DNA studies at 900 MHz EM fields by a TEM plane transmission line

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Abstract

A suitable plane transmission line was developed and its behaviour analysed at 900 MHz radiofrequency fields to study the DNA mutability and repair of microorganisms. In this work, utilizing such a device, we investigated the behaviour of the DNA mutability and repair of Escherichia coli strains. The transmission line was very simple and versatile in changing its characteristic resistance and field intensity by varying its sizes. In absence of cell samples inside the transmission line, the relative modulation of the electric and/or magnetic field was ±31% with respect to the mean values, allowing the processing of more samples at different exposure fields in a single run. Slight decrease in spontaneous mutability to rifampicin-resistance of the E. Coli JC411 strain, was demonstrated in mismatch-repair proficient samples exposed to the radio-frequency fields during their growth on solid medium.

INTRODUCTION

In the last years, the population has increased enormously the communication by cellular phones (CP) and the use of many other RF devices. Therefore, due to the base station antennas distribution, the position of the cellular mobile antennas near the brain and the diffusion of RF devices, the population exposure level to high-frequency (HF) electromagnetic fields (EMF) has grown. The RF range used for communication is limited from extremely low frequency (3 Hz) to extremely high frequency (300×10^9 Hz). The lower frequency values do not give arise much alarm because they are comparable with the EM signals of human nervous system; instead the higher spectrum values need investigations to determine possible influences on living organisms. In fact, at the moment the most widely used global system for mobile communication (GSM) operates just at frequencies of 900 and 1800 MHz pulsed at 217 Hz.

The radio-frequency-modulated electromagnetic radiation (RF-EMR) power emitted from CP is rather little (~1 W) and the intensity at the exposed tissue position, same centimetres from the antenna (about 20 mW/cm^2), is very low to suppose thermal effects. Nevertheless, researchers have tried to investigate specific effects on various biological systems and the obtained results are still questionable [1]. Moreover, due to the CP position during the communication, namely near the head and ears, it is particularly important to investigate the possible non-thermal bio-hazard.

The photon energies corresponding to the frequency of 900 and 1800 MHz are 3.7×10^{-6} and 7.4×10^{-6} eV, respectively, six orders of magnitude lower than the light one. Therefore these values can not provoke substantial quantum energy transitions and still less chemical bond breaking. Instead, other processes such as multi-photon effects [2] might not be negligible in the interaction of photons with biological tissues.

Experiments designed to investigate under well-controlled temperature conditions the non-thermal coupling of microwave fields to protein structure and dynamics produced contrasting conclusions. Using optical rotation dispersion, acceleration of unfolding and refolding of β-lactoglobulin in urea solution by 2.45 GHz microwave irradiation [3], and non-thermal inactivation of thermophilic S-adenosylhomocysteine hydrolase by 10.4 GHz irradiation [4] could be observed. A similar reduction in enzymatic activity and loss of helicity was reported for thermophilic alcohol dehydrogenase using circular dichroism [5]. Using light scattering, enhanced aggregation of bovine serum albumine was reported following exposure

to 1.0 GHz [6]. In contrast a combined approach with absorption spectroscopy at visible wavelengths, optical rotation dispersion and measurement of tryptophan fluorescence lifetime failed to detect difference in myoglobin dynamics before and after exposure to 1.95 GHz irradation [7]. A recent study using in-situ X-ray diffraction on protein crystals of hen egg-white lysozyme came to about the same conclusion [8].

Nevertheless, the ability of RF-EMF to modulate cellular signal transduction and to induce stress response pathways has been investigated using cell cultures or animal models[9, 10]. There are several studies indicating non-thermally-induced biological effects of RF-EMF, where the authors explore the possibilities of induction of cancer [11-15], disturbance in functioning of blood-brain barrier [16-20], activation of oxidative stress [21]. In addition, the ability of RF-EMF to modulate cellular signal transduction and to induce stress response pathways as well as heat shock proteins has been assessed using cell cultures or animal models [22-27]. Viewing this cellular response toward RF-EMF exposure, it is possible to include RF-EMF into the wide variety of environmental stimuli that trigger stress response pathways. Many studies have tried to motivate whether RF-EMF may interact with DNA and eventually damage it, and/or may enhance the genotoxicity of other environmental "pollutants". They led to many interesting results, but conclusions have been contradictory [28]. The majority of investigations have shown that exposure of cells or animals to RF-EMF is not able to induce chromosome or DNA damage at power intensities that are low enough to exclude thermal effects [29-31]. On the contrary, using alkaline single cell gel electrophoresis (SCG) (or Comet) assay and micronuclei assay it has been shown that RF-EMF at moderate power levels purported to be non-thermal are capable of inducing chromosomal damage in cultured human blood cells [32-35]. In addition, using classical chromosome aberration or sister chromatide exchange analyses many reports demonstrated that exposure of cells to RF-EMF alone may have no genotoxic effects, whereas the combined treatment with a chemical mutagen may enhance the genotoxicity of the latter [31, 36]. Different factors may account for these discrepancies: i. the methodology that has been used to detect a possible effect on genome stability; ii. the mode of exposure, e.g., frequency modulation that may be a determining factor with regard to the biological effect of microwaves.

The majority of investigations have been performed utilizing household ovens, RF emitters and seldom transverse electromagnetic (TEM) cells. In the first and second setup the typology of the fields is not well known, apart the total power. The electromagnetic wave in an oven is emitted and reflected many times by the metallic walls irradiating the specimen with an EM field whose direction changes after every reflection. In a RF emitter, the near field has got a field vector direction not quite perpendicular to the propagation velocity causing, also in this case, an irradiation with the field direction not well known. Therefore, especially for the above reason and in order to get well known fields, dedicated TEM cells have been constructed [37-39]. They are composed by an internal conductor and an external one which limits the outer electromagnetic irradiation. Inside the cell, the field is considered to be uniform only in the central zone between the two conductors. Its value can be changed only varying the input power. Instead, in this work we developed a suitable planar device of well known characteristics, capable to process simultaneously different cell plates at various exposure conditions by well defined - both in direction, intensity and spatial distribution - electric and magnetic fields. The amplitude of the fields can be changed either varying the input power or easily adjusting some typical sizes of the system like the distance between the electrodes [40]. The electric field distribution inside the chamber can be easily mapped by means of an opportune probe that exploits the antenna effect. Besides, this device is very versatile because its electric characteristics can be easily changed and its cost is very cheap.

In the present study we utilized such a device to assess the effects of the exposure to the RF-EMF on survival and mutability to rifampicin-resistance of a DNA repair-proficient *Escherichia coli* collection strain.

MATERIALS AND METHODS

The experimental apparatus utilised to perform this work was composed by a RF generator, Wavetek Mod. 2000, 50 W, operating at 900 MHz, and two identical climatic-controlled home-made transmission lines. A line was connected to the generator while the second one was used for non-exposed (sham-exposed) samples used as control. They were two parallel-plate line made of brass plate 1 mm thick.

By theory, to transmit RF energy without generating reflections, the transmission line has to get a characteristic impedance of 50 W, like the generator one. Therefore, by utilizing the electromagnetic laws related to the field propagation [40], for a transmission line the characteristic impedance R_0 is given by the following formula:

$$R_o(p) = \sqrt{\frac{R + pL}{G + pC}} \quad (1)$$

where *R, L, G* and *C* are the resistance, inductance, conductance and capacitance per unit length, respectively, and *p* the Laplace transformation variable. Our line must contain cell plates, made of polystyrene, of 3.5 cm in diameter and for this reason we chose to construct plane transmission lines by width larger than the cell plate diameter.

Now, let us neglect the line width and to consider the electrode distance very small with respect to the other dimensions, the inductance and capacitance per unit of length are:

$$L = \mu_o \frac{h}{a} \quad \text{and} \quad C = \varepsilon_o \frac{a}{h}$$

where *h* and *a* are the distance between the electrodes and the width of the electrodes, respectively, Fig. 1.

Assuming that the electrode resistance and the conductance of the insulating medium (air or

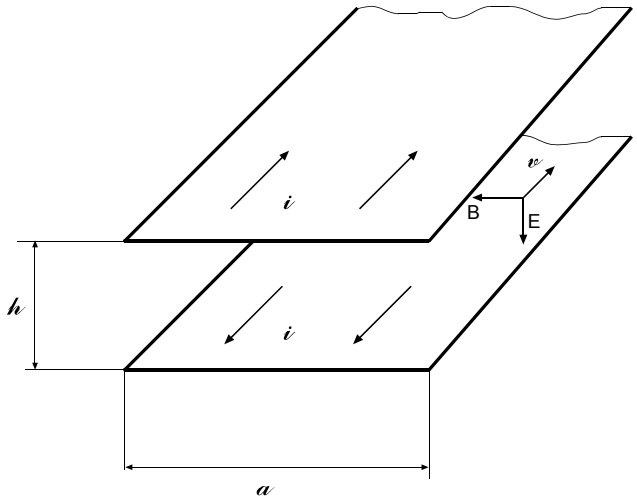

Fig. 1. Schematic sketch of the transmission line irradiation chamber. *h* is distance between the conductors; *a* is width of the conductors; *i* is the hypothetic current.

cell plates) are approximately zero and neglecting the lateral irradiation, the characteristic impedance becomes independent of variable *p*, namely:

$$R_o = \sqrt{\frac{L}{C}} = \sqrt{\frac{\mu_o}{\varepsilon_o}} \frac{h}{a} \quad (2)$$

Then, choosing the line width a = 10±0.1cm, the electrode distance h = 1.5±0.1 cm, we got a characteristic impedance of about 50 W. This value should assure the matching of the signal transmission and reflections should be avoided. By this analysis we can observe that the total length *l* of the line does not influence its characteristic impedance. However, it was fixed at 40 cm in order to process more cell plates in a run.

Two 50 W BNC connectors were mounted on their longitudinal ends, while the lateral edges were bent in order to limit the scattering of radiation. Fig. 2 shows a sketch of the experimental apparatus.

One BNC was connected to the generator output, while the second one to a 50 W resistor. This system should allow us to get a travelling electromagnetic wave, type TEM, with the electric (*E*) and magnetic (*B*) field directions lying on the plane perpendicular to the propagation direction, as one can see in Fig. 1.

To assess the electric field amplitude distri-

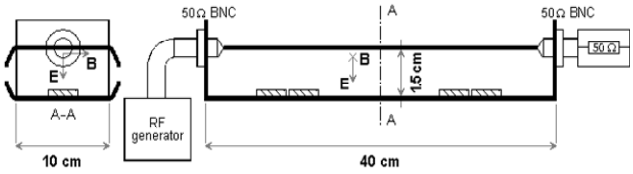

Fig. 2. Experimental apparatus (side and cross sections). **E** and **B** are the electric and magnetic field directions lying on the plane perpendicular to the wave vector (***v***).

bution inside the transmission line we mapped it by inserting a suitable home-made antenna in the exposure volume after having made small holes on the grounded electrode. The output antenna signal was relative to the electric potential on a plane parallel to the electrode surfaces. The small holes were arranged in a 9x39 matrix centred on the longitudinal axis and spaced by 1 cm along each direction, filling quite all the exposure area. The output antenna signal was connected to a fast digitizing oscilloscope, Le Croy Wavepro 7100, 1 GHz bandwidth (20GS/s) by a 50 Ω transmission line and closed on a 50 Ω resistance. Fig. 3 shows a sketch of the antenna having the detecting plug 10 mm long.

The electric field amplitude distribution is plotted in Fig. 4. It shows an overlap of a forward and backward wave having as result the formation also of a standing wave along the longitudinal axis, while transversally it presents a good uniformity

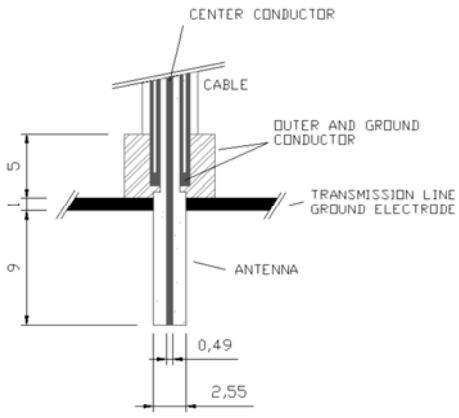

Fig. 3. Sketch of the antenna used to map the electric field amplitude distribution inside the transmission line irradiation chamber. Sizes are expressed in mm.

[41]. The presence of the standing wave was due to not optimal geometrical boundary conditions in our device, in spite of the characteristic impedance matching.

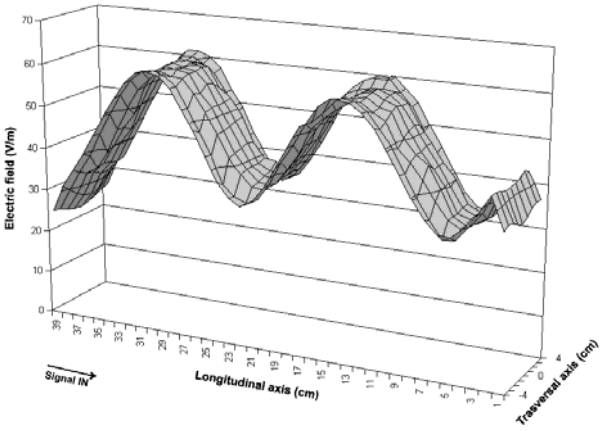

Fig. 4. Electric field amplitude distribution inside the plane transmission line.

Numerical solutions were calculated of the voltage inside the transmission lines closed on a load resistance [40]. Cases of impedance mismatching were simulated. Then, comparing the experimental results for the voltage amplitude distribution with the numerical code ones, iteratively calculated for different load resistance values, we concluded that the effective load resistance of the line resulted of 28 Ω, value lower than the actually utilised load, R_0. This behaviour is due to the line transversal dimension comparable with the RF wavelength.

In order to assure a homogeneous irradiation of the cells under these conditions, we decided to apply pairs of adjacent plates placed transversally to the line axis in correspondence of the voltage maximum points. In addition, it is also possible to apply cell plates in correspondence of the voltage minimum points, in order to treat simultaneously more samples with different field values. In correspondence of the maximum and minimum voltage values, an exposure area of 3.5 cm in diameter underwent an uniform field within ±3.5% and ±7.5% around the local mean value, respectively.

Besides, by means of our irradiation chamber we could easily change E and B. In fact, denoting by V_M and V_m the maximum and minimum difference of potential of the line, the electric field between the electrodes, when the cell plates are absent, is given by the ratio V_M/h and V_m/h , respectively. On the contrary, the maximum magnetic field, $\mu_0 V_M/(R_0 a)$, is present in correspondence of the minimum voltage position, while the minimum one, $\mu_0 V_M/(R_0 a)$, is present in correspondence of the maximum voltage position [40]. Therefore, changing the parameters h and a, it is possible to change E and B along the line and to vary the matching.

In this experiment, the electric field intensity was evaluated measuring the output voltage signal at the line end as shown in Fig. 4. It was 0.55 V large when the line was closed on 50 Ω. So, taking into account the occurrence of a minimum in the potential distribution at the output end of the transmission line, the electric and magnetic fields at the maximums of the potential distribution resulted of about 59 V/m and 100 nT. Instead, at the minimums, they resulted of 31 V/m and 214 nT. The magnetic field values were found theoretically, while the mean power of the device was of 6 mW, (V^2_{out}/R_0), determined by the output voltage value where V_{out} represents the output voltage measured on the load resistor R_0=50Ω, Fig. 2.

In absence of the cell plates, the mean value of the electric field, E', over the exposure area at the voltage peak, resulted about 57 V/m, while the variation was of ±2 V/m. When cell plates were inserted into the waveguide, the electric field inside the cell layer was estimated by employing a simple model of stratified dielectric medium with weak conductivity, composed of layers of polystyrene (1.8 mm thick), culture medium (agar, 3 mm), cells (2 mm) and air (10.2 mm). We carried out the following relation to calculate the electric field amplitude E_i in the i-th layer, for the case of sinusoidal oscillations:

$$E_i = E' h \left[\varepsilon_i \sqrt{1+\left(\frac{\sigma_i}{\omega\varepsilon_0\varepsilon_i}\right)^2} \cdot \left| \sum_n \frac{d_n}{\varepsilon_n} \left(1 - j\frac{\sigma_n}{\omega\varepsilon_0\varepsilon_n}\right)^{-1} \right| \right]^{-1} \qquad (3)$$

where j is the imaginary unit, w is the angular frequency and d_n, $\varepsilon_n(\omega)$ and $\sigma_n(\omega)$ are the thickness, the relative dielectric constant and the electric conductivity of the n-th layer, (note that $\Sigma_n d_n = h$). Under the condition and $\sigma_n/\omega\varepsilon_0\varepsilon_n \ll 1$, well satisfied at microwave frequencies for the materials considered, Eq. (3) is reduced to:

$$E_i = E' \frac{h}{\varepsilon_i \sum_n \frac{d_n}{\varepsilon_n}} \qquad (3')$$

Making use of data reported in literature for the dielectric constant values of polystyrene (e=2.5)[41] and agar ($\varepsilon \approx 80$)[44] at microwave frequencies, and assuming that *E. coli* dielectric properties are assimilable to *Salmonella typhimurium* ones (e=74) [43], the mean value of the field inside the cell layer, E_{cl}, resulted in 1.06 V/m increasing the electric field over the plates as expected.

This result was also confirmed by the one obtained with the simulating code Femlab 3.1i which gave an electric field over the plates of about 70 V/m and inside the cell layer of about 1.1

V/m. Considering the field strength on the cell layer we can observe an uniform distribution on the cell plate central part, while a variation of 10 % near the edges, see Fig. 5. Therefore, we can suppose that the electric field inside the cell layer is influenced by the same percentage.

In this work a rough estimation of the specific absorption rate (SAR) was obtained by the usual expression considering a purely sinusoidal electric field:

$$SAR = \frac{\sigma E_{cl}^2}{2\rho} \quad (4)$$

where σ and ρ are the electric conductivity and density of the biological matter, respectively. Assuming σ=0.36 S/m[41] and ρ=1000 kg/m^3, the SAR value was 2.2x10^{-4} W/kg.

The temperature of the cell plates was monitored during RF-EMF field application and was found to be identical and constant in all cases. It was monitored by a platinum probe (Pt-RTD 100Ω) connected to a voltmeter and immersed in the culture medium.

Biological assay

E. coli strain used in this study was JC411 (*leuB6*, *fhuA2*, *lacY1*, *glnV(44)AS*, *gal-6*, l-, *hisG1* (F_6), *rfbD1*, *recA1*, *galP69*, *argG6*, *rpsl104*, *malT1*l^R, *xylA7*, *mtlA2*, *metB1)*, kindly provided by the CGSC (*E. coli* Genetic Stock Center Web server, cgsc.biology.yale.edu/top.html). This strain is naturally sensitive to the antibiotic rifampicin that blocks RNA synthesis at the level of transcription initiation [45]. Mutation rate to rifampicin-resistance was used as a parameter of the mutability. In bacteria the rifampicin-resistance phenotype is generally associated to mutations in the *rpoB* gene encoding the RNA polymerase β-chain [46], and it is widely used to test the mutability of a strain [47].

To analyze the effects of the exposure to the RF-EMF on bacterial survival and mutation rates to rifampicin-resistance, the following protocols were used. Single colonies were inoculated in 5 ml Luria-Bertani (LB) broth and incubated to late logarithmic phase (about 5 x 10^8 cfu ml^{-1}). 1 ml of the cultures were laid on LB agar (1.5%) plates and exposed to the RF-EMF for 24 h at 30°C. Non-exposed control plates were incubated at the same time in an identical climatic-controlled chamber. Bacteria were then gently recovered by the LB agar plates and resuspended in 1 ml LB broth. Opportune dilutions were plated on selective LB agar plates containing 50 mg/ml rifampicin, or on non-selective LB agar plates and incubated over night at 37°C. After the incubation the number of rifampicin-resistant colony forming units (cfu) and total cfu were determined. Data were obtained by 6 independent experiments. In each experiment, 9 independent cultures were tested. Mutation rates were determined by the Lea-Coulson[48] method of the median with the equations (5) and (6):

$$\mu = m\,(N_t - 1) \approx m\,N_t \quad (5)$$

$$r\tilde{}/m - \ln(m) = 1.24 \quad (6)$$

where μ is the mutation rate, m the number of mutations per culture, N_t the final number of cells in a culture and $r\tilde{}$ the median number of mutants in a culture. Lea and Coulson observed that for m from 4 to 15, the distribution of the function $r\tilde{}/m - \ln(m)$ has a skewed distribution about a median of 1.24. Within the limits $1.5 \le m \le 15$, the Lea-Coulson's median estimator is the method of choice for determining mutation rates[49]. Values in Fig. 5 represent means ± standard deviations of the μ values obtained in the six independent experiments.

For statistical analysis a standard *t* test [50] was used. Fluctuation is usual with the mutation rates seen for rifampicin-resistance so that only differences of a factor 2 or more are considered significant [47].

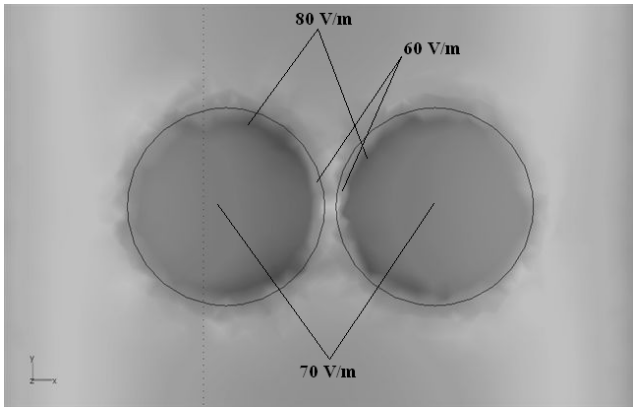

Fig. 5. Electric field simulation by the Femlab 3.1i code.

RESULTS AND DISCUSSION

In this experiment electric field amplitude and SAR values (about 57 V/m in air and 2.2x10^{-4} W/kg, respectively) were chosen that closely match the limits imposed by the authority in EC. The RF-EMF power levels we used did not produce significant thermal effects between exposed and control samples (< ± 0.3 °C, comparable with the measurement uncertainty of the platinum probe), and did not affect bacterial growth. Mutagenesis data, shown in Fig. 6, demonstrated that the mutation

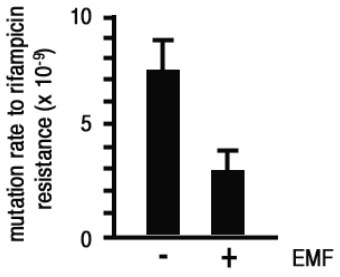

Fig. 6. Mutation rates to rifampicin-resistance of strain JC411 exposed or not exposed to the 900 MHz RF-EMF. Values represent means from 6 independent experiments. Bars indicate standard deviations.

rates to rifampicin-resistance was slightly lower (about 2.7 -fold) in bacteria exposed to the RF-EMF than in non-exposed bacteria. Differences between means (exposed *versus* non-exposed) were significant as demonstrated by standard *t* test [50]. Besides, considering the simulation results we did not observe any hot spots that might modify deeply the results.

This finding is apparently in contrast with previous studies that failed to demonstrate an effect of the exposure to RF-EMF on mutation in bacteria [51-53]. However, it should be noted that our data cannot be directly compared to those produced in these studies due to differences in microwave sources, frequencies, field intensities, SAR values and samples utilized to test. In particular, it should be emphasized that: i. two of these studies were performed with DNA repair-defective bacterial strains [52,53]; ii. none of these studies explored the effect of the 900 MHz frequency radiation; iii. the SAR values in all these studies were orders of magnitude higher than that used in our investigation; iv. most importantly, the experimental design of these studies was aimed to test a possible mutagenic effect of the RF-EMF, while, in contrast, we found an anti-mutagenic effect of the 900 MHz RF-EMF for *E. coli* JC411 strain.

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