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Incidental/absorbed exposure electromagnetic field energy ratio analysis under laboratory experiment conditions (for Russian- French Immunology Project)

Final Project Technical Report

on the work performed from December 01, 2006 to August 31, 2007

**Federal State Unitary Enterprise State Research Centre – Institute of
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14. ABSTRACT This report results from a contract tasking SRC-Institute of Biophysics as follows: Since early 1950s, the significant number of experimental studies were elaborated to examine health effects induced by acute or chronic exposure to the radiofrequency electromagnetic field (RF EMF). In such studies, the RF EMF characteristics (exposure (dose), essentially) of the irradiation in different biological objects were predominantly identified basing upon the measured intensity of the non-distorted incidental RF EMF. Thus, the RF EMF distribution in the biological object body was not taken into account. Such approach does not give the opportunity to compare the obtained results versus similar data obtained in different foreign laboratories. However, the absorbed energy information (so-called SAR concept application) is very important, when establishing maximum permissible values of RF EMF intensity and harmonizing the international electromagnetic safety standards under the framework of World Health Organization International EMF Project. Under this research, the study of the ratio pattern of calculated exposure dose, when identifying the energy of the incidental and absorbed RF EMF via data of the laboratory experiment, will be elaborated in the framework of Russian-French Immunology Project under the umbrella of the World Health Organization.					
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1. Brief description of the work plan: objective, expected results, technical approach

Since early 1950th, the significant amount of experimental studies of health effects induced by acute or chronic exposure to the electromagnetic field of radiofrequency range (RF EMF) was elaborated in the USSR and Russia. When doing these studies, the assessment of RF EMF characteristics (the exposure dose, especially) was predominantly elaborated basing upon the measurement results of the incidental not-scattered RF EMF intensity [1–3]. The RF EMF biological body distribution evaluation was not widely applied because of both lacks of corresponding computational tools and the purpose aided measurement equipment. It made impossible to compare the results to similar studies done in different foreign laboratories. However, the absorbed energy information is very important to establish the maximum permissible RF EMF levels and to harmonize the international and national standards of the electromagnetic safety under the framework of WHO International EMF Project.

When elaborating the present Project, the investigations of the ratios of calculated incidental/absorbed RF EMF energy at 2,450 MHz frequency were elaborated on laboratory experiment data obtained from Russian-French Immunology Project elaborated under the WHO umbrella [4]. The major purpose of Russian-French Immunology Project was the reproducing 1970–1980 studies done in the USSR to evaluate RF EMF effects in the immune system of experimental animals [5–10]

Major goals of the present study were as follows:

- the assessment of ratios for incidental/absorbed RF EMF exposure dose at 2,450 MHz frequency for experimental animals (rats) under exposure conditions similar to that present in Russian-French Immunology experiment;
- the assessment of feasibility of quantitative dose approach to compare past results versus Russian-French Immunology experiment results;
- the elaboration of basic recommendations for experimental studies of RF EMF health effects taking into account the energy ratio of incidental/absorbed RF EMF energy.

To fulfill the study goals, following tasks were formulated:

- accumulation and critical analysis of literature data (present in the USSR and Russia) devoted to laboratory dosimetry methods applicable for replicated experimental studies devoted to identify the threshold of RF EMF harmful

effects;

- measurements of the absorbed and incidental RF EMF intensity in rat phantom and calculation of absorbed RF EMF (2,450 MHz) applying the mathematical modeling of exposure conditions present in the experimental animal installation used under Russian-French Immunology Project.

2. Methods and, Experiments, Theory etc.

When elaborating the Project, the analysis of experimental animal exposure conditions present in immunology studies elaborated in the USSR to develop RF EMF maximum permissible levels (MPL) was done. Basing upon the summarized data, the experimental installation was assembled to reproduce the exposure conditions present in early experiments. EMF equivalent plane wave power density (PD) measurements were done in the experimental installation room with special attention to PD measurements in the cage placement points.

The biological model design methods were analyzed to have the adequate reproduction of experimental study results to the human being. Taking into account the requirements to the correct biological model, the model was developed to calculate the specific absorption rate (SAR) in the experimental animal as well as the phantom requirements. The calculation results were correlated to phantom measurements, which have provided the opportunity to the PD and SAR ratios for rat in case of the 2,450 MHz EMF exposure.

2.1. Experimental animal exposure installations and RF EMF dosimetry methods of replicated studies

The description of experimental animal exposure installations used in the replicated studies are described in parts by the following papers [3, 5–9]. The general specification for exposure and dosimetry of RF EMF in biological experiment is provided by [1].

1970–1980 experimental exposure was elaborated in anechoic chambers of $2.5 \times 2.5 \times 2.5 \text{ m}^3$; inner walls were covered by the ferrite-based absorber of pyramidal working surfaces of 0.05 m pyramid height. The absorber operational frequency range was 300 MHz – 15 GHz. The absorber reflection factor was 1–3% for the whole operational frequency range. The outer surfaces of the compartment were composed of metal sheets of the electromagnetic shielding. The microclimate conditions were provided by air conditioners. Air temperature was kept at 21 ± 2 °C. Chambers had the inflow-outflow ventilation with additional air cleaning.

The EMF sources were the diathermia apparatus (“Luch-2” or “Luch-58” magnetron generators) with helical antennas. The sources have provided the

continuous EMF generation for $2,375 \pm 50$ and $2,450 \pm 50$ MHz frequencies. The animal exposure was elaborated by the plane elliptically polarized electromagnetic wave (far field zone) from the top to the down. Animals were placed in individual plastic cages (open top) of $0.16 \times 0.20 \times 0.14$ m³. Simultaneously, four cages placed on the foam plastic holders symmetrically to the antenna. The distance between neighboring cages was about 0.15 m. The distance from cages to antenna was 2.20 m. Food and water was not placed in cages at the exposure period.

The EMF exposure was evaluated on mean PD values for the incidental non-disturbed EMF. Different PD values were applied to animals (basically, 5, 0.5 and 0.1 W/m^2). PD values were measured by the measurement set composed of power meter (M3-51 type, for instance) and P6-32 measuring horn antenna (all equipment was made in the USSR). The declared PD measurement accuracy was $\pm 20 \%$.

2.2. The replicated animal exposure installation reproducing past experiment exposure conditions

According to the elaborated analysis and Study Protocol statements, the following exposure conditions of RF EMF were created and maintained in experimental animals (Wistar male rats) [4]:

- whole body exposure to RF EMF;
- the RF EMF exposure direction from top to the down;
- experimental animals placement in the far field zone of RF EMF (plane electromagnetic wave);
- elliptic polarization of RF EMF;
- RF EMF frequency of 2,450 MHz (continuous wave);
- PD was 5 W/m^2 in points of animal placement under “free space” condition;
- exposure regimen of 7 hour per day, 30 days duration;
- air temperature and relative humidity of 20–24 °C and 40–60 %, respectively;
- air ventilation system;
- lighting with high efficiency lamps.

The RF EMF exposure was done inside the shielded anechoic chamber. Walls, floor and ceiling of the chamber were covered by the ferrite-based absorber (“Don” type) with pyramidal (0.05 m height of each pyramid) surface. The operational frequency range of the absorber is 300 MHz – 15 GHz, the reflection factor is 15–20 dB in the whole frequency range. The outer surfaces of the chamber were welding linked steel sheets. The chamber door has the inner steel cover and represents the part of Faraday shell; it can be fixed to the door frame with soft packers of high contact area. The chamber has the inflow-outflow ventilation.

Chamber sizes (L×W×H): approximately 6 m × ~3 m × ~3.5 m.

The natural lighting was absent in the chamber. The artificial lighting was provided by 6 high-effective luminescent lamps of 26 W power and 4,200 K color temperature (day light).

To place the experimental animals, the specialized ring-shaped cages were used (see figure 1). Cage manufacturer is "Atelier Déco Volume" (France). Cages are completely made of dielectric materials (organic glass and PVC). They have ventilation holes. The ‘ring’ has contained 16 experimental animals; one rat per cage. Cages had transparent covers. Each cage was placed on 8 holders (0.18 m height) made of styrofoam.

To decrease the vapor condensation in walls and covers of cages, the diameter of side ventilation holes was increased to 10 mm.

Similarly to replicated experiments previously done in the USSR, the EMF source was the diathermia apparatus of SMV-150-1 “Luch-11” magnetron generator, manufactured by “Electronic medical equipment factory”, Moscow, Russia. The generator creates the continuous electromagnetic oscillations of 2,451 MHz, which was tested by spectrum analyzer, Agilent 8562E, equipped with Rohde & Schwarz HL 562 antenna. The generator has 7 step power control and provides the maximal output power of ca. 150 W on the adjusted load of 50 Ω. To provide the continuous operation (7 hours and more), the timer limiting the exposure time to 30 minutes was switched off.

To create the electromagnetic field, the helical antenna tD5.861.003 of SMV-150-1 “Luch-11” magnetron generator was used (90 mm external diameter). The antenna has provided the RF EMF elliptical polarization.

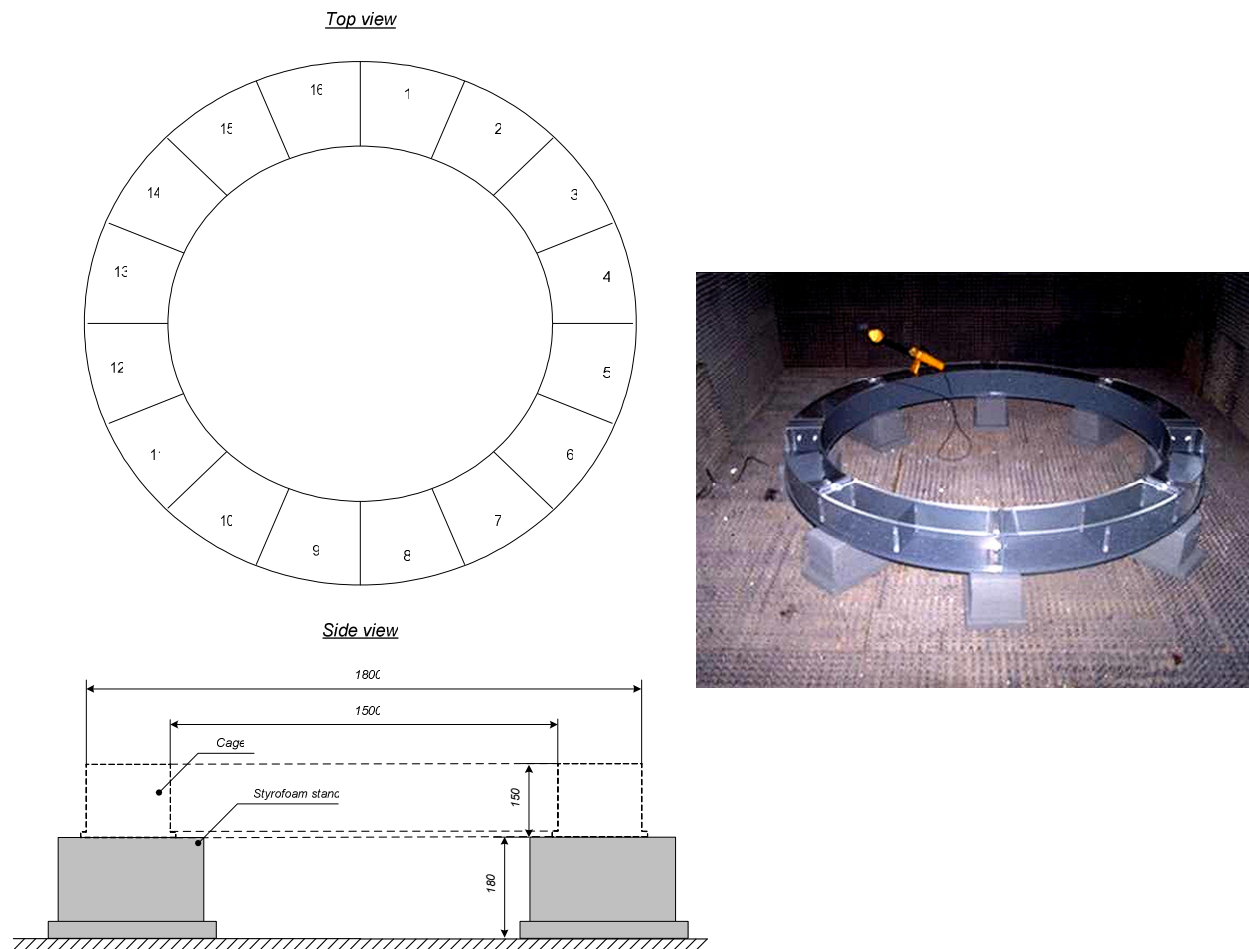


Figure 1 – Scheme and exteriors of the “ring” for experimental animal placement (sketch)

SMV-150-1 “Luch-11” magnetron generator was connected to aerial via feeder of approximately 8.5 m length (coaxial cable with Teflon insulation of RK50-11-21 type (GOST 11326.39–79) and connectors of SR-50-184FV (M) and SR-50-365FV (F) types. Electrical specifications of this cable are given by Table 1.

Table 1 – Electrical specifications of coaxial cable of RK50-11-21 type (GOST 11326.39–79)

Impedance, Ω	Attenuation, dB/m				Permissible power, kW			
	10 MHz	100 MHz	1 GHz	15 GHz	10 MHz	100 MHz	1 GHz	15 GHz
50	0.015	0.054	0.23	0.40	21	5	1.15	0.75

The antenna was fixed on the dielectric holder made of plastic and wood.

Preparation measurements were done before the experiment.

SMV-150-1 “Luch-11” magnetron generator output power measurements at the antenna output were done by bi-directional coupler (-30 dB) and M3-56 power meter. Measurement results are shown by Table 2.

Table 2 – SMV-150-1 “Luch-11” magnetron generator output power and aerial input power measurements

Positions of output power control of the generator	Average generator output power, W	Average aerial input power, W
1	14.9 ± 1.5	8.4 ± 0.9
2	33.3 ± 3.6	19.0 ± 1.9
3	50.9 ± 5.3	28.2 ± 2.8
4	65.9 ± 6.8	36.8 ± 3.9
5	94.1 ± 9.6	51.8 ± 5.4
6	126.2 ± 12.8	71.0 ± 7.3
7	153.7 ± 15.5	85.2 ± 8.7

Measurements have demonstrated that measured SMV-150-1 “Luch-11” magnetron generator output power corresponds to technical specification and the measured power attenuation in the aerial feeder does not exceed 1.8 times (2.5 dB).

The amplitude modulation at SMV-150-1 “Luch-11” magnetron generator output was done by bi-directional coupler (-30 dB) and detector head connected to Nihon Kohden VC-10 oscilloscope. Measurements have revealed the parasite amplitude modulation of the output signal. The modulating signal frequency is 100 Hz. The insufficient filtration and anode current stabilization of magnetron of SMV-150-1 “Luch-11” generator were concluded to be the cause of such modulation.

Mean PD values were done by broadband Wandel & Goltermann EMR-20 meter fiber-optically connected to the personal computer. The meter is equipped by isotropic E-field sensor (type 8.1) represented by 3 electrically small dipoles loaded to diodes. Measured frequency range is 0.1–3000 MHz. Measurement limits of mean PD are 0.0017–1700 W/m². Basic accuracy of PD measurement is ± 2 dB (PD > 0.0106 W/m²).

All preparations and exposure operations were elaborated by specialists of Test Laboratory of Centre for Electromagnetic Safety certified according to ISO/IEC 17025 standard on "General requirements for the competence of testing and calibration laboratories" (certificate No. GSEN.RU.TsOA.213 valid until 31 January 2010 and issued by State Sanitary and Epidemiological Service of Russian Federation).

2.3. SAR assessment

2.3.1. Selection of model for experimental studies of RF EMF health effects

The theoretical justification of maximum permissible levels (MPL) for the electromagnetic field is based upon the experimental tests in animals, which has provided the assessment of organism reactions under specific exposure conditions. The experimental model issue and followed extrapolation to human is more actual, because of frequent practices of long-term EMF exposure of human, comprehensive human exposure to EMF of non-thermal intensities. The experimental EMF exposure has to simulate hygienically significant conditions of human contact to EMF.

To have the correct extrapolation of biological model to human, the similarity principle should be adequately followed for the experimental model and EMF exposure attempted to reproduce. The similarity of EMF health effect simulation is determined by both physical parameters of the object and its biological nature. The human extrapolation challenge for animal experiments should involve adaptation, compensatory and recovery abilities of the organism.

Basing upon the many year experience of studies elaborated by the Institute of Biophysics, one can conclude that the similarity principle should be realized via following similarities: morphological and physiological characteristics of human and selected model, metabolism, critical organs and systems responding to the exposure and following reproducibility of the symptoms. Besides, it is necessary to consider the time progress of other pathology development in human and used animal. Thus, when simulating any processes progressing in time (rate of the process development, kinetics and reparation parameters, for instance), it is necessary to determine the grade of time criterion similarity of the model, which can be done through corresponding factor calculation [11].

When designing the biological model for future human extrapolation of experimental results, it is important to understand that organism is the opened, dynamic, self-regulating and self-maintaining system, which, nevertheless, is often considered as quasi-static approximation for the process description. The permanent metabolism and environmental exchange is the way to maintain equilibrium stationary state: atomic and isotopic content, micro- and macrostructure of all organs and tissues, metabolism rates and their persistent correlation to all processes in the organism provide the stable homeostasis of the biological object [12]. The peculiar feature of objects used to investigate EMF health effects, is the obligatory accountancy to biotropy of examined factor.

Methods applicable for EMF exposure models can be separated into two groups. The first group is composed of rather formal models of experimental data extrapolation to human, which consists in the comparison of some animal health indices to those in human, in case of EMF exposure of the same parameters. The character of specific reaction of the systemic function of the organism, its response expressiveness to the EMF exposure of specific parameters is determined but the general biological regularity of different early and late effects induced in different species for the same exposure power is neglected.

The second group models are based upon the quantitative regularity assessment and should take into account general regularities of inter-species differences related to EMF exposure as well as regularities of damage and recovery in different animal species and human.

The animal species peculiarities are important for the mammal ability to regulate the additional load. The rat metabolism intensity can be increased for 3 times, when changing the rest to the active state, whereas the human (young male) can increase metabolism for 8 times. The metabolism intensity range for different physical activities is also the assessment of thermoregulation range. When assessing the electromagnetic energy effect in thermoregulation abilities, the lowest SAR level should be assessed, which level results to activation of thermoregulatory and other physiological reactions.

According to Russian researcher concept, to specify the features of damage at different levels of organism organization, it is necessary to apply different biological criteria corresponding to each organizational level. To evaluate the molecular damage, criteria applicable to vital biochemical systems are suitable; the cellular level damage assessment needs to use knowledge of spatial structure of most important cellular structures; the tissue level should be applied by physiological and morphological features of the tissues as well as their sensitivity and renovation periods. Processes of this level are integrated and manifested via the peculiarities of damage at the whole organism level. To specify the damage at *whole* organism level, it is necessary to apply criteria for critical systems most affected from specific factor as well as for regulating systems (like nervous-endocrine and immune systems) which regulate physiological processes and maintain the internal stability of organism and its reactive abilities [11].

The selection of criteria and assessment methods is of multi-level organizational character including physiological, biophysical, neuropsychological and societal levels. Usually, the basic level is composed of physiological parameters, clinical laboratory counts and biophysical indices. The higher level of organization includes supreme nervous activity functions including neurodynamic reactions,

abilities for organized activities and inter-personal interactions. Obviously, the context of the present study relates to basic level processes.

Basing upon the concept of exogenic energy transferred to the organism exposed to RF EMF, the particular modeling issue of EMF health effect examination in animals is the equivalence of exposure conditions for human and experimental animal.

Obviously, the correlation of PD and SAR is most important for biological species of different body sizes and for different frequency ranges. This information is also essential, because PD values are easy to measure in the experiment, whereas SAR assessment requires additional calculation and mathematical simulation. It is important for studies directed to MPL justification for EMF to get the reliable practical implementation of the resulted assessment, which requests the reliable PD assessment.

The next stage of modeling is the assessment of differences in rates of biological damage and recovery resulted from the exposure, which would determine the exposure time differences (with same SAR values), to have the similar response in human and animals. Inter-species differences related to EMF exposure resistibility should be evaluated.

However, the data analysis demonstrates that available clinical and experimental materials related to EMF health effects is not clearly sufficient to manage all challenges of the modeling for EMF health effect experiments [13].

One of fundamental effects of RF EMF is the absorption of field energy accompanied by the heat release. The increase of biological object temperature resulted from EMF exposure can determine the functional changes. However, this rough index of living object functioning is applicable for relatively short time EMF exposure of moderate and high (thermal) intensity. The heat release can be well measured and forecasted in such cases. It was also found that resulted health effects are similar to that resulted from the traditional heating.

However, the significant amount of experimental materials on health effects of low (non-thermal) intensity EMF exposure does not have explanations from thermal hypothesis, which justifies the investigation of other possible mechanisms of EMF health effects. The obtained quantitative differences can be explained by significant differences in dynamics and volumetric dissemination of the excessive heating of biological tissues exposed to EMF, if compared to effects induced by traditional heating. Mammals used for experimental studies have the well developed thermoregulation system via the blood circulation rapidly re-distributing the heat in the body and its release. Some tissues are

thermoregulated passively because of remote position against blood vessels (inner media of the eye-ball and some others). The volumetric heating of such tissues by radiation exposure nearly to threshold can result to several tenth to several degrees increase, which is not indifferent for the organism [13, 14].

The EMF exposed animals (Wistar rats) have the complex spatial and volumetric shape and significant heterogeneity of electro-physiological parameters of the body. Therefore, in some specific combinations of external field parameters, geometric and electro-physiological parameters of the exposed object, the “hot spots” are possible (local elevated EMF absorption concentration). Thus, the application of body averaged SAR is not the exact assessment of EMF exposure and results to the additional uncertainty, when extrapolating results to the human.

The above mentioned facts follow to the conclusion that the assessment of absorbed specific power is most important, because the absorbed energy induces EMF effects without any dependence from the effects in the exposed body heat balance.

In case of the EMF exposure, the partial reflection of the incidental wave is present as well as its penetration inside the exposed object with following absorption (of resonance or non-resonance type) during the attenuated propagation of the electromagnetic wave in the dielectrics. The modeling is definitely complicated by the complex composition of the exposed object composed of different organs and tissues with different electrical features and comprehensive interaction mechanisms (regulation, self-regulation and feedback) to maintain homeostasis. Therefore, to get the qualitative and quantitative evaluations of EMF propagation in the body, it is necessary to calculate the volumetric distribution of SAR in model tissues of sufficient detalization; the calculated results should be tested by phantom measurements. The phantom should be well described in details to confirm or reject the computational regularities.

When determining SAR, several types of models are used (both computational models and phantoms):

1. Homogeneous model. Most simple model; averaged electric parameters of tissue are used.
2. Heterogeneous model. It reflects the internal structure of the body more precisely with the extreme phantom equivalent of phantom represented by the animal cadaver.

3. Heterogeneous model with vital functional activities (including regulation). Most complex model for mathematical realization; it can not be realized as the phantom.

If applying to the present study, the results obtained for correlation factor of PD and SAR under model calculation and rat phantom measurements can be applied to solve the inverse task of EMF exposure simulation under experimental conditions. It is necessary because of the fact that the equivalence of EMF exposure of model versus human can be reached by the equivalence of averaged electric field flux values inside the body, as well as PD; it cannot be done via the equivalence of PD in the point of future placement of the animal. Therefore, to get the equivalent exposure conditions under the experiment, it is necessary to use EMF of different extra-body values; these values are determined by species peculiarity of the exposed animal including shape and size of the body, electric properties of tissues, and orientation of the body in the field and some other conditions.

2.3.2. Computational model for SAR assessment

To calculate SAR basing upon data on EMF frequency and polarization, type of emitting aerial, emitted power, general geometry of the installation etc., the electro-physical model of the experiment was created. The rat body was represented by the simple heterogeneous structure. 5 types of tissue were identified for the anatomical details.

Figure 2 provides two cross-sections of the model (digital phantom) – top view (a – middle; b – at the spine level). The plane wave is directed from the top, so the Pointing vector (PD) is perpendicular to the model surface and the electric field power vector is parallel to the long axis of the model. The computational voxel size is $1 \times 1 \times 1 \text{ mm}^3$. Total voxel number is 149,469.

Table 3 provides electrophysiological features of the rat model [15].

Table 3 – Electrophysiological features of the rat model

Tissue	Color code	Relative permittivity	Conductivity, S/m	Wave length of 2,450 MHz in tissue, mm
Brain	Dark gray	36.2	1.2	20
Liver	Red	43	1.69	18
Dry skin	Yellow	38	1.46	20
Fat	Blue	5.28	0.1	53
Bone	Grey	11.38	0.39	36

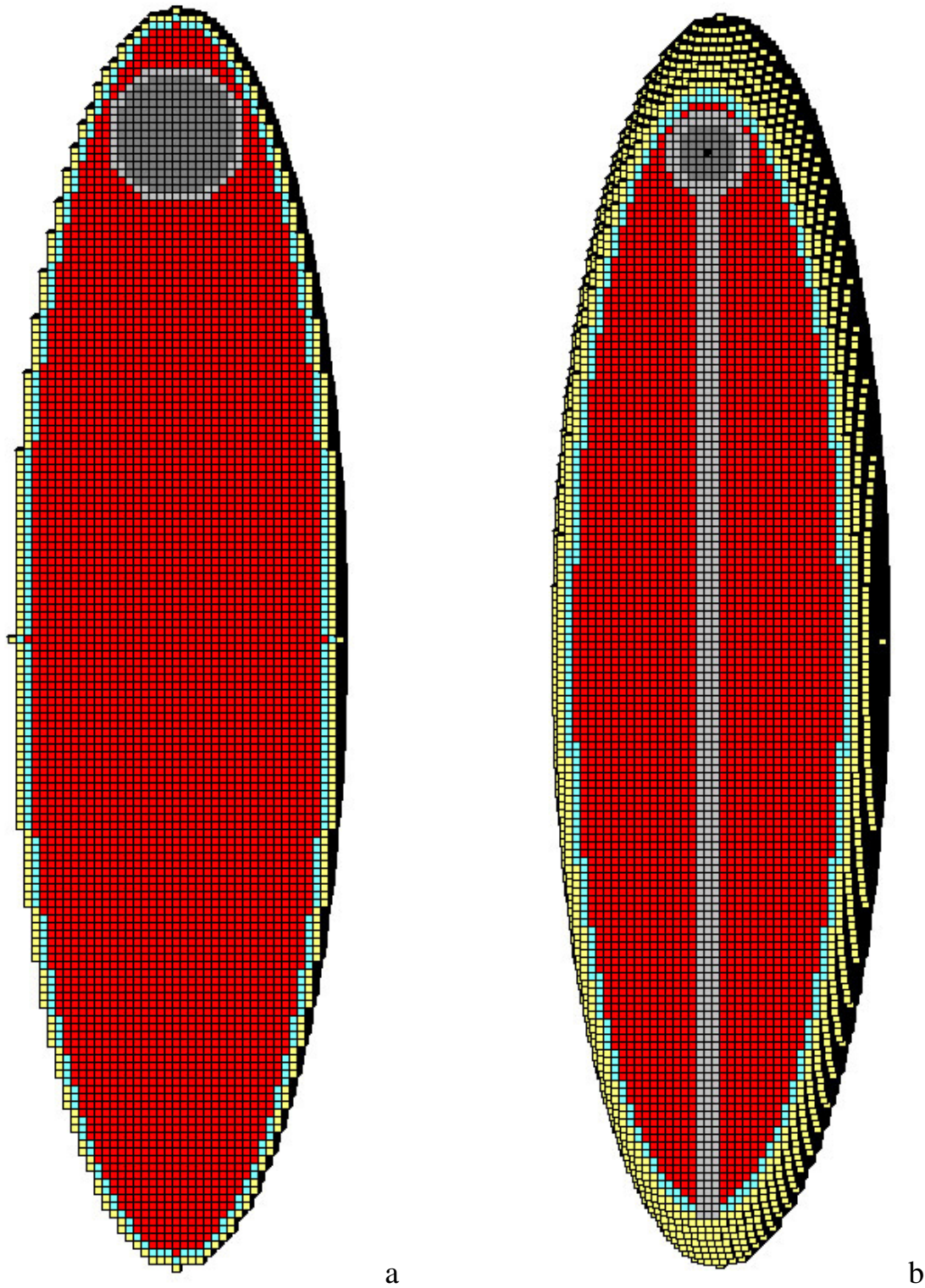


Figure 2 – Rat model cross-sections (top view)

Thus, the condition of dielectric simulation of digitizing step of less than $1/5$ of the wavelength (in dielectric) is fulfilled.

SAR calculations (averaged in voxel and body) were done using non commercial FDTDpro software (Russia). This software uses the Finite Difference Time Domain (FDTD) method to calculate the electric field strength inside the matter.

2.3.3. SAR assessment phantom model

Basing upon the literature references published in Russia and abroad, the experimental test bench was designed, manufactured and calibrated (under “free space” conditions) to evaluate the absorption of EMF energy in biological media [16, 17].

The test bench consists of E-field experimental probe and homogeneous phantom of experimental animal body (Wistar male rats).

The E-field probe with diode detector provides measurements of RMS values of the electric field strength inside the liquid simulating the biological tissue. Quasi-constant voltage at probe output was measured by Mastech MY-68 electronic voltmeter. The probe calibration data at 2,450 MHz obtained by “TANO” laboratory are shown by Table 4.

Table 4 – The E-field probe calibration data at 2,450 MHz

Established value of E, V/m	Established value of E^2 , V^2/m^2	Measured voltage at probe output U, mV
1.0±0.1	1.0±0.2	1.5±0.1
1.5±0.2	2.3±0.5	3.4±0.1
2.0±0.2	4.0±1.0	5.8±0.2
5.0±0.6	25.0±6.0	32.5±1.3
7.0±0.8	49.0±11.8	53.8±2.2
10.0±1.2	100±24	104.0±4.2
15.0±1.8	225±54	218.7±8.7
20.0±2.4	400±96	388±16
30.0±3.6	900±216	861±34
40.0±4.8	1600±384	1523±61

The rat body homogeneous phantom contains the tissue equivalent liquid of 50% water solution of diacetine (glycerol diacetate, E1517) [18]. Its electrical properties (at 2,450 MHz frequency) correspond to muscular tissue ones ($\epsilon_r' = 40$, $\sigma = 1.9$ S/m at 20–22 °C temperature). The shell of the homogeneous phantom is made of polyethylene of 0.3-0.5 mm thickness. Maximal sizes of phantom are: 120 mm length, 50 mm radius, about 0.22 kg weight. These parameters approximately correspond to sizes and masses used under Russian-French Immunology Project (see Figure 3).

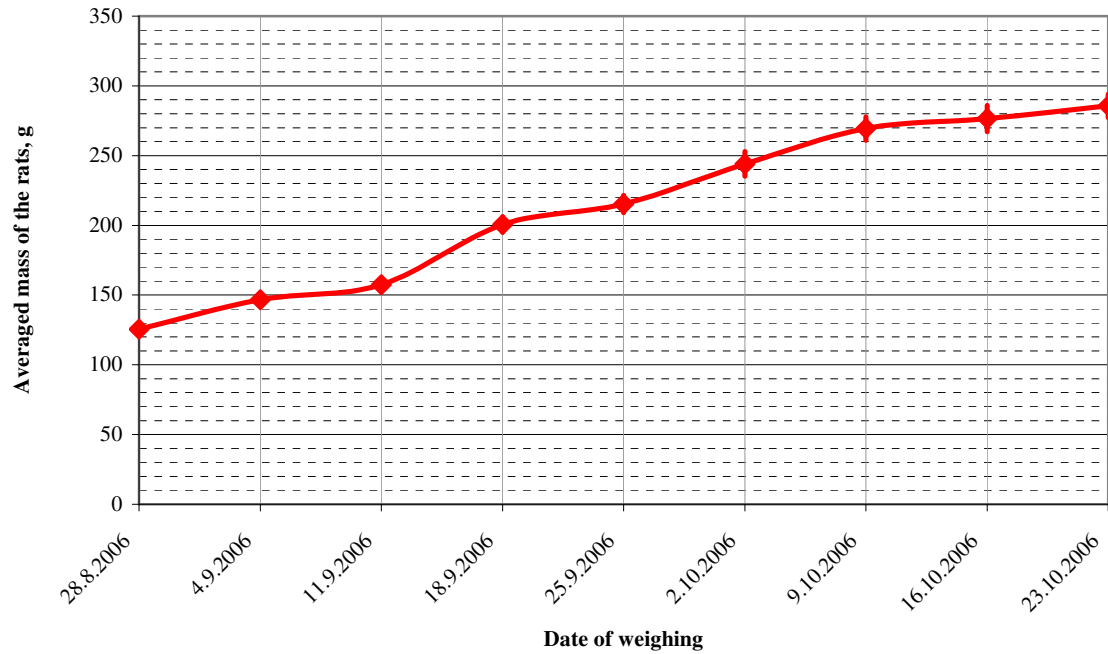


Figure 3 – Body mass changes of experimental animals (Wistar rats) at the time of experiment

Applying E-field experimental probe, the electric field strength measurements were done and SAR values were calculated for points shown by Figure 4.

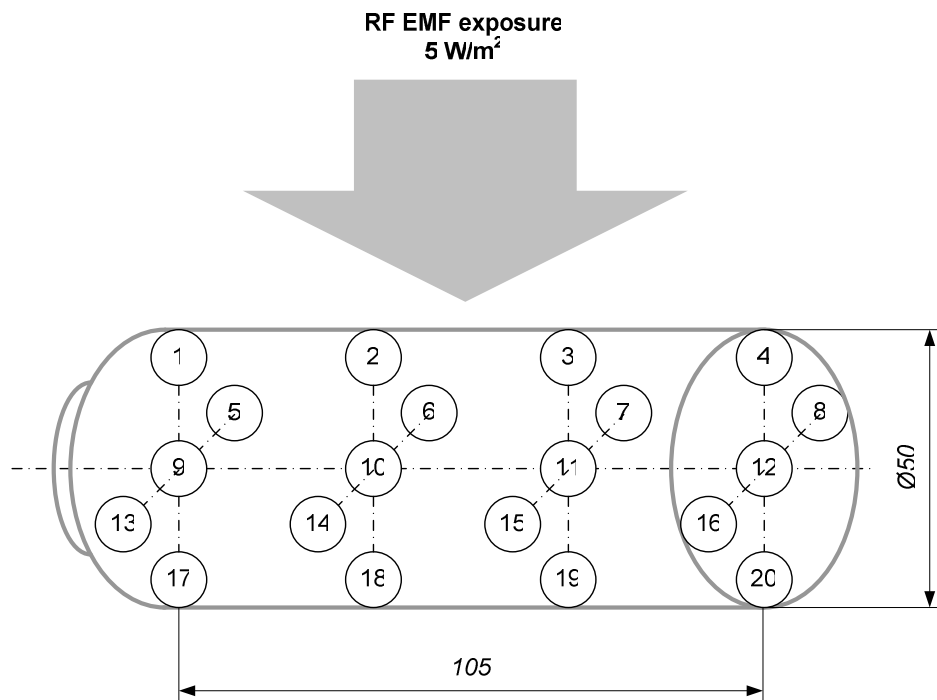


Figure 4 – Measurement points in rat phantom

SAR was calculated as follows [18]:

$$\text{SAR} = \sigma \cdot \frac{E^2}{\rho},$$

where σ is the electric conductivity of the tissue equivalent liquid, S/m; E is the RMS electric field strength value, V/m; ρ – specific density of the tissue equivalent liquid, kg/m³.

In general, the phantom was exposed under conditions similar to experimental animal exposure: elliptic polarized EMF of 2,450 MHz frequency, far field zone, mean PD values are 5 W/m² under “free space” conditions.

3. Results

3.1. PD measurements in the experimental installation

Measured background integral mean PD values inside anechoic chamber did not exceed 0.0017 W/m² at 0.1–3000 MHz.

After the preliminary measurements a computational assessments of mean PD values under “free space” conditions, the aerial was placed at 2.35 m height above the chamber floor level. The output power control of SMV-150-1 “Luch-11” generator was placed in “6” position. To establish the cage placement area, the chamber was partially mapped for “free space” PD at 0.22 m height from the floor level. Mapping results are shown by Figure 5.

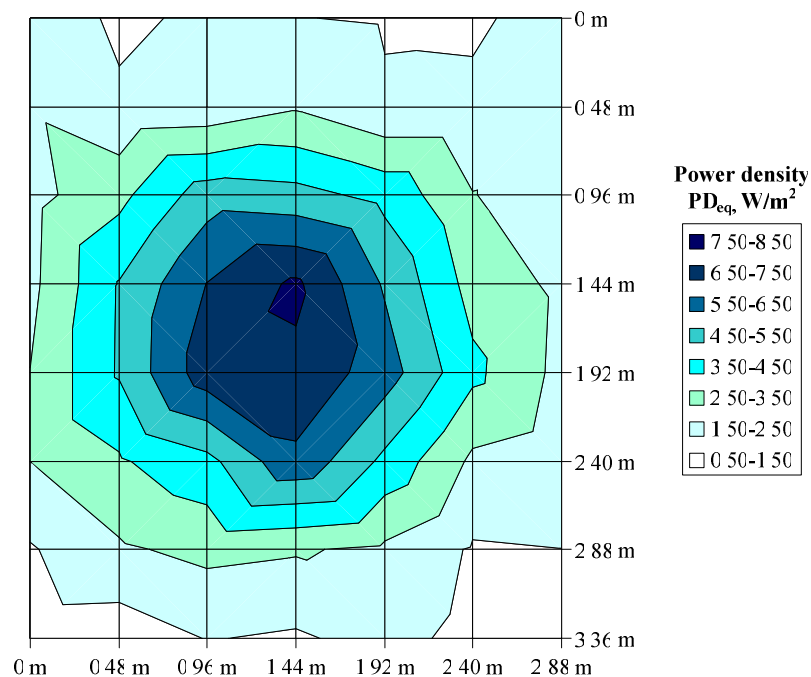


Figure 5 – PD mapping results inside the anechoic chamber under “free space” conditions

The scheme of ‘ring’ placement and general view of the installation are shown by Figures 6 and 7, respectively

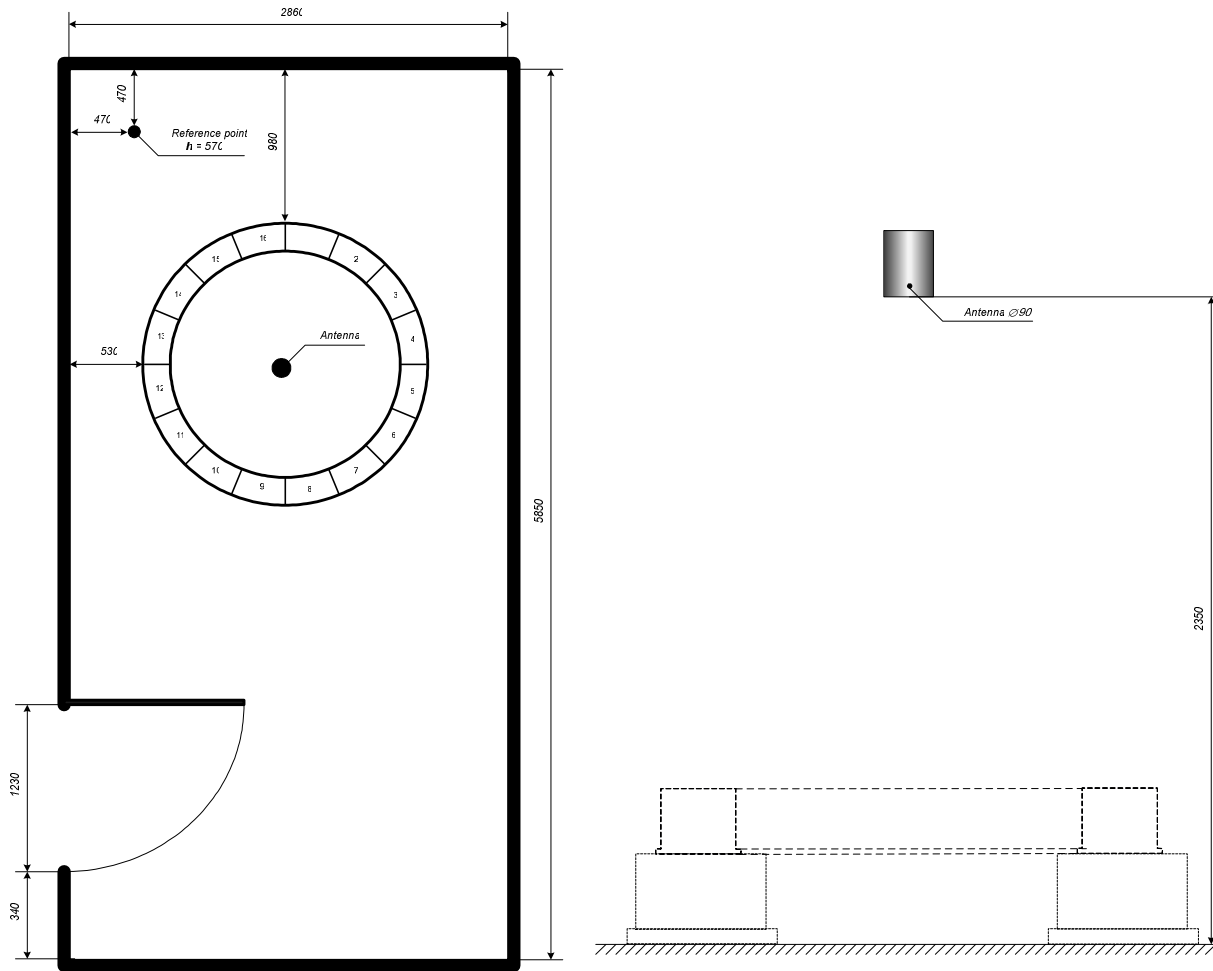


Figure 6 – The scheme of ‘ring’ placement (sketch)



Figure 7 – General view of the installation

When the cage area was established, mean PD values the plane were measured in points of geometrical centers of cages. Measurements were done at 0.22 m height from the floor under “free space” conditions (see Figure 8). Measurement results are given by Table 5 (cage numbers in accordance to Figure 6).

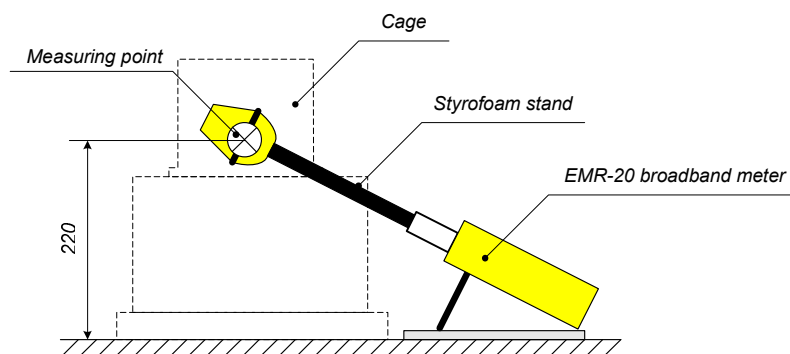


Figure 8 – Measurement conditions for mean PD values in points of geometrical centers of cages

Table 5 – Measurement conditions for mean PD values in points of geometrical centers of cages at the height of 0.22 m under “free space” conditions (including absolute accuracy of measurement)

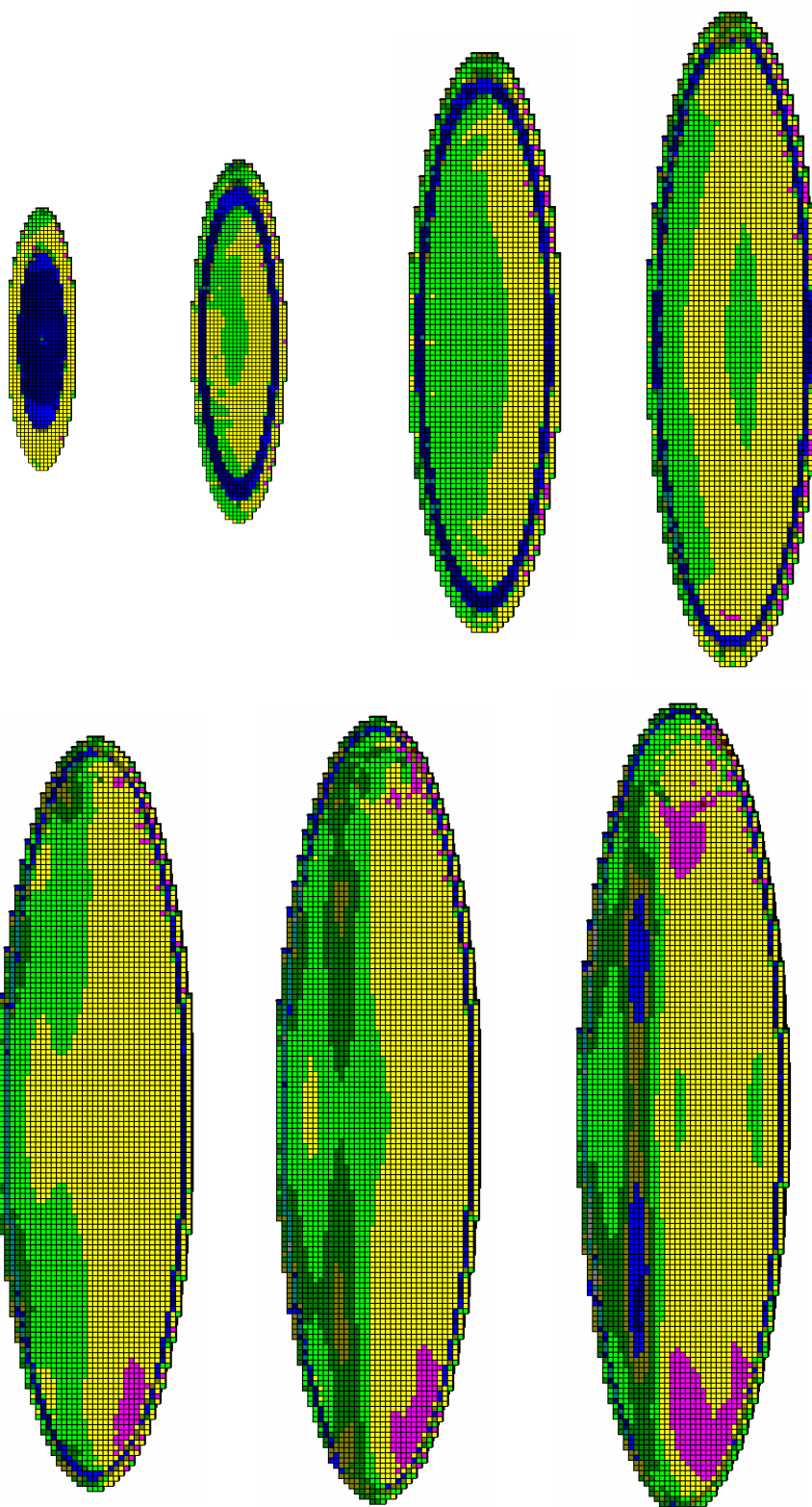
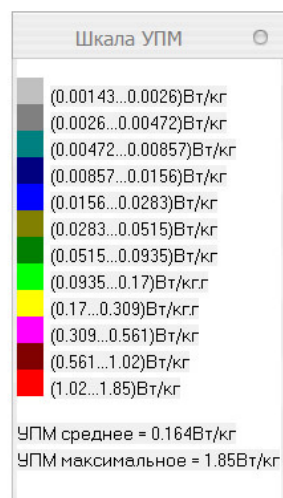
Measurement point	PD, W/m ²
Cage 1	4.93 ^{+2.86} _{-1.82}
Cage 2	4.80 ^{+2.79} _{-1.78}
Cage 3	4.66 ^{+2.7} _{-1.72}
Cage 4	5.09 ^{+2.95} _{-1.88}
Cage 5	5.06 ^{+2.93} _{-1.87}
Cage 6	4.97 ^{+2.89} _{-1.84}
Cage 7	5.14 ^{+2.98} _{-1.90}
Cage 8	4.68 ^{+2.72} _{-1.73}
Cage 9	4.58 ^{+2.65} _{-1.69}
Cage 10	4.76 ^{+2.76} _{-1.76}
Cage 11	4.75 ^{+2.75} _{-1.76}
Cage 12	4.87 ^{+2.83} _{-1.80}
Cage 13	5.61 ^{+3.26} _{-2.08}
Cage 14	5.93 ^{+3.44} _{-2.19}
Cage 15	5.09 ^{+2.95} _{-1.88}
Cage 16	4.29 ^{+2.49} _{-1.59}
Reference point	1.55 ^{+0.90} _{-0.57}

Average PD value in cage sections was $4.95^{+2.87}_{-1.83}$ W/m².

3.2. SAR calculation results

Figure 9 provides SAR distribution calculation results in selected cross-sections of the phantom. The EMF is directed from the right. Section sequence is from the far to the near ones.

Body averaged SAR value is 0.16 W/kg, maximal SAR value is 1.85 W/kg. Maximum SAR values (from 1.02 to 1.85 W/kg) are the point findings and can be the computational mistakes. These phantom voxels are in the head and rear parts of the phantom at the “liver (muscles) – subcutaneous fat” border line and practically do not involve the brain. Voxels of 0.56–1.02 W/kg look like rather big areas in the head and rear parts of “ellipsoid”; they have junction in central sections near the long central axis. These voxels practically cover the whole brain (central part, essentially) and rear part.



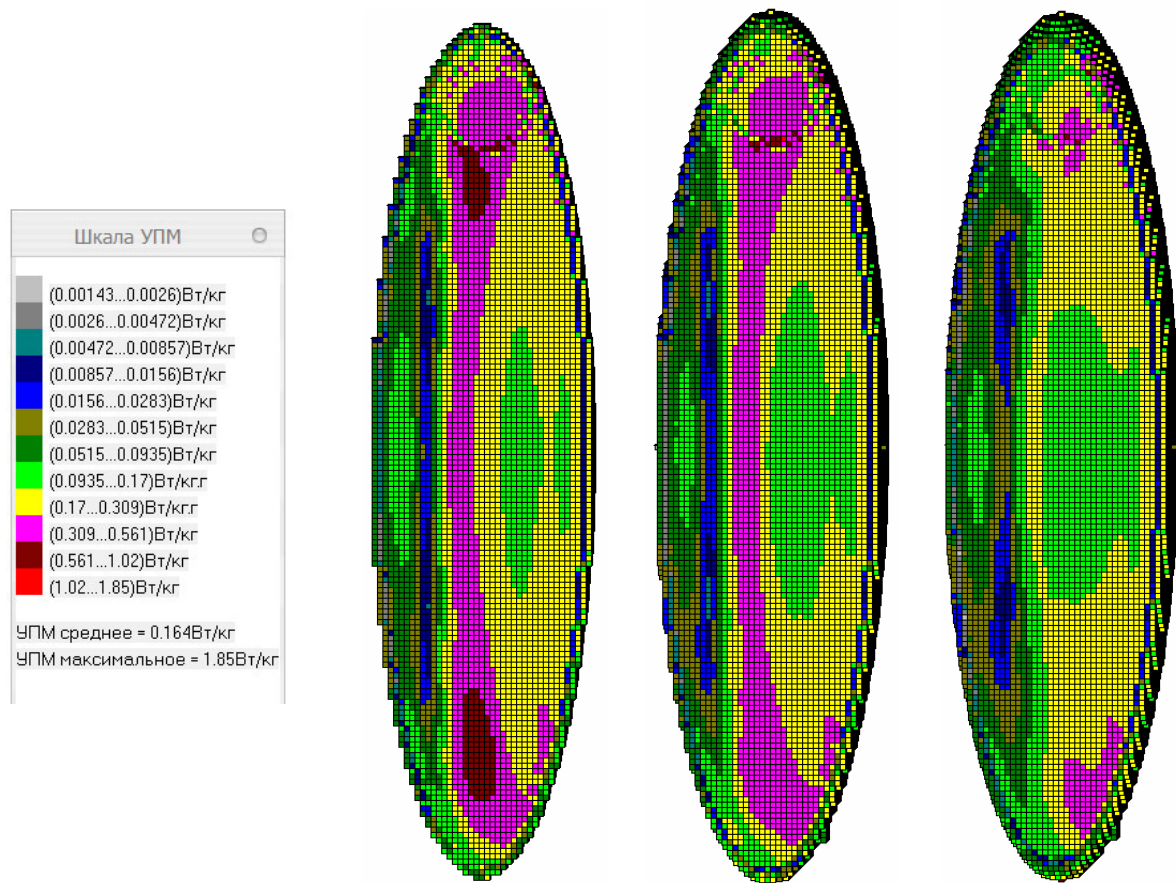


Figure 9 –SAR value distribution in the rat model

3.3. SAR measurement results in phantom

The measurement results for quadratic electric field strength and calculated SAR values are provided by Table 6.

Thus, Table 6 concludes that phantom averaged SAR value is 0.18 W/kg. The comparison of this value to calculated averaged SAR (0.16 W/kg) indicates to the result coincidence with $\pm 10\%$ accuracy.

3.4. Evaluation of SAR to PD ratio

The present study provides the PD measurement results under RF EMF exposure of rats (200–250 g body mass) to plane elliptically polarized EM wave under “free space” conditions as well as the SAR assessment under the same experimental conditions (see 3.1–3.3 above). Basing upon these data, the ratio of body averaged SAR_{avg} , W/kg, and PD of incidental non-disturbed EMF, W/m^2 , is:

$$SAR_{avg} = 0.033 \cdot EFP$$

Previously, when SAR was assessed applying calorimetric method, similar results were obtained for SAP/EFP ratio ($\text{SAR}_{\text{avg}} = (0.026 \div 0.028) \cdot \text{PD}$) for similar exposure conditions and PD of 100–300 W/m² [3]. Thus, the obtained results can be considered as confident and used to assess results and exposure conditions for retrospective analysis of studies elaborated in 1970–1980th in the USSR to establish MPL of RF EMF.

Table 6 – The measurement results for quadratic electric field strength and calculated SAR values for rat phantom

Measurement point number (see Figure 4)	Measured value of E^2 , V ² /m ²	Calculated SAR value, W/kg
1	143	0.25
2	116	0.20
3	110	0.19
4	141	0.25
5	94	0.16
6	62	0.11
7	70	0.12
8	84	0.15
9	302	0.53
10	88	0.15
11	78	0.14
12	241	0.42
13	77	0.13
14	81	0.14
15	73	0.13
16	78	0.14
17	69	0.12
18	36	0.06
19	28	0.05
20	77	0.13

4. Conclusion

The elaborated study has resulted to the evaluation of incidental/absorbed EMF energy ratio at 2,450 MHz for small laboratory animals of 200–250 g body weight, which ratio is $\text{SAR}_{\text{avg}} = 0.033 \cdot \text{PD}$.

The obtained result can be used to indirectly assess results and exposure conditions for retrospective analysis of studies elaborated in the USSR to establish MPL of RF EMF.

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