense white lighting at day time and red at night time; b) facilities for eating and drinking; c) temperature in the range 20°C–24°C; d) humidity (percent) in the range 45%–65%. The first two items are accomplished in our system, as it is described in Section 2. In order to obtain the climatic conditions, in addition to the airing we described previously, the system must operate in an air-conditioned environment. In such a condition, variations of the temperature and of the humidity inside the mentioned limits can be obtained as we verified in several tests with the laboratory animals (Figure 1(e)) inside the cage. As an example Figure 2 shows the temperature and humidity trends recorded by the humidity-temperature sensor during about six days running of the system, with several hours of exposure every day.

Since, the rotation of the stirrer is necessary for a correct running of a reverberation chamber, the second problem to solve was the definition of the most suitable value of the spin velocity ω. At this purpose, in a few points inside the chamber, we measured E every second for 6 minutes, by means of the probe fixed on the EB or IB bearing, using different spin velocities and input powers. As an example, the result obtained in one point approximately located in the centre of the cage (absent) zone, is shown in Figure 3, with an input power of 0.5 W. An evident decrease in the dispersion of the E values stands up by increasing the spin velocity of the stirrer. A field that is more stable in time is a good goal of the system. But if the rotation velocity of the stirrer is too high, noise and wind are produced inside the cage and the habitat for the animals worsens. A compromise solution was obtained by choosing $\omega = 2\pi$ rad/s, i.e., one stirrer turn per second.

A reverberation chamber is able to produce an internal electric field which should be averagely uniform and isotropic one. If the stirrer is not rotating, the chamber becomes a resonant cavity characterised by a steady-state electromagnetic field [14]. A test of this behaviour was made measuring E with the EB and IB bearings in 60 different points,

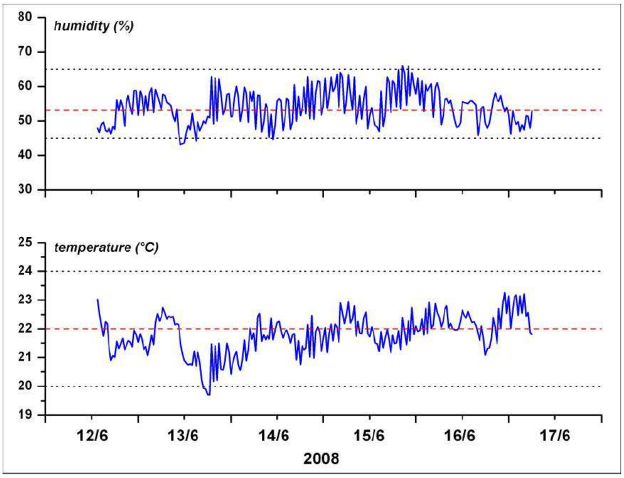

Figure 2. Humidity and temperature trends inside the chamber during 6 days. In each panel, the dashed horizontal line indicates the mean value of the data and the two dotted lines represent the limit for a normal habitat of laboratory animals.

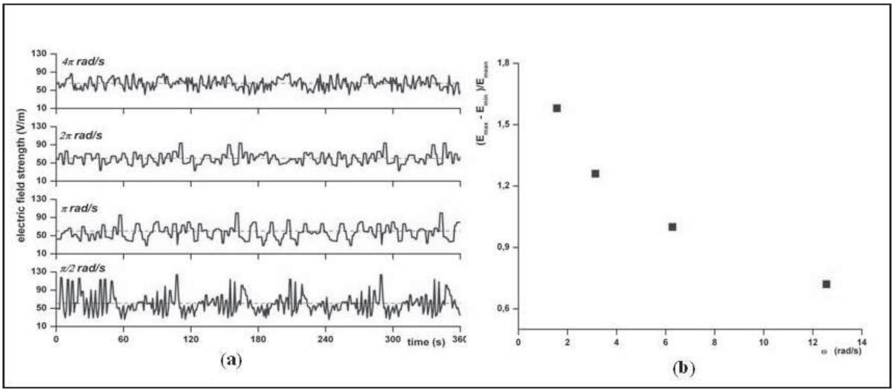

Figure 3. (a) Time series of the electric field strength at four different spin velocities of the stirrer. The horizontal dashed line in each trend represents the mean value of the relative data set. The measurements are collected at a 0.5 W input power in a point located approximately in the center of the cage zone without the cage itself, inside the reverberation chamber. (b) Relative dispersion $(E_{\text{max}} - E_{\text{min}})/E_{\text{mean}}$ of the electric field strength values as a function of the spin velocity.

regularly distributed inside the chamber on three different horizontal planes at 20 cm, 30 cm and 45 cm height, avoiding the zone of the stirrer. This choice seems able to give a significant representation of the features of the electric field in the chamber. In the case of still stirrer each value of E was obtained directly by a single measurement; with the stirrer rotating each value was obtained as average on a 6 min range time. The result obtained using a 0.5 W input power, is reported in Figure 4(a), where the distribution of the electric field strength values with the stirrer either still or in rotation is shown. A fair uniformity of the field appears when the stirrer is in rotation unlike when it is still. We have checked that the quality of the uniformity practically does not change using values of rotation velocity of the stirrer different from the one we selected.

In principle, every object introduced inside the chamber produces a perturbation in the electric field. We verified this effect considering the following four situations: 1) absence of the cage inside the chamber, 2) cage inside without food and water; 3) cage inside with food but without water, 4) cage inside with food and water (500 cc). In each case, 42 points distributed on the horizontal plane area representing the floor of the cage, that is a part of the plane at 20 cm height, were considered. Taking into account the dimensions of the cage and of the electric probe, this number represents a choice able to give a representation statistically significant of the electric field on each horizontal plain of the cage. In each point, the value of E averaged on a 6 min range time was determined four times; then the mean value was considered as representative of the point. Finally, the value averaged on the quoted 42 points was plotted in the mentioned different situations. The results relative to 0.05 W and 0.5 W input powers, are presented in Figure 5, where a decrease of the mean E value appears from the 1 to the 4 situation. Measurements made in other points distributed in the chamber have revealed that the previous decrease is not limited to the plane we investigated, but it happens everywhere inside the chamber. The following indications were deduced from the trends we obtained: the cage without food and water produces a 25% reduction of E; the food produce a further 5% reduction and the water (500 cc) a further 10% reduction. On the whole, the cage with food and water for the laboratory animals produces a reduction of E inside the chamber of 40% order. It should be remarked that the E intensity decreases are the only effects produced on the electric field by the different objects inserted in the chamber, i.e., no variation in the field stationariness, in the field uniformity and in the measurements repeatability was pointed out.

4. NUMERICAL SIMULATIONS

A numerical computation of E inside the chamber, for a standard 1 W input power, was performed by using the Microwave CST 5.0 software. The chamber without the cage inside was simulated and, in order to reproduce the electric field with the stirrer in rotation, the previous software was run varying every time the position of the stirrer of a 1 degree rotation to cover a round angle; then, the values of the electric field strength in every points were averaged. The distribution we obtained in 5500 points distributed on the horizontal plane area (20 cm height) coinciding with the floor of the cage, is reported in the right hand side of Figure 4(b). For comparison, in the left hand side of the Figure 4(b) the distribution with the stirrer still in one position is shown. It must be noted the similarity between the numerical results reported in Figure 4(b) and the experimental results shown in Figure 4(a). Then, we have observed that in order to obtain the electric field strength in every points with the stirrer in rotation, only a few positions of the stirrer, random distributed on a round angle, can be selected. A satisfactory result can be obtained with a number of position around 40.

For the numerical distribution of Figure 4(b) (right hand side) the average electric field is: $E_{\text{mean}} = 63.1\,\text{V/m}$; the maximum

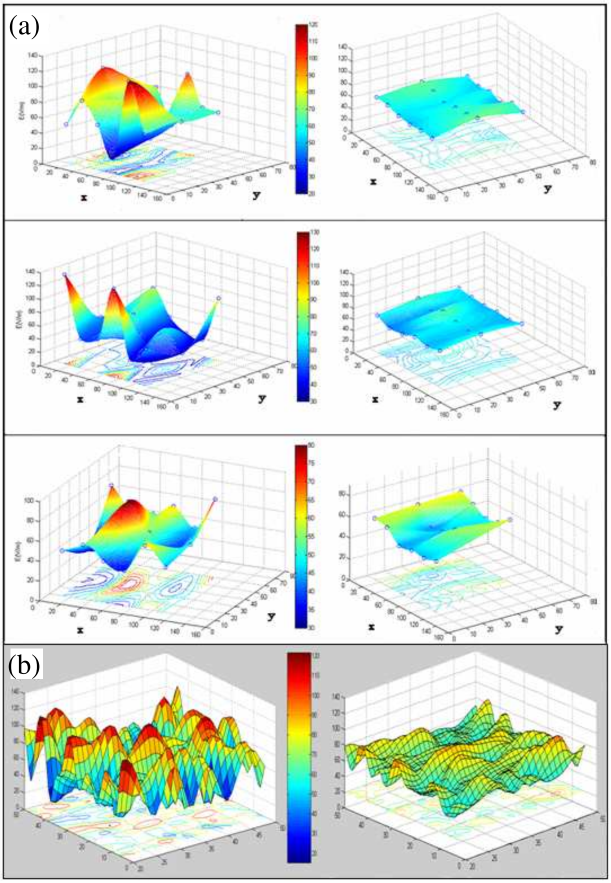

Figure 4. (a) From top panel downward: distribution of the experimental values of the electric field strength inside the reverberation chamber (cage zone) over horizontal planes at 20 cm, 30 cm and 45 cm height respectively. In the panels x indicates the length of the chamber and y its width. (b) Theoretical simulation of the chamber in the horizontal plane area (cage zone) at 20 cm height. In both the cases (a) and (b) the panels in the left column are for stationary stirrer and those in the right column are for rotating stirrer.

and minimum values are $E_{\max} = 93.6\,\mathrm{V/m}$ and $E_{\min} = 39.6\,\mathrm{V/m}$, respectively. In order to evaluate the corresponding experimental values, the chamber without the cage inside was considered and 1 W input power was used. Using the 42 points mentioned in the previous section and the same measurement method we obtained:

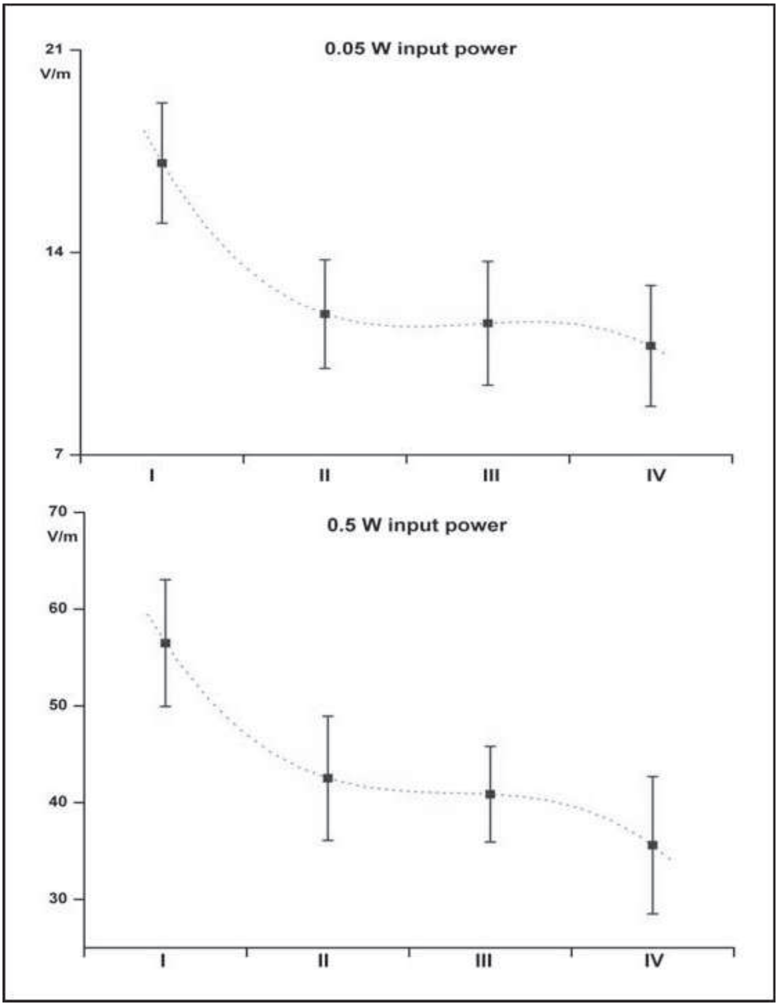

Figure 5. Electric field strength averaged on 42 points distributed in the horizontal plane area (20 cm height) representing the floor of the cage, in the configurations: 1) without the cage in the chamber, 2) cage inside without food and water; 3) cage inside with food but without water, 4) cage inside with food and water (500 cc). At the top the plot for a 0.05 W input power; at the bottom for a 0.5 W input power. The measurement in every point has been repeated four times and the averaged value with the relative semi dispersion has been considered. In each panel the dashed line represent the 3th order polynomial fit.

$E_{mean} = 61.9\,\mathrm{V/m}$, $E_{\max} = 73.6\,\mathrm{V/m}$ and $E_{\min} = 45.8\,\mathrm{V/m}$. So, a good agreement between theory and measurements stands up; only a larger dispersion of the numerical values can be noted. The justification of this discrepancy is that, in the computation, each point corresponds to a geometric point, but experimentally each point has more or less the dimensions of the probe (Section 2), that is a volume of about $25\,\mathrm{cm}^3$; so, the measured value represents the mean value over all the geometric points inside this volume. Practically, the experimental values with respect to the numerical ones are adjacent averaging smoothed. So, a smaller dispersion of the experimental values than the numerical ones should exist.

5. CHARACTERIZATION OF THE EXPOSURE SYSTEM

The E inside the cage with food and water (500 cc) in the reverberation chamber was measured for the input powers: 0.02 W, 0.05 W, 0.5 W and 2.0 W. These powers were selected to obtain E values ranging from few units to several dozen. Higher powers were avoided because they might produce some damage to the measurement equipment, taking into account the temporal variability of the electric field in each point mentioned in Section 2 and the 90 V/m upper limit value of the measurement probe. Only the zone at the bottom of the cage, that is the part where the laboratory animals generally live, was investigated using 84 points: 42 points distributed on the horizontal plane (plane 0) representing the floor of the cage and 42 points on the horizontal plane (plane 1) 5 cm higher than the previous one. The value of the E averaged on a 6 min range time was measured in every point. Each measurement was repeated four times and the mean value of the

Table 1. Mean values of the electric field strength E at different input powers in the bottom part of the cage: on its floor (plane 0), on the horizontal plane 5 cm higher (plane 1) and on the space including plane 0 and plane 1. The error is the semi dispersion of the values.

input power (W)	E (V/m)		
0.02	6 ± 1	6 ± 1	6 ± 1
0.05	11 ± 2	10 ± 1	11 ± 2
0.5	36 ± 8	33 ± 5	35 ± 8
2.0	63 ± 12	60 ± 7	61 ± 12
	plane 0	plane 1	space

four measurements in every point was determined. Then, the values averaged on the 42 points of the plane 0, on the 42 points of the plane 1 and on the total spatial distributed 84 points (space) were calculated with the relative semi dispersion. The results are reported in Table 1; practically, these values characterize the exposure in the environment for the laboratory animals without them. Table 1 points out that the E-field intensity increases about by 10 times when the input power increases from 0.02 to 2 W (100 times).

6. PHANTOMS AND THEIR EFFECT ON THE ELECTRIC FIELD

Traditionally, phantoms are used to simulate laboratory animals. Many different phantom forms have been proposed as well as many different phantom materials have been developed to simulate the properties of the body and of the head of the animals at different frequencies [19–22]. In this preliminary study we used very simple phantoms; each one is made of Plexiglas (2 mm thick) and is formed by a parallelepipedal box $(8 \times 6 \times 8)\,\mathrm{cm}^3$ with a mobile cover and is suitable to contain substances to simulate the animals (Figure 6(a)). A physiological liquid characterized by σ(conductivity) $= 1.585\,\mathrm{S/m}$ and ρ(density) $= 1006\,\mathrm{kg/m}^3$ was selected. An amount of 300 cc of liquid was used so that as concerns the weight, rats are simulated.

According to the statements in Section 3, a phantom introduced in the chamber produces a decrease of the electric field strength. We evaluated the perturbation with respect to the environment composed

Table 2. Mean spatial values of the electric field strength at different input powers in the bottom part of the cage, with one (E_1) or two (E_2) phantoms. The error is evaluated by the semi dispersion of the values. The SAR and the power efficiency (Pe=SAR/input power) values are reported, too.

	1 phantom			2 phantoms		
input power (W)	E_1 (V/m)	SAR (W/kg)	Pe (W/kgW$_{\mathrm{inp}}$)	E_2 (V/m)	SAR (W/kg)	Pe (W/kgW$_{\mathrm{inp}}$)
0.02	5 ± 1	3.2×10^{-4}	1.6×10^{-2}	4 ± 1	2.8×10^{-4}	1.4×10^{-2}
0.05	10 ± 2	9.3×10^{-4}	1.9×10^{-2}	9 ± 2	7.2×10^{-4}	1.4×10^{-2}
0.5	30 ± 7	1.0×10^{-2}	2.0×10^{-2}	29 ± 7	5.4×10^{-3}	1.1×10^{-2}
2.0	54 ± 9	3.2×10^{-2}	1.6×10^{-2}	52 ± 9	2.2×10^{-2}	1.1×10^{-2}
4.5	~ 90	7.8×10^{-2}	1.7×10^{-2}	~ 75	5.2×10^{-2}	1.2×10^{-2}

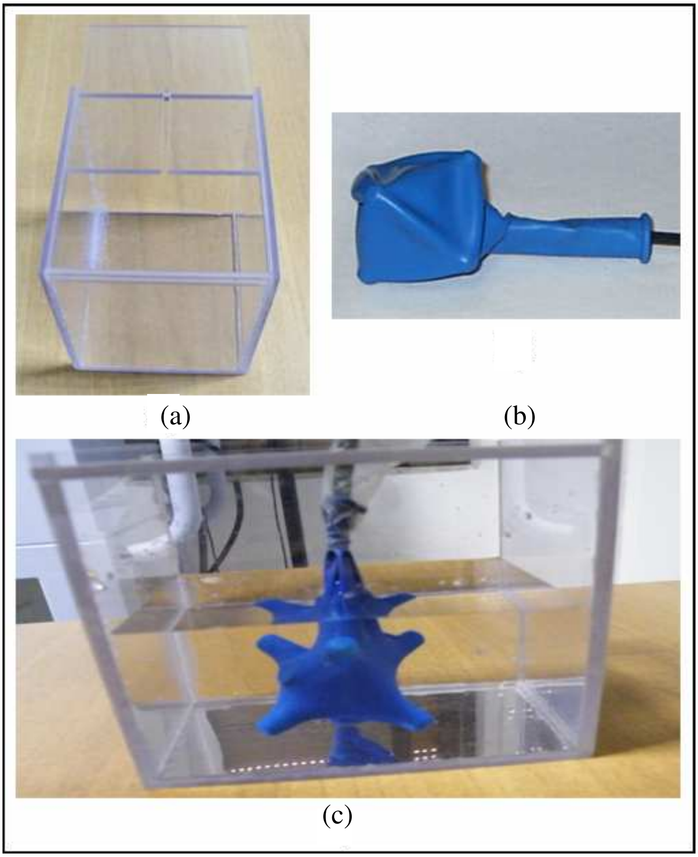

Figure 6. (a) The box $(8\times6\times8)\,\mathrm{cm}^3$ in Plexiglas with a mobile cap used as phantom. (b) The inflatable balloon with inside the electric field probe PMM EP-600 to waterproof the probe. (c) The waterproofed probe located inside the physiological liquid of a phantom.

by the cage inside the chamber, with food and water (500 cc), using one or two phantoms in a still position in different sites inside the cage. Using the 84 points mentioned in Section 5 and the same measurement method, the mean values of E on the two planes and the corresponding space were evaluated. In the case of one phantom, a 12% mean decrease of E was obtained; in the case of two phantoms, a 16% decrease was evaluated on average. Generally, no particular relation of the decreases with the position of the phantoms was pointed out. The spatial values of E obtained with one phantom or two at the different input powers are reported in Table 2. Practically, these values indicate the electric field strength to which one or two laboratory animals (rats) could be exposed in the system. In Table 2, approximated E values at the 4.5 W input power are reported, too. These values cannot be obtained directly because they are too large and damages of the electric probe (Section 2) could be produced. So, they were extrapolated by the E values measured inside the phantoms (Section 7) for a 4.5 W input power taking into account that such values in the other cases are about one tenth of the corresponding external values.

7. DOSIMETRY

The specific absorption rate (SAR) is very useful in the medical and biological research on the effects of the RF exposure. The SAR (W/kg) can be obtained by the relation:

$$\mathrm{SAR} = \sigma E^2/\rho \tag{2}$$

where σ is the electrical conductivity (S/m), ρ the mass density (kg/m^3) and E the effective electric field strength (V/m) inside the body.

In our case, we had to settle the technique for the measurement of E inside the physiological liquid of the phantoms.

At first, it was necessary to solve the problem of the impermeabilization of the measurement probe. Different attempts were made and the best result was obtained with an inflatable balloon, inserting the probe inside and leaving it open at the top, that is in contact with the air (Figure 6(b)). In order to check the calibration of the probe (Section 2) measurements were made with the probe inside the balloon; precisely, using 4 points on the horizontal plane representing the floor of the cage and the same measurement method used previously, the mean values of E were evaluated for the four different input powers. For comparison, the equivalent values collected with the probe without balloon (Section 5) were considered. In both the cases, an environment composed by the cage inside the chamber, with food and water (500 cc), was considered. As an example, Figure 7 shows the results for 0.05 W and 0.5 W. None significant difference stands up with the probe inside the balloon and without it; so, the technique described does not produce effects on the calibration of the probe.

The next step was the definition of the probe calibration (waterproofed as we have just explained) when it is inserted inside the physiological liquid of a phantom (Figure 6(c)). We have proceeded comparing the experimental data with those obtained by the numerical

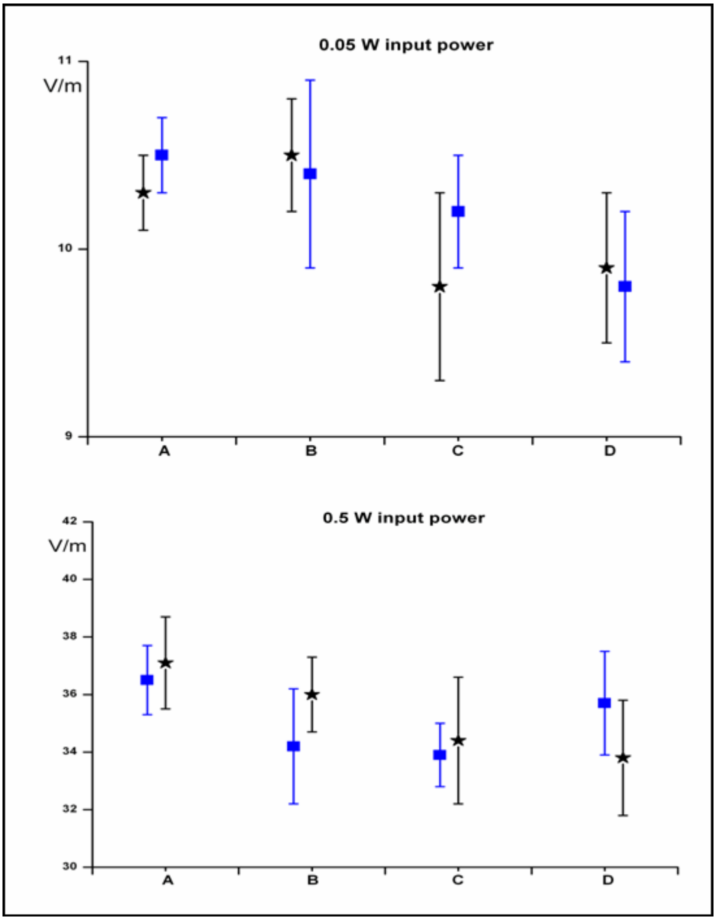

Figure 7. Electric field strength on the points A, B, C and D distributed in the horizontal plane area representing the floor of the cage. The values indicated with stars were obtained with the probe inside the balloon (Figure 6(b)); the values indicated with squares without the balloon. At the top the plot for a 0.05 W input power; at the bottom for a 0.5 W input power. In each point the measurements has been repeated four times and the averaged value has been considered with the relative semi dispersion. The points (A, B, C, D) are the same for the two types of measurements, but in both the plots the relative abscissa was a little separated to avoid superimpositions in the graphic.

computation. At this purpose, in the chamber without the cage inside, a phantom similar to the experimental one (Section 6) was inserted. For the filling liquid the following parameters were used: conductivity $= 1.585\,\mathrm{S/m}$, density $= 1006\,\mathrm{kg/m^3}$, permittivity $= 76.3(\mathrm{real}) - 23.3(\mathrm{imaginary})$.

Then, numerical estimations of E inside the liquid of the phantom in four different location inside the cage were performed using, each time, 40 different stirrer positions. At the same time, using the waterproofed probe, E inside the physiological liquid of a phantom located each time in the same four places was measured using 1 W input power. The numerical estimations represent the values of E in a volume corresponding to that occupied by the probe; in fact, in each location, the E value was calculated by averaging the values in the points contained in this volume. The comparison between the numerical and experimental data has indicated a correction factor $e = E/E_{\mathrm{act}} = 1.3$, where E_{act} is the effective electric field strength value inside the liquid and E is the value averaged on 6 min indicated by the instrumentation. It must be noted that the probe inside the liquid phantoms is big and so it can perturb the field in the liquid itself. The previous correction includes also this effect.

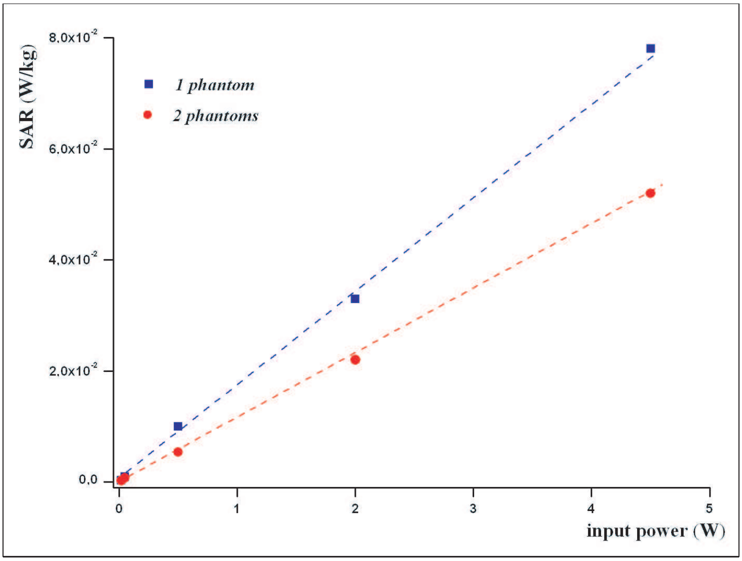

Figure 8. SAR values for 1 phantom (squares) and 2 phantoms (circles) versus the input power to the transmitting antenna. The dashed lines represent the best linear fitting.

Finally, the measurement of the E were performed for the input powers: 0.02 W, 0.05 W, 0.5 W, 2.0 W and 4.5 W. To simulate the moving of the rats, a plastic plate on which a phantom can be put was used. Four wires were fixed at this plate; the wires reach the outside of the chamber and they can be pulled from outside the chamber. For the mentioned input powers, E was measured several times. In the case of only one phantom, we obtained values either in the phantom in a still position in different sites of the cage or in the phantom moving inside the cage. No significant difference of the values was revealed in the two mentioned configurations. In the case of two phantoms either in still position or moving in the cage, we measured E with the electric probe inside one or the other one phantom. Again, no significant difference of the values was observed.

The correction factor we mentioned previously was applied to the mean E values of these measurements obtaining in such way the effective electric field strength (E_{act}) values inside the liquid. Using these values the SAR was calculated by the relation (2) and the results in the different cases are reported in Table 2. These values range from 2.8×10^{-4} to 7.8×10^{-2} W/kg. The minimum value is related to two phantoms with an exposure of 4 V/m (0.02 W input power) and the maximum one to one phantom with an exposure of about 90 V/m (4.5 W input power).

From the mentioned results the power efficiency Pe, that is SAR/input power, can be evaluated. These values are reported in Table 2 and the average power efficiency is 1.8×10^{-2} $\mathrm{W/kgW_{inp}}$ (with a semi dispersion of 2×10^{-3}) for one phantom and 1.3×10^{-2} $\mathrm{W/kgW_{inp}}$ (with a semi dispersion of 2×10^{-3}) for two phantoms. The trends in Figure 8 show the SAR values in function of the input power in the case of one and two phantoms. In both the cases a good linearity appears, as expected.

Recently, an average power efficiency of about 4.0×10^{-1} $\mathrm{W/kgW_{inp}}$ was obtained for a RF (900 MHz) "in vivo" exposure system consisting of TEM cells [23]. From the previous data, our system based on a reverberation chamber, is characterized by a very low power efficiency.

8. CONCLUSION

A preliminary study regarding a system for researching bio-medical and behavioural effects on laboratory animals at 1.8 GHz electromagnetic exposure was carried out. The system is based on a reverberation chamber with a cage inside. An input power up to 5 W can be used. The system has been characterized determining the electric field strength inside the cage with food and water (500 cc) for different input powers. A 53 mm large probe was used. Then, Plexiglas boxes containing 300 cc of physiological liquid were used as simple phantoms (1–2) in the cage and the electric field strength was determined inside, using the same probe waterproofed. A correction factor for the calibration of the probe was estimated, using numerical computation. Then, the SAR have been obtained in different cases. Values in the range $2.8 \times 10^{-4} - 7.8 \times 10^{-2}$ W/kg were obtained; such values are too low for the bio-medical studies and this is a drawback of the actual system. But, the system reproduces a habitat similar to the usual one for the animals and this is a great advantage and, as concerns the behavioural research, it is ready for use.

Further analysis should be carried out using larger input powers. Different transmitting antennae as well as different cages with food and water for the animals, should be tested. Other techniques for the calibration of the probe inside the phantoms should to be investigated. Finally, in order to obtain useful SAR values, more realistic phantoms might to be used.

ACKNOWLEDGMENT

This research was conducted in the framework of the project PE_100 titled "Sistema espositivo a radiofrequenza per animali da laboratorio" supported by the Puglia Region (Italy). The authors are very grateful to Fabiana Di Maio for carrying out a large amount of measurements and to Prof. Vincenzo Petruzzelli of the Electrical Engineering Bari Faculty for helpful discussion. The authors wish to thank the reviewers for helpful suggestions and constructive criticism.

REFERENCES

1. Adey, W. R., et al., "Spontaneous and nitrosourea-induced primary tumors of the central nervous system in Fischer 344 rats chronically exposed to 836 MHz modulated microwaves," *Radiat. Res.*, Vol. 152, 293–302, 1999.
2. Adey, W. R., et al., "Spontaneous and nitrosourea-induced primary tumors of the central nervous system in Fischer 344 rats exposed to frequency-modulated microwave fields," *Cancer Res.*, Vol. 60, 1857–1863, 2000.
3. Frei, M. R., et al., "Chronic exposure of cancer-prone mice to low-level 2450 MHz radiofrequency radiation," *Bioelectromag.*, Vol. 19, 20–31, 1998.
4. Gatta, L., R. Pinto, V. Ubaldi, L. Pace, P. Galloni, G. A. Lovisolo,

C. Marino, and C. Pioli, "Effects of in vivo exposure to GSM-modulated 900 MHz on mouse peripheral hymphocytes," *Radiat. Res.*, Vol. 160, 600–605, 2003.

5. Wu, B. I., F. C. A. I. Cox, and J. A. Kong, "Experimental methodology for non-thermal effects of electromagnetic radiation on biologics," *Journal of Electromagnetic Waves and Applications*, Vol. 21, No. 4, 533–548, 2007.
6. Lopez-Martin, E., J. C. Bregains, F. J. Jorge-Barreiro, J. L. Sebastián-Franco, E. Moreno-Piquero, and F. J. Ares-Pena, "An experimental set-up for measurement of the power absorbed from 900 MHz GSM standing waves by small animals, illustrated by application to picrotoxin-treated rats," *Progress In Electromagnetics Research*, PIER 87, 149–165, 2008.
7. Heikkinen, P., V. M. Kosma, T. Hongisto, H. Huuskonen, P. Hyysalo, H. Komulainen, T. Kumlin, J. T. Laitinen, S. Lang, L. Puranen, and J. Juutilainen, "Effects of mobile phone radiation on x-ray-induced tumorigenesis in mice," *Radiat. Res.*, Vol. 156, 775–785, 2001.
8. Heikkinen, P., V. M. Kosma, L. Alhonen, H. Huuskonen, H. Komulainen, T. Kumlin, J. T. Laitinen, S. Lang, L. Puranen, and J. Juutilainen, "Effects of mobile phone radiation on UV-induced skin tumourigenesis in ornithine decarboxylase transgenic and non-transgenic mice," *Int. J. Radiat. Biol.*, Vol. 79, 221–233, 2003.
9. Imaida, K., M. Taki, T. Yamaguchi, T. Ito, S. Watanabe, K. Wake, A. Aimoto, Y. Kamimura, and T. Shirai, "Lack of promoting effects of the electromagnetic near-field used for cellular phones (929 MHz) on rat liver carcinogenesis in medium-term bioassay," *Carcinogenesis*, Vol. 19, 311–314, 1998.
10. Imaida, K., M. Taki, S. Watanabe, Y. Kamimura, T. Ito, and T. Shirai, "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.*, Vol. 89, 995–1002, 1998.
11. Malyapa, R. S., et al., "DNA damage in rat brain cells after in vivo exposure to 2450 MHz electromagnetic radiation and various methods of euthanasia," *Radiat. Res.*, Vol. 149, 637–645, 1998.
12. Toler, J. C., et al., "Long-term low-level exposure of mice prone to mammary tumors to 435 MHz radiofrequency radiation," *Radiat. Res.*, Vol. 148, 227–234, 1997.
13. Verschaeve, L. and A. Maes, "Genetic, carcinogenic and teratogenic effects of radiofrequency fields," *Mutation Research*, 141–165, 410, 1998.

14. Corona, P., G. Ferrara, and M. Migliaccio, "Reverberating chambers as sources of stochastic electromagnetic fields," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 38, 3, 1996.
15. Hill, D. A., "Electromagnetic theory of reverberation chambers,"NIST Technical Note 1506, National Institute of Standards and Technology, Boulder, Colorado 80303-3328, USA, 1998.
16. Kouveliotis, N. K., P. T. Trakadas, and C. N. Capsalis, "FDTD modeling of a vibrating intrinsic reverberation chamber," *Progress In Electromagnetics Research*, PIER 39, 47–59, 2003.
17. Crawford, L. and G. H. Koepke, "Design, evaluation and use of a reverberation chamber for performing electromagnetic susceptibility/vulnerability measurements," *National Bureau of Standard (NBS)*, Technical Note 1092, 1986.
18. IEEE C95.3-2002, IEEE Recommended Practice for Measurements and Computations of Radio Frequency Electromagnetic Fields with Respect to Human Exposure to Such Fields, 100 kHz–300 GHz, The Institute of Electrical and Electronic Engineers, Inc., New York, NY, 10016–5997, 2002.
19. Andreuccetti, D., M. G. Bini, A. Ignesti, R. Olmi, N. Rubino, and R. Vanni, "Use of polyacrylamide as a tissue-equivalent material in the microwave range," *IEE Trans. Microw. Theory Tech.*, Vol. 35, 275–277, 1988.
20. Chou, C.-K., G.-W. Chen, A. Guy, and K. H. Luk, "Formulas for preparing phantom muscle tissue at various radiofrequencies," *Bioelectromag.*, Vol. 5, 435–441, 1984.
21. Lazebnik, M., E. L. Madsen, G. R. Frank, and S. C. Hagness, "Tissue-mimicking phantom materials for narrowband and ultrawideband microwave applications," *Phys. Med. Biol.*, Vol. 50, 4245–4258, 2005.
22. McCann, C., J. C. Kumaradas, M. R. Gertner, S. R. H. Davidson, A. M. Dolan, and M. D. Sherar, "Feasibility of salvage interstitial microwave thermal therapy for prostate carcinoma following failed brachytherapy: Study in a tissue equivalent phantom," *Phys. Med. Biol.*, Vol. 48, 1041–1052, 2003.
23. Ardoino, L., V. Lopresto, S. Mancini, C. Marino, R. Pinto, and G. A. Lovisolo, "A radio-frequency system for in vivo pilot experiments aimed at the studies on biological effects of electromagnetic fields," *Phys. Med. Biol.*, Vol. 50, 3643–3654, 2005.