DESIGN, INSTALLATION AND STANDARDIZATION OF HOMOGENOUS MAGNETIC FIELD SYSTEMS FOR EXPERIMENTAL ANIMALS

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Abstract: In this study, the experimental studies on the design, installation, and standardization of magnetic field systems suitable for animal experiments which are currently used in researches on "Biological Effects of Magnetic Fields" in the Bioelectromagnetic Laboratory of Gazi Biophysics Department have been presented. Helmholtz coils' pair was selected as the system to supply a homogeneous magnetic field. System was composed of two coils with 42.75 cm diameters consisting of 154 loops each made from insulated copper wires with a distance of 21.375 cm between them, and positioning them parallel each other with centers in the same direction. Specifications of system were tested experimentally with measuring the changes in the field intensity at horizontal, vertical, and angle-dependent distances from the axis of the system. From these measurements, the area that the field within the coil system changed the least was found; and the dimensions of the cage placed were determined. Homogeneity and temperature characteristics were determined. After design and installation of "Homogeneous Magnetic Field System" was completed, two additional systems were installed and the total number of systems was increased to three to the number of animals exposed to ELF magnetic fields. Standardization was ensured by repeating the measurements of homogeneity and temperature for all the three systems.

Introduction

After the Second World War, background levels of Electromagnetic (EM) fields in urban domestic and industrial environments have increased exponentially in parallel with growing technology and electricity consumptions. This increase has prompted the evaluation of effects of electromagnetic fields (EMFs) on biological systems. The number of investigations about the biological effects of EM fields has been carried out due to the growing public concerns. In many epidemiological and laboratory studies, low frequency EM field exposure have been linked to increased cancer risk [1-5].

Biological effects of EMFs have been investigated in Bioelectromagnetics Laboratory in Biophysics Department of Medical Faculty. In this study, design and construction of the magnetic field exposure system, which is suitable for animal experiments, have been planned in our laboratory.

The best-known homogeneous magnetic field sources in the electromagnetic theory are solenoid and Helmholtz coil systems. In the literature, it is noticed that various EM field systems have been developed for the exposure of humans and experiment animals, and organs, tissues, and/or cell cultures for using in bioelectromagnetic studies. In general, these systems are developed according to the basic principles of solenoid or Helmholtz coil systems. It is seen that experiment animals (guinea pigs, rats, mice, etc) are exposed to EM fields as a whole are in coil pairs constructed in circular, square, or rectangular shapes [5-12]. In the study of Shigemitsu et al., it has been reported that the amount of deviation of the B field in the cage of the experiment animal is less than 2% in an EM field system created by square Helmholtz coil pairs (Modified Helmholtz coils) [7].In bioelectromagnetic studies, systems called experiment modules that consist of more than one coil pairs that are suitable for working on more than one animal cage have also been used. It has been reported for similar experiment modules that the amount of deviation from the B field targeted in areas that the cages of animals have been placed are approximately in levels of ±10-15 % [6,8].

In this study Helmholtz coils' pair has been chosen for homogenous field configuration. Following design procedure, pair of circular coils of either 42.7 cm diameter and 21.375 cm clearance was constructed by insulated copper wire and made of 154 turns. Sinusoidal current of frequency 50 Hz was generated by the specially designed variable transformer, 2.7 kVA in power.

Variations of magnetic fields obtained from coils have been measured in the vertical, horizontal and two different angular directions, 30 and 45 degrees, in the centre of the Helmholtz coils in order to determine field homogeneity. Dimensions of animal cages, which have been used between the coils during experiment and homogeneity percentage in this cage, have been determined. The heat characteristics of experimental system, which has been worked continuously during 8

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hours, were obtained by temperature measurements in the room and between the coils. Temperature changes in the animal cage were calculated by taking a difference between room and coil temperatures.

Three exposure systems which is suitable for animal experiments and harmonisation studies between these systems have been realized under working conditions.

Materials and Methods

A homogeneous magnetic (B) field throughout the axis is obtained with the "Helmholtz Coil Pair". Homogeneity of the magnetic field can be shown mathematically by the equality of the first and second derivatives of B field expression at the midpoint of an axis of the coils to zero.The point where the first and second derivatives of the B field are equal to zero (z = r/2) shows that a B field of high homogeneity can be obtained around the axis in the centre of the system.

Magnitude of the B field generated in the centre of a Helmholtz coil pair can be found with the formula,

$$B = \frac{8N\mu_0 I}{5^{3/2} r} \approx 0.72\mu_0 \frac{NI}{r}$$

where N is the number of turns, r is the radius and I is the current flow.

Two coils' pairs with different sizes (Prototype I and Prototype II) were wrapped to obtain homogeneous magnetic field. Electrical characteristics of the coils were measured and after the determination of the consistency of the measured values with the designed values, Prototype II suitable for animal experiments was constructed. In this study pair of circular coils of either 42.75 cm diameter and 21.375 cm clearance was constructed by insulated copper wire and made of 154 turns. The electrical parameters of each coil were resistance, 1.2 ohms (Ω); and inductance, 19.6 milliHenry (mH) (Figure 1). The magnetic field generated by the coils was classified as vertical field (field lines perpendicular to the bottom plane of the animal's cage). Three coil pairs with these characteristics were prepared in order to minimize the level of being affected of the animals from seasonal conditions and circadian rhythm changes and to perform the study under standard conditions, consequently, to be able to work on as much animals as possible. The names, System I, System II and System III will be used in this manuscript for these coil pairs. Specifications of the coils and electrical properties of the systems are given in Table 1 and Table 2 respectively.

Coils were fed with VARIAC (Variable Transformer) with a power of 2.7 kVA. Since the output voltage of VARIAC could be reduced as low as about 3 Volt under load, it was possible to obtain magnetic fields with rather low intensities, and the magnetic field limits of the systems constructed were determined to be 0.4 G - 100 G. Magnetic field was measured with a Hall-Effect Gaussmeter. Frequency and waveform of the magnetic field were monitored over an oscilloscope.

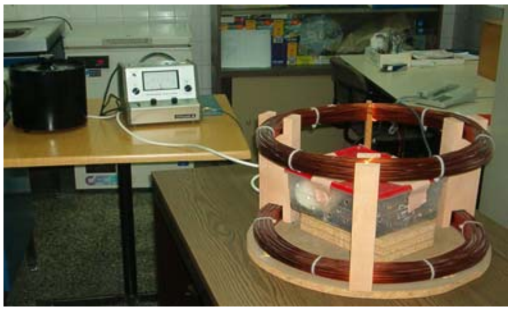

Figure 1: Helmholtz coils pair

Homogeneity Measurements

Measurements of the B field created in the axis centre of the magnetic field systems according to the distance in horizontal, vertical, and angular directions, and the change of the magnetic field intensity within the volume created by the Helmholtz coil pair was determined. Reference system used in homogeneity measurements is given in Figure 2.

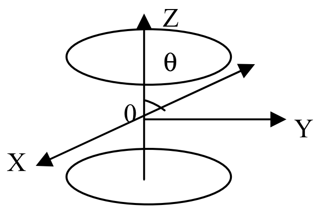

Figure 2: Reference system used in homogeneity measurements

Table 1: Specifications of Helmholtz coils

Resistivity ρ (Ω.m)	1.72×10^{-8}
Conductor diameter (mm)	2.2
Number of turns - N	154
Inner diameter - a (mm)	400
Outer diameter - b (mm)	455
Average diameter - r (cm)	21.375
R (Ω)* / coil	0.936
R_T (Ω)* / coil pair	1.872

*) calculated value

Table 2: Electrical properties of System I, System II and System III

	SYSTEM I	SYSTEM II	SYSTEM III
R_T (Ω)/coil pair	2.40	2.57	2.51
L_T (mH)/coil pair	39.15	39.69	39.98
Voltage (V)	25.35	24.90	25.10
Current (A)	2.50	2.50	2.50
$B_{measured}$ (G)	16.40	16.60	16.50
$B_{calculated}$ (G)	16.30	16.30	16.30

Magnetic field B was found to be 19.95 ± 0.37 G as a result of 23 measurements performed in positive and negative directions on the axis z according to the distance on the axis of the coils (θ=0°) (Table 3). Amount of deviation of the magnetic field was found to be an average -2.83 %. To System I, 48.6 Volt and 3.78 Ampere was applied, and the change in the intensity of the 20.5 G magnetic field created in the axis centre was determined with measurements.

It was found that the average magnitude of the magnetic field in the space created by the coils, B = 18.05 ± 3.60 G by measuring the change in magnetic field intensity in 22 points in +y direction (Table 4), and deviation from the magnetic field intensity in the axis was found to be an average of -11.94 %.

Table 3: Deviations of B field in the vertical (θ=0°) direction (Bgeo=0.33G)

Distance on **z-axis** (cm)	B (Gauss)	Deviation (%)
+ 11.25	19.6	-4.40
+ 10.25	19.7	-3.90
+ 9.25	19.9	-2.90
+ 8.25	20.0	-2.44
+ 7.25	20.0	-2.44
+ 6.25	20.0	-2.44
+ 5.25	20.0	-2.44
+ 4.25	20.1	-1.95
+ 3.25	20.1	-1.95
+ 2.25	20.2	-1.46
+ 1.25	20.5	0.00
Midpoint of axis (Center)	**20.5**	
- 0.75	20.3	-0.97
- 1.75	20.1	-1.95
- 2.75	20.1	-1.95
- 3.75	20.0	-2.44
- 4.75	20.1	-1.95
- 5.75	20.1	-1.95
- 6.75	19.9	-2.90
- 7.75	19.8	-3.40
- 8.75	19.7	-3.90
- 9.75	19.0	-7.30
- 10.75	19.0	-7.30

Changes of the magnetic field on axes changing angles to θ=30° and θ=45° with the z axis, in the counter clockwise directions, were measured on 30 points according to the distance (r) starting from the centre (Tables 5 and 6).

For θ =30°, the average of all the measurements were found to be B=21.00±0.05 G. The average of deviation amount of the magnetic field intensity from the field intensity in the centre of the axis (B=20.5 G) was calculated to be +2.44% (Table 5).

For θ=45°, the average of all the measurements was found to be B= 21.43± 0.83 G. The average of deviation amount of the magnetic field intensity from the field intensity in the centre of the axis (B=20.5 G) was calculated to be +4.52% (Table 6).

Magnetic field homogeneity test was repeated for all three systems. The change of the magnetic field of 30 G created in the axis centre of the coils according to the distance in given directions were recorded by field strength measurements in a total of 225 separate points on the systems.

In conditions of high homogeneity, since it is required that all parts of the body of the animals should be exposed to magnetic field, these measurements were used to determine the areas where homogeneity is high, and the dimensions and standard positions of the cages that the animals will be put in.

Determinationof the Cage Dimentions

The amount of deviation of the magnetic field intensity (B=20.5 G) in the axis in vertical direction was calculated to be –2.83%. However, this figure falls to –1.94% at points on the axis between -8.75 cm and +8.25 cm. Thus, it was understood that the *height* of the cage selected for the animal should be 17 cm at the most. In this area (between –8.75cm and +8.75cm), the average magnetic field intensity, B was calculated to be = 20.11± 0.19 G.

Table 4: Deviations of B field in the horizontal (θ=90°) direction (Bgeo=0.33G)

Distance of y-axis (cm)	B (Gauss)	Deviation (%)
Center	**20.5**	
1	20.5	0.00
2	20.6	+0.49
3	20.6	+0.49
4	20.6	+0.49
5	20.6	+0.49
6	20.5	0.00
7	20.5	0.00
8	20.3	-0.98
9	20.1	-1.95
10	20.0	-2.44
11	20.0	-2.44
12	19.8	-3.41
13	19.0	-7.32
14	18.5	-9.76
15	18.0	-12.20
16	17.0	-17.07
17	16.0	-21.95
18	14.5	-29.27
19	13.0	-36.59
20	11.0	-46.34
21.5	8.0	-60.98

Table 5: Deviations of B Field in the direction of θ=30° (Bgeo=0.33G)

Distance r (cm)	**B (Gauss)**	**Deviation (%)**
Center	**20.5**	
1	21	+2.44
2	21	+2.44
3	20.9	+1.95
4	20.9	+1.95
5	21	+2.44
6	21.1	+2.93
7	21.1	+2.93
8	21	+2.44
9	21	+2.44
10	21	+2.44
11	21	+2.44
12	21	+2.44
13	21	+2.44
14	21	+2.44

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The amount of deviation of the magnetic field intensity in the y-direction was found to an average of –11.94%. However, since it had been observed that the change in the intensity of the magnetic field increased rapidly starting from 13 cm, it was determined that the distance of movement of the experimental animal in the cage should be maximum of 13 cm. Deviation of the magnetic field intensity within 13 cm from the magnitude of the magnetic field in the axis (B=20.5 G) was found to be an average of –0.77%. According to this, it was determined that the width and length of the cage could be 26 cm each at the most, provided that the centre of the cage would be localized so as to coincide with the centre of the axis of the Coils. Within this distance, the magnitude of the magnetic field, B = 20.34±0.29 G was found to be very near to the value in the axis.

Table 6: Deviations of B Field in the direction of θ=45° (Bgeo=0.33G)

Distance r (cm)	**B (Gauss)**	**Deviation (%)**
Center	**20.5**	
0.5	20.5	0.00
1.5	20.7	+0.98
2.5	20.9	+1.95
3.5	20.9	+1.95
4.5	20.9	+1.96
5.5	21.0	+2.44
6.5	21.0	+2.44
7.5	21.0	+2.44
8.5	21.1	+2.93
9.5	21.3	+3.90
10.5	21.5	+4.88
11.5	22.0	+7.32
12.5	22.5	+9.76
13.5	22.9	+11.70
14.5	23.2	+13.17

Temperature Changes in the Systems

Temperature measurements of the systems were recorded at 2 separate points .

1) Cage Temperature: Point of measurement of temperature change in the cage.

2) Room Temperature: Point of measurement of temperature change in the room within the working period of time.

For each working magnetic field intensity and application time, net temperature change in the cage were calculated from the difference of the cage temperature and room temperature values.

Net temperature change in the cage = Cage temperature – Room temperature

Room temperature changes and temperature measurements for each system at 10 G, 20 G and 30 G field strengths were recorded on three different days for 8 hours. Daily changes of the room temperature are given in Figure 3, and cage temperature differences for System I, System II, and System III obtained from data recorded at different magnetic field strengths are given in Figure 4 – Figure 6. Net temperature differences in the cages in the systems (mean ± standard deviation) are given in Table 7 according to the magnetic field strength and the application time.

Table 7: Net temperature changes in the cages

	B (G)	Exposure Periods (hours)	Cage temp (°C)	Net Temperature change in the cage (°C)
SYSTEM I	10	4	18.68 ± 0.20 °C	0.00
	10	8	19.32 ± 0.20 °C	0.02
	20	4	19.07 ± 0.20 °C	0.20
	20	8	19.76 ± 0.20 °C	0.40
	30	4	19.82 ± 0.30 °C	0.52
	30	8	20.65 ± 0.30 °C	0.98
SYSTEM II	10	4	18.87 ± 0.20 °C	0.00
	10	8	19.37 ± 0.20 °C	0.01
	20	4	18.96 ± 0.30 °C	0.28
	20	8	19.68 ± 0.20 °C	0.38
	30	4	19.80 ± 0.30 °C	0.50
	30	8	20.68 ± 0.30 °C	1.00
SYSTEM III	10	4	19.28 ± 0.20 °C	0.00
	10	8	19.72 ± 0.20 °C	0.04
	20	4	19.08 ± 0.20 °C	0.21
	20	8	19.78 ± 0.20 °C	0.42
	30	4	19.38 ± 0.30 °C	0.70
	30	8	20.36 ± 0.30 °C	1.06

Results

Following design procedure, three pairs of circular coils of either 42.75 cm diameter and 21.375 cm clearance was constructed with insulated copper wire made of 154 turns. Deviation amounts between the calculated values of the systems and measured values were calculated to be respectively 0.61% for System I, 1.81% for System II, and 1.21% for System III.

Data obtained at the homogeneity measurements performed for System I, System II and System III are given in Table 8 after taking the mean value for each system. The changes of the field within the space created by the coils with a strength of 30 G created in the center of the axis were found to be 29.55 ±1.29G, 30.55 ± 1.19 G and 30.1 ± 1.16 respectively.

Table 8: Variations of B field in the coils
(mean ± standard deviation)

	Horizontal Q=0°	Vertical Q=90°	Angular Q=45°	Directions Q=60°
System I*	28.2±3.3	28.7±1.2	30.5±0.9	30.8±0.3
System II*	29.2±2.9	29.9±0.7	31.4±0.6	31.7±0.2
System III*	28.8±3.1	29.5±0.9	30.7±0.7	31.4±0.1

***) B=30 G**

From all the vertical, horizontal and angular measurements taken, it was calculated that the widest cage in the magnetic field system to keep the experiment animals in that the homogeneity changed least could have the dimensions of 26 cm x 26 cm x 17 cm, and the centre of this cage should coincide with the centre of the axis. For the mentioned cage dimensions, the deviations of the magnetic field in angular directions were found to an average of + 3.3% and + 2.44% for 30° and 45° respectively.

According to the homogeneity records of the system, the amount of deviation of the magnetic field strength within the space created by the coils from the magnetic field strength in the centre of the axis was calculated from the arithmetic average of all the measurements performed in horizontal, vertical and angular directions to be –1.95%. This value was to be +1.06% for the widest cage (26 cm x 26 cm x 17 cm).

The dimensions of the cages used were reduced to 26 cm x 22 cm x 10 cm after taking the sizes of the guinea pigs and the fact that magnetic field showed minimal deviation from the value in the axis. For a dielectric cage in these dimensions, the amount of deviation was calculated to be an average of +0.44%.

Helmholtz coil system was operated continuously for 8 hours at 10 G, 20 G and 30 G magnetic field strengths, and temperature data were recorded every half hour. According to these records, temperature in the cage did not change at the end of 4 hours at 10 G, and the net temperature change in the cage was found to be 0.02 °C at the end of 8 hours. For 20 G, the net temperature changes at the end of 4 and 8 hours were found to be 0.2 °C and 0.4 °C respectively. When the system was operated continuously at field strength of 30 G, it was found that the net temperature change in the cage was 0.52 °C at the end of 4 hours, and 0.98 °C at the end of 8 hours.

Discussion

The system established in our laboratory is compared to the similar systems in the literature and it was seen that our system is the one with a rather high homogeneity and it is suitable for working only with less numbers of experimental animals. Yasui et al had ensured the simultaneous exposure of 24 separate cages in a system consisting of 4 rectangular coils with dimensions 3.85 m x 1.8 m x 0.66 m, with 50 Hz frequency, and capable of creating fields in 5 G-50 G range. They managed to obtain a deviation of ±15% from the targeted field strength in the region where the cages were placed [6]. Gauger et al. performed the design and establishing of a laboratory where 1200 mice and 1200 rats were exposed to EM fields simultaneously, and reported the deviation amount to be ±10% in the area where 20 mice and 20 rats were kept [8]. Shigemitsu et al. composed a system that exposing 96 mice to a magnetic field simultaneously, and reported that homogeneity was higher than 98% [7]. We planned to create the experimental conditions that will make working with high numbers of experiment animals by increasing the number of systems to three with dimensions of diameter was 0.4275 m and height was 0.2137 m, with which we were able to obtain a field of high homogeneity. This way, it was ensured to work with at least 12 mice or 6 guinea pigs in one application according to the sizes of the experiment animals.

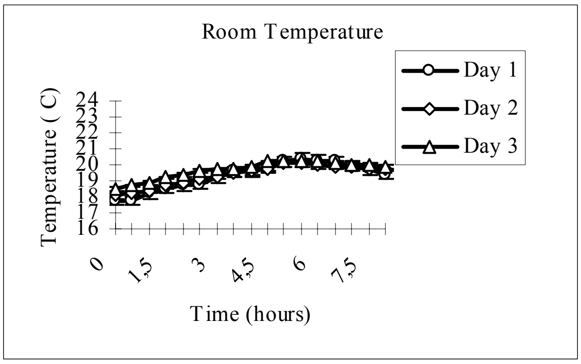

Figure 3: Daily changes in room temperature for 3 days

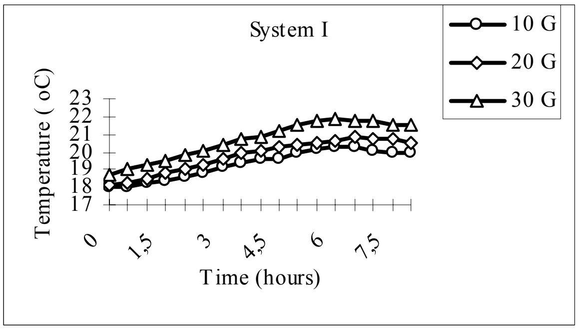

Figure 4: Temperature changes in System I

Conclusion

Three of Helmholtz coil systems with the specifications given in this manuscript for investigating the biological effects of ELF Magnetic fields were established in Gazi Bioelectromagnetic Laboratory. Homogeneity and temperature measurements of the systems that will ensure application of magnetic fields with 50 Hz frequency in 0.4 Gauss-100 Gauss range to experimental animals with high level of homogeneity were performed, and standardization of the experimental conditions were ensured.

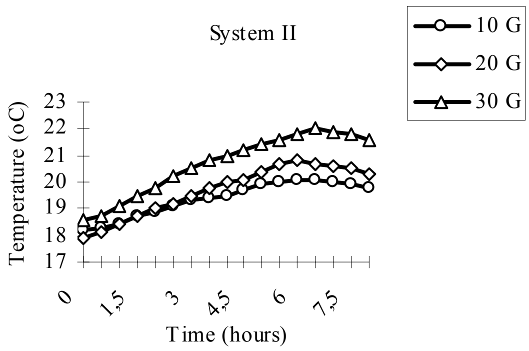

Figure 5: Temperature changes in System II

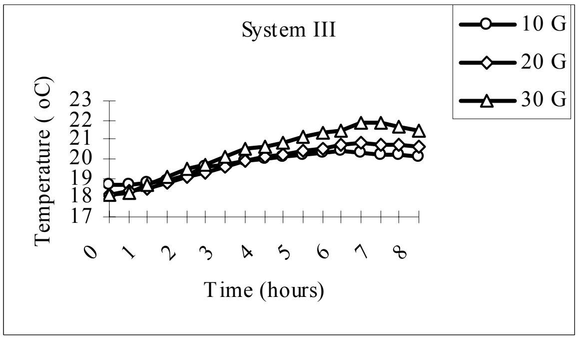

Figure 4: Temperature changes in System III

It was found according to the results of the homogeneity measurements that the actual field strength to be applied to the experimental animals during the study, each system would be reduced about 1.5% as compared to that found for System I. For System II and System III however, the field to be applied to the experimental animals would be greater than those found with ratios of 1.83% and 0.3% respectively.

Standardization of the test conditions was completed with a total 360 temperature measurements for all three systems together with homogeneity tests for the systems, and compliance with animal experiments were ensured.

From the temperature measurements for Helmholtz coil systems of 10 G, 20 G and 30 G, it was found that the temperature in the cages of the animals would increase for about 1 °C at the most with the uninterrupted application of a magnetic field of 30 G. Since it would be rather difficult to decide whether the biological effect observed during the experiment is caused by the field itself, or by the rise in temperature arising from the heating of the Coils, it is understood that a temperature control unit should be added to system whenever the intensity of the magnetic field is selected over 30 G.

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References

[1] FREY, A.H. (1994): 'An Integration of the Data on Mechanisms with Particular Reference to Cancer', in FREY, A.H., (Ed.): 'Medical Intelligence Unit :
[2] MILHAM, S.J. (1982): 'Mortality from Leukemia
[3] Electromagnetic Fields and Public Health - Extremely low frequency fields and cancer, WHO Fact Sheet N° 263, October 2001 (http://www.who.int/docstore/peh-emf/publications/facts_press/efact/efs263.html)
[4] KHEIFETS L. (2004): ' Childhood Leukemia and EMF, WHO EMF Project', Sensitivity of Children to EMF Exposure Workshop Proceedings, Istanbul, 2004
[5] STUCHLY, M.A., LECUYER, D.W., MCLEAN, J. (1991): 'Cancer Promotion in a Mause-Skin Model by a 60 Hz Magnetic Field : I. Experimental Design and Exposure System', *Bioelectromagnetics*, **12**, pp.261-271
[6] YASUI, M., OTAKA, Y. (1993): ' Facility for Chronic Exposure of Rats to ELF Magnetic Fields', *Bioelectromagnetics*, **14**, pp. 535-544
[7] SHIGEMITSU, T., TAKESHITA, K., SHIGA, Y., KATO, M. (1993): ' 50 Hz Magnetic Field Exposure System for Small Animals', *Bioelectromagnetics*, **14,** pp. 107-116
[8] GAUGER, J.R., JOHNSON, T.R., STANGEL, J.E., PATTERSON, R.C., WILLIAMS D.A., HARDER, J.B., MCCORMICK, D.L. (1999): 'Design, construction, and validation of a large capacity rodent magnetic field exposure laboratory', Bioelectromagnetics, *Bioelectromagnetics*, **20**, pp.13-23
[9] MIKHAIL, E.L., FAM, W.Z. (1993): ' Incidence of Lymphoma in CFW Mice Exposed to Low-Frequency EMFs', in BLANK, M. (Ed):'Electricity and Magnetism in Biology and Medicine', (San Francisco Press, USA), pp. 389-392
[10] ROGERS, W.R., REITERS, R.J., ORR, J.L. (1993): ' 60 Hz Electric and Magnetic Fields and Primate Melatonin', in BLANK, M., (Ed): 'Electricity and Magnetism in Biology and Medicine', (San Francisco Press, USA), pp. 393-397
[11] LAZETIC, B., NIKIN, B., PEKARIC-NADJ, N. (1993): 'The Effects of Intrauterine Exposure of Rats to Low-Intensity AC EMFs', in BLANK, M. (Ed): 'Electricity and Magnetism in Biol. and Med.', (San Francisco Press, USA), pp. 349-350
[12] RUTTAN, L.A., PERSINGER, M.A., KOREN, S. (1990): 'Enhancement of Temporal Lobe-Related Experiences During Brief Exposures to Milligauss Intensity Extremely Low Frequency Magnetic Fields', *J. Bioelect.*, **9**, pp. 33-54