Magnetic field exposure systems for the study of ELF effects

E. Cardelli, A. Faba, N. Palotti, M. Pompei and F. Tissi

Dept. of Industrial Engineering, University of Perugia, Perugia, Italy

This paper deals with the design and the experimental verification of two distinct magnetic field exposure systems for applications related respectively to the in vivo and the in vitro analysis of the magnetic field effects at extremely low frequency ELF. The performances of the two systems in exposure uniformity, magnetic induction and frequency range are discussed in the paper, and verified with a dedicated series of experimental tests. Finally some information about the level of temperature and vibration increase expected and their control are given, in order to show the capability of the exposure systems presented to be efficient tools for magnetic ELF exposure studies not affected by typical artifacts produced by this kind of mechanical parasitic effects.

Index Terms— **Magnetic field, Extremely low frequency, Exposure systems, Computer design, Experimental verifications.**

I. INTRODUCTION

A CONSIDERABLE variety of exposure systems has been proposed to investigate the biological effects due to the exposure of ELF magnetic fields. [1]-[9] The requirements for the exposure systems have been formulated by several authors [10-12]: large loading volume with uniform exposure, high dynamic (µT-mT) and frequency ranges (subHz–kHz), allowance of complex signals and intermittent exposure, good insulation between exposure and sham, identical parameters for exposed and sham cell (preferably placed in the same incubator), blinded exposure protocols by a computed controlled random decision maker, continuous monitoring of all environmental and technical parameters in order to detect any malfunctions, evaluation of possible artifacts such as parasitic E fields, temperature loads, vibrations, etc. This paper report the main aspects of two different exposure systems designed and manufactured in our laboratory: the first one dedicated to the in vivo exposure, the second one dedicated to the in vitro exposure. These exposure systems have been and are currently used for the experimental investigation about the long term effect of ELF magnetic field.

II. THE IN VIVO EXPOSURE SYSTEM DESIGN

The radiation apparatus for the in vivo exposure is based on two identical coils connected in series. Each coil is made of copper wire insulated by dielectric enamel and placed in a wood case. The coils are then spaced and rigidly hold by a suitable wood structure. The wood surface is treated against humidity by a special paint. The coil system has been designed in order to have a known field uniformity in the exposure region, determined by the dimensions of the mice gage used. The magnetic design has been done by using Biot-Savart law. This was possible because in this case there are not ferromagnetic or other non linear magnetic materials, and the Biot-Savart formula gives results without any approximation of other numerical schemes. Each straight segment of conductor has been modeled as a current line. The total magnetic field has been estimated as the vector sum of the effect of each current line. This has been done by a dedicated

MATLAB$^©$ numerical code. The applied field in the exposure region is, in general, proportional to the current in the coils. The exposure geometry defined in Table I allows to define a slab volume of 300x300x100 mm, centered between the coil system, where the uniformity of the magnetic field is almost constant. We have computed for the configuration above the value of a percentage magnetic field uniformity coefficient, defined as

$$\frac{H_m - H_{\max} + H_{\min}}{H_m} \cdot 100 \qquad (1)$$

Where $H_{\max}$, $H_{\min}$ and H_m are respectively the maximum, the minimum and the mean value of the magnetic field in the exposure region (control volume). The computed value of this coefficient is in our case higher than 96%. The two coils are usually feed in series by a 50 Hz sinusoidal current. The current can be derived by the electrical network via a suitable power network. An uninterruptible power supply unit is used in order to prevent possible energy lack from the 50 Hz network. The power network is constituted by an insulation transformer with multiple voltage ratio, in series with a variable amplitude transformer. The power network is placed far from the exposure region, in order to not influence the magnetic field generated by the coils. The system is additionally protected by fault, short circuit, and direct or indirect touch by a suitable automatic switchgear. The root mean square value of the voltage and current in the coils is measured by a digital volt-meter and a digital ampere-meter, respectively. The exposure system is made by two identical sections, the first one is for the exposed group, and the second one is for the sham group. The sections are placed at a distance sufficient to make the magnetic interference of the exposed section on the sham section negligible. This point will be further explained in the next section. In Fig. 1 is shown a photography of the exposure system.

III. EXPERIMENTAL VERIFICATION OF THE IN VIVO EXPOSURE SYSTEM

The exposure parameters of the system have been verified experimentally. The values of the magnetic induction have been measured in the exposure volume by means of a digital field meter. The field meter (PMM Mod. 8053 with Probe

Mod. EHP 50) measures the three components of the magnetic induction and its absolute value. It is equipped with a series of bandwidth filters in order to verify and eventually remove parasitic external magnetic effects, and it has accuracy of +/- 5% of the upper scale value and resolution less than 1 nT. The digital meter has been placed in a regular grid of 6x6x3 point.

Fig. 1. Picture of the in vivo exposure system.

The magnetic induction measurements have been done for three different rms current values, 1.37, 2.78 and 4.20 A, corresponding to a mean induction value of 1, 2 and 3 mT respectively. The waveform of the current was practically sinusoidal with a mean shape factor of 1.1135 and a mean amplitude factor of 1.4969 in the range of 0.5 - 5.0 A. In Fig. 2 are reported the values of the magnetic induction measured for the three current levels in the 108 points of the grid in the exposure volume. It can be noted the flat shape of the magnetic induction attained. The percentage uniformity factor for the magnetic field has been respectively 92.4%, 94.1% and 95.7%. In Fig. 3 is reported a comparison between the magnetic induction value computed and measured in the center of the exposure volume, for the current range 0 – 5.5 A. It can be noted the strong agreement between the measured values and the predicted ones by the computed aided design. Finally, we have investigated the distance between the exposure unit and the sham unit, in order to have no magnetic interaction between the exposed and sham volume.
We have defined the parameter

$$\frac{H_{shame}}{H_{\exp}}100 \qquad (2)$$

In order to check the position of the shame unit to have negligible induced magnetic field. In figure 4 is reported the value of such parameter vs the distance from the exposure unit. The predicted data have been confirmed experimentally, as shown in the same Fig. 4.
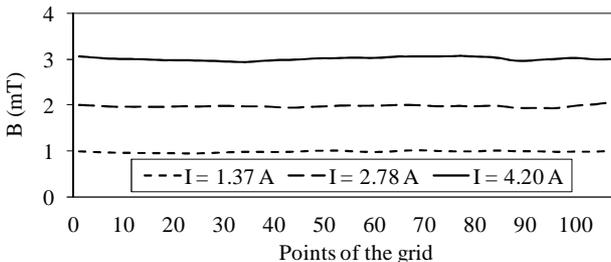

Fig. 2. In vivo exposure system. Distribution of the magnetic field in the exposure volume at different current rate.
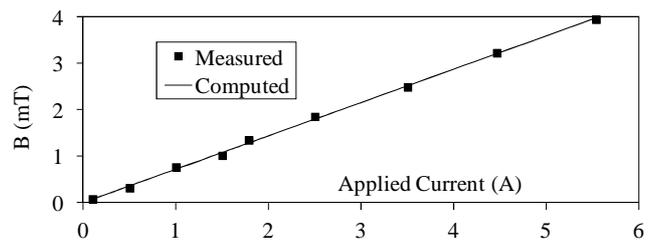

Fig. 3. In vivo exposure system. Experimental validation of the exposure volume design.
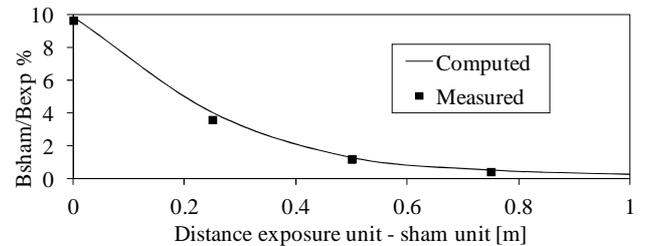

Fig. 4. In vivo exposure system. Magnetic field in shame volume vs the distance to the exposure unit.

IV. THE IN VITRO EXPOSURE SYSTEM DESIGN

After the successful work and the experience done about the in vivo exposure design we have moved our attention to the design and the set-up of a in vitro exposure system. Using the experience of the previous work we have modified a little the set-up of the in vivo exposure system above described. In addition the design in this case must account of the fact that the exposure volume must be placed in a CO_2 atmosphere, and that the exposure system is surrounded by a closed stainless iron structure. We have used again two identical copper wire coils connected in series. The wires are insulated by transparent dielectric enamel. The coil are insulated by an epoxy resin enclosure. The coils are then spaced and rigidly hold by a suitable stainless iron structure. The coil system are placed inside a CO_2 incubator. The incubator has a 170 liters seamless chamber with rounded corners. The CO_2, temperature and humidity levels are automatically controlled by a no-fan system. The magnetic design has been done by a FEM approach in frequency domain using Ansys-Maxwell©. This was necessary in order to take into account the effect of the induced currents in the stainless cage. The circulation of eddy currents can change the magnetic field in the exposure volume, and can have a possible thermal effect, by joule's heating. The FEM approach in frequency domain was possible because we have considered a constant value of the magnetic permeability in the metallic part of the structure, mainly stainless iron. This has been postulated taking into account that the level of the magnetic induction in the magnetic materials is far from the saturation state, and that the hysteresis effect is usually negligible. The value of the relative magnetic permeability used in the numerical simulations is 65. The value has been deduced by measurements, and it is in good agreement with the data given by the manufacturers. In Fig. 5 is reported a typical graphic output of the code used for the design: it is shown the typical distribution of the magnetic field induction in a plane of the exposure region with and without the stainless cage. In the Fig. 6 is reported the typical

distribution of the ohmic losses on the stainless cage.The exposure geometry allows to define a slab volume of 210x210x105mm, centered between the coil system, where the uniformity of the magnetic field is almost constant. To give an idea about the typical computational cost for a complete FEM numerical simulation we have used about 157,000 tetrahedral elements and the CPU time of almost 13 minutes and a PC with 3 GB RAM using an Intel Core 2 Duo© main processor at 2.00 GHz. The two coils are feed in series by a sinusoidal current in the range 0,1 Hz – 400 Hz. In this case it is possible to investigate about the exposure to ELF magnetic field in a broad range related to practical applications. In addition it is possible to expose the bio cultures at magnetic field with different components simultaneously. The current is generated by a suitable power supply. This power network is constituted by: 4 quadrant amplifier Spitzenberger&Spies, mod. PAS 2000/DDS2; digital voltmeter Agilent, mod. U1241B; Potentiometer, max 10 Ω, max 2.7 A; Digital oscilloscope Tektronix, mod. TDS2024B; Current probe Hameg, mod. HZ56. The system is additionally protected by over current and ground fault by microprocessor controlled switchgear. The current waveforms are measured by the digital oscilloscope described above. In Fig. 8 is shown a photography of the incubator modified for the in vitro exposure system and the power supply.
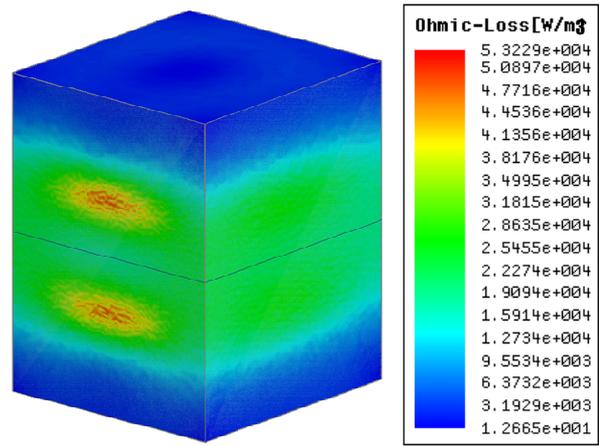
Fig. 7. Typical distribution of ohmic losses on the stainless cage.
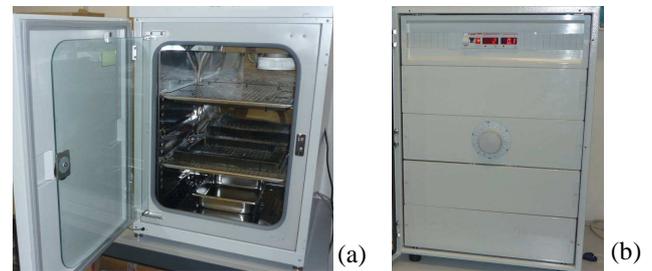
Fig. 8 (a) Picture of the in vitro exposure system and view of the embedded coil. (b) Picture of the power supply of the in vitro exposure system.

The components of the magnetic induction and its absolute value have been measured in the exposure volume by means of the digital field meter mentioned in the section III. A series of measurements of the magnetic induction has been made in a series of points in the exposure volume, and for different values in the frequency and amplitude range of the exposure system. The percentage uniformity factor for the magnetic field has been always higher than 91,0%.

VI. TEMPERATURE AND VIBRATION ARTIFACTS

A. Temperature

The design of the coils has been made in order to reduce the current density and the Joule's losses. In addition the heat produced by Joule's losses is dissipated by forced ventilation. In the in vivo exposure system the temperature is regulated by the air conditioning system of the Lab. In the case of the in vitro exposure system the temperature of the exposure volume is computer-controlled by a closed circuit fan less direct heath system. Anyway, in order to check that the temperature in the exposure and in the sham volume is almost the same, and therefore to avoid typical artifact due to different heat exposure we have measured with a temperature probe (ASITA Mod. AS2 with Probe Mod. ATT29) the temperature in the center of the exposure volume, initially at zero current and successively at the maximum current rate available for each system, respectively 3 and 6 A. The current has been applied for 1 hour. The room temperature has been checked by a twin probe, suitably calibrated. The temperature rise in the center of the exposure volume and the room temperature (shame) measured are represented in Fig. 9 for the in vitro exposure
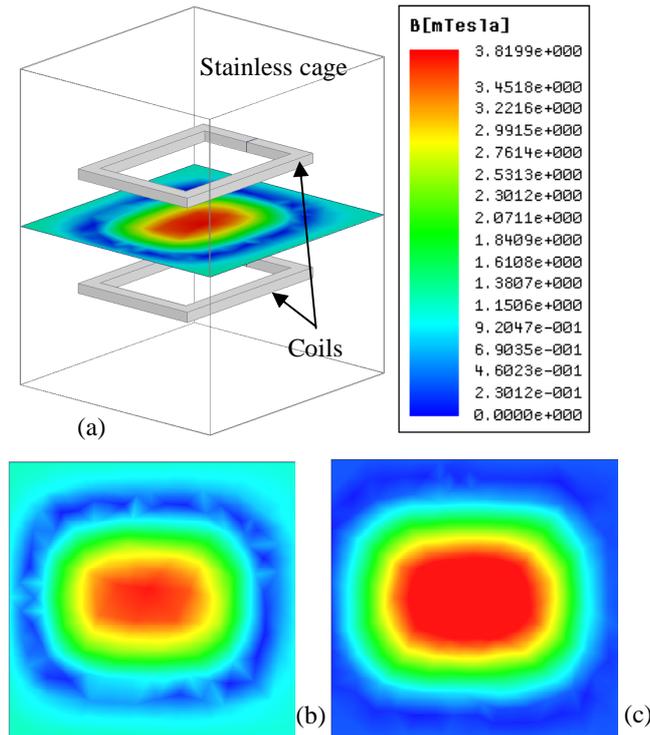

Fig. 5. (a) B map in the exposure region of the in vitro exposure system (3D view). (b) B map with the stainless cage. (c) B map without the stainless cage.

V. EXPERIMENTAL VERIFICATION OF THE IN VITRO EXPOSURE SYSTEM

In analogy with the case of the in vivo exposure system the working parameters of the system have been verified experimentally.

system. We have seen that increase in temperature is less than 0,5 °K with the maximum working current: in the usual exposure conditions it is almost negligible. In the case of the in vitro exposure system the increase in temperature is always less than 0.3 °K: this is due to the inner air conditioning system of the incubator, that is computer controlled in temperature.

B. Vibration

A second possible cause of artifacts in the experimental research of the ELF effects can be identified in the different vibration level in the exposure and in the sham volume. In the exposure volume the vibration level can be enhanced by the magneto-motive forces acting in the coils. We have measured the vibration in the exposure volume by means of suitable digital piezo-electric accelerometers (PCB PIEZOTRONICS Mod. 352C34) coupled to the exposed containers (mice cages, Petri dishes, ecc.). The accelerometer signals have been amplified by a digital linear amplifier. We have checked that the piezo electric accelerometer measure is not influenced by the applied field generated. The sensitivity of the accelerometer is 101.2 mV s2 m-1, and its maximum deviation is 2%). It has seen that the vibration level is very low and the increase is mainly due to components multiple of 50 Hz. In addition we have measured by a suitable microphone and digital transducer (Buel & Kjaer Mod. 4189, PROSIG P8004) the acoustic noise level in the exposure volume. The uncertainty of the measure is 0.2 dB and the sensitivity is 53.6 mV/Pa. This measurement has been done in the bandwidth 10Hz-20 kHz for the only case of the in vivo exposure system, because this can be an additional cause of artifacts in this case. It has been evidenced a reduced increase of acoustic noise, mainly distributed in the range 500-1200 Hz.
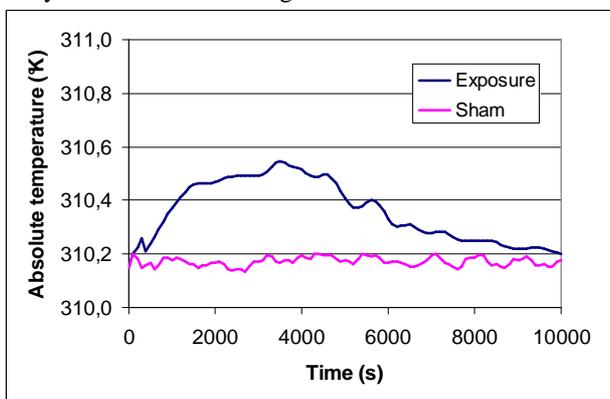

Fig. 9. Temperature in the exposure volume for a current of 6 A - 50 Hz applied for 1 hour (exposure) and room temperature (sham).

VII. CONCLUSIONS

We have designed and realized two different exposure systems for the in vivo and in vitro analysis of the ELF magnetic field effects. The magnetic field is generated by two coils in Helmoltz configuration. The magnetic design has been done using suitable computer codes. In the case of the in vitro exposure system it has been necessary to model the system by a FEM approaches in frequency domain, in order to take in to account the presence of the metallic parts in the incubator, and to minimize the related eddy currents effects, such as magnetic

induction distortion and heating in the exposure volume. The working parameters of the system, magnetic induction, current and frequency are handled and controlled by suitable computed controlled blocks. Experimental test have demonstrated the good uniformity of the magnetic induction in the exposure volume. The waveform of the magnetic induction in the exposure volume is practically sinusoidal in the whole working frequency range of the systems. In addition it is possible to use exposure waveforms different from the sinusoidal ones, such as a sum of different harmonic components. In order to investigate about the influence of the exposure system in the sham system it has been checked the magnetic induction level out of the exposure system. In addition the difference of temperature, vibration and acoustic noise in the exposure system and in the sham system has been verified. We have proved that this difference is very small, and this could guarantee a minimum number of artifacts during the analysis of the in vivo and in vitro exposure.

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