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Numerical Simulation of the Induced Currents in Occupational Workers Induced by Body-Motion around Different MRI Fields

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Abstract— MRI, occupational workers are exposed to strong, non-uniform static magnetic fields generated by the main different type of magnets. Previous studies have indicated that movement of the body through these fields can stimulate in situ electric fields/ current densities approaching physiological significance. The relationship between the magnetic field pattern/strength and the current distribution/level induced in the body is not well understood. This paper presents numerical evaluations of electric fields/currents in tissue-equivalent, whole-body (occupational workers) at various positions and a variety of normalized body motions around three superconducting magnets with central field strengths of 1.5T, 1T and 0.5T. Possible correlations between the magnetic field characteristics and the induced current density distribution are described with high significance p<0.01 and simulation show that the induce electric current fields is directly proportional to the static field magnitude with a significance of decreasing the induced current when using the active shielding, results shows current densities above the ICNIRP and IEEE safety standards.

Keywords— MRI Occupational exposure, MRI safety, induced current density, Static magnetic fields, Radiology.

I. INTRODUCTION

The large diffusion of MRI in diagnostics and research and the trend towards higher field systems, has focused the attention of the scientific community on the possible health risks resulting from the occupational exposure in these kinds of environment. At the same time the suspension of the Directive 2004/40/EC [17] connected especially to the exposure assessment in MRI, has induced many researchers to carry out measurement campaigns in different MRI sites [2]. Magnets of magnetic flux density of 0.2–3 tesla (T) are currently used as a source of static magnetic field. MRI scanners of higher fields (up to 9 T) are under intensive pre-clinical investigations. Workers operating MRI scanners are one of the occupational group highest exposed to static magnetic fields, because normally superconductive or permanent magnets generate the field constantly. Only resistive magnets can be switched off, when the investigation is over. Exposure of workers to RF and gradient fields is, on the contrary, uncommon among MRI workers because the clinical staff is usually far from the magnet during patients' examination, controlling examinations by a computer-console. Physical effects of static magnetic fields (translation and orientation of charged molecules) cause electrodynamic forces on moving electrolytes, and effects on electron spin states of chemical reaction intermediates [2],[3],[7]. Translation and orientation of molecular and cellular substances such as retinal rods, and some living cells have been experimentally observed in vitro-studies of static fields of high level (above 1 T), in various materials—dia and paramagnetic such as hemoglobin, collagen, fibrin, and also on ferromagnetic particles such as magnetite. Water distribution can be also affected by high-gradient magnetic fields of high flux density (e.g., 8 T, 50 T/m), producing the force directly proportional to the square of the magnetic field strength and inversely proportional to the radius of the magnet e.g. force up to 30% the force of gravity in abovementioned 8 T magnetic field, but only about 1% of gravity in whole-body 4 T magnet . [13],[16]. Medical staff working near magnetic resonance imaging (MRI) scanners are exposed both to the static magnetic field itself and also to electric currents that are induced in the body when the body moves in the static magnetic field. This study is a movement simulation and computationally investigates the movement induced current due to the motion in a different static magnetic field of 0.5, 1, 1.5 T MRI .

II. MATERIALS AND METHOD

Theory

The electrical behavior of the biological matter can be described by the conductivity (σ) which interacts with the electric field (E) applied to the tissue. The current (J) is obtained by (1):

$$J = \sigma E \qquad (1)$$

Where J is the induced current in (A/m^2)

When an electric conductor, such as the human body, moves in spatial heterogeneous static magnetic fields B, it induces an electrical field E expressed by the equation below [18].

$$E = k\frac{dB}{dt} = k(\frac{\partial B}{\partial x}.vx + \frac{\partial B}{\partial x}.vy + \frac{\partial B}{\partial x}.vz) \qquad (2)$$

Where E is the electric field in (v/m) k is a geometry factor for a given subject, a radius of 0.64 m is assumed for a typical current loop in the body, while for the head a radius of 0.07 m [18]. Worker walking speed components (v_x or v_y) are vectors chosen as 1.6, 1.4 and 1.2 m/s based upon worker motion speed around the path, only movement in the ground plane that is along x, y directions is considered. A computational modeling for induced current for both head and trunks then created through Matlab,

Methods

Computational Modeling and plotting of MRI field distribution around 0.5- 1- 1.5 T:

The iso-gauss line map (fringe field) of the MRI scanner brand Sigma GE 1.5 Tesla , Siemens 1T , Toshiba 0.5 T was actually measured using a Gaussmeter brand OXFORD Instruments using the HALL effect with resolution of 0.01mT (0.1 Gauss).

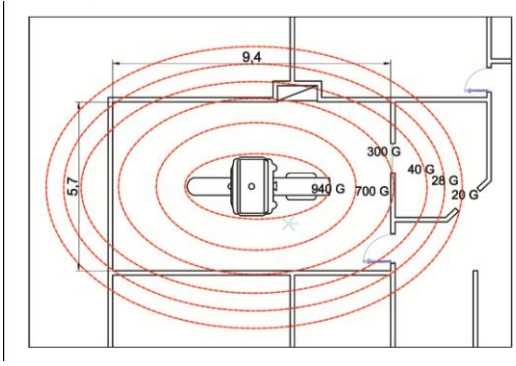

Fig 1.: Fitted fringe field to Ellipse (G= Gauss) for the 1.5T scanner

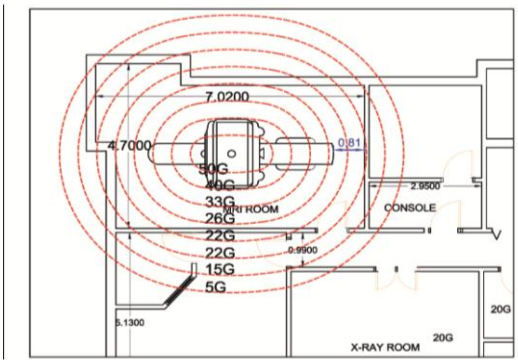

Fig 2. : Measured fringe field (G= Gauss) for the 0.5T scanner

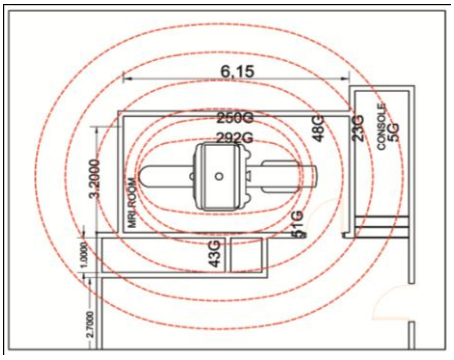

Fig 3. : Measured fringe field (G= Gauss) for the 1 T scanner

Fig.1,2,3. Shows the measured fringe field of the scanners which have been approximated to ellipses. In order to obtain a fitting model that can be used accurately for estimation of MRI static magnetic field map inside an MR room. We use the knowledge of ellipse geometric theorem Where a and b are the minor and major radii respectively of an ellipse. Applying the Pythagorean identity (3) Ellipse circumference is defined by (5).

As any point located in the contour of each ellipse has same static magnetic field, we defined objects in the X and Y directions for any geometric points in the SMF field of the scanner , a polynomial interpolation function between all ellipses contour points and static magnetic field (B) was then generated using polyfit method.:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \tag{3}$$

$$\frac{a_i}{b_i} = constant \tag{4}$$

$$\text{Circumference} \approx 2\pi \sqrt{\frac{1}{2}(a^2 + b^2)} \tag{5}$$

A Matlab script was created to estimate the static magnetic field value (B) at each point of the MR room in the x, y Axis, the Matlab script is used to compute the induced current density associated with worker’s movements during conduction of any MR procedure is dependent on the walking speed and on the spatial gradient fields associated with a specific path. The operator walking speed along the chosen path is easily set, once the walking path and speed are chosen which are 1.2, 1.4, 1.6 m/s , the tool estimates induced current density J using (1), (2), with special gradient calculation for each point on the path, , the maximum value J along the path expressed in A/m^2.

III. RESULTS

A result of the Matlab script for plotting the MRI field around the 1.5 , 1, 0.5 T was a polynomial interpolated function of the 7th degree that fits measured data. Table I shows computed induced current (J) for different MRI intensity scanners Maximum induced current reported was 1.6 A/m2.

TABLE I COMPUTED INDUCED CURRENT

Tissue Name	J (A/M^2) FOR 1.5 T	J (A/M^2) FOR 1 T	J (A/M^2) FOR 0.5 T
Aorta	0.335	0.065	0.116
Bladder	0.218	0.042	0.075
Blood	0.936	0.182	0.325
Blood vessel	0.335	0.065	0.116
Body fluid	1.17	0.228	0.406
Bone cancellous	0.124	0.024	0.043
Bone Cortical	0.046	0.009	0.016
Bone marrow	0.015	0.003	0.005
Breast fat	0.023	0.004	0.008
Cartilage	0.351	0.068	0.121
CSF	1.615	0.314	0.560
Cervix	0.561	0.109	0.195
Colon	0.499	0.097	0.173
Duodenum	0.686	0.133	0.238
Fat	0.023	0.004	0.008
Gall bladder	0.757	0.147	0.262
Gall bladder bile	1.155	0.225	0.400
Gland	0.6	0.117	0.208
Heart	0.53	0.103	0.184
Kidney	0.577	0.112	0.200
Liver	0.343	0.066	0.119
Lung deflated	0.413	0.080	0.143
Lung inflated	0.226	0.044	0.078
Lymph	0.6	0.117	0.208
Mucous membrane	0.382	0.074	0.132
Muscle	0.53	0.103	0.184
Nail	0.046	0.009	0.016
Nerve	0.241	0.047	0.083
Oesophagus	0.679	0.132	0.235
Ovary	0.53	0.103	0.184
Pancreas	0.6	0.117	0.208
Prostate	0.686	0.133	0.238
Skin dry	0.335	0.065	0.116
Skin wet	0.374	0.073	0.130
Small intestine	1.24	0.241	0.430
Spinal chord	0.241	0.047	0.083
Spleen	0.577	0.112	0.200
Stomach	0.679	0.132	0.235
Tendon	0.366	0.071	0.127
Testis	0.686	0.133	0.238
Thymus	0.6	0.117	0.208
Trachea	0.405	0.079	0.140
Uterus	0.71	0.138	0.246

A statistical analysis was performed using SPSS which shown in the following results :

Table II . Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	1.5	.512674	43	.342	.052
	1	.099628	43	.067	.010
Pair 2	1.5	.512674	43	.342	.052
	.5	.177674	43	.119	.018
Pair 3	1	.099628	43	.067	.010
	.5	.177674	43	.119	.018

Table III. Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	1.5 & 1	43	1.000	.000
Pair 2	1.5 & .5	43	1.000	.000
Pair 3	1 & .5	43	1.000	.000

Table IV. Paired Samples Test

	Paired Differences					t	df	Sig. (2-tailed)
				95% Confidence Interval of the Difference				
	Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
1.5 - 1	.413	.275	.042	.328	.498	9.832	42	.000
1.5 - .5	.335	.223	.034	.266	.404	9.834	42	.000
1 - .5	-.078	.052	.008	-.094	-.062	-9.827	42	.000

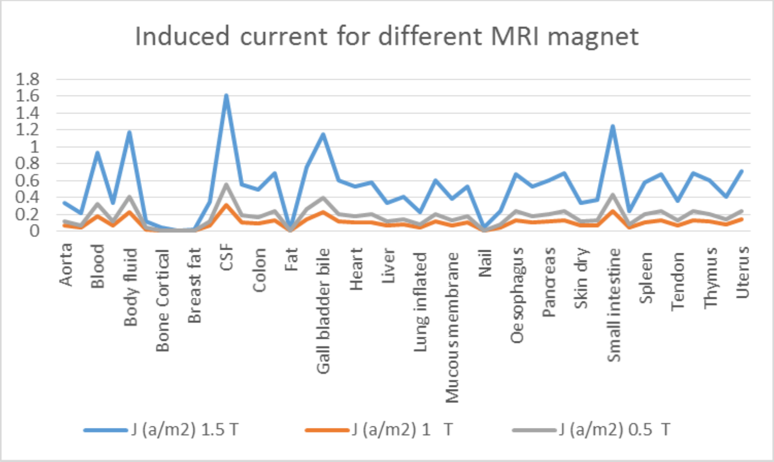

Fig 4. : A sample line graph which map the different induced currents for different MRI magnet field.

A predicted formulae correlate induced current (J) and static magnetic field (B) is then generated :

$$J = -0.072 +0.335 B \tag{6}$$

IV. DISCUSSION

The predicted formulae agree well with the current density distributions illustrated in figure 4 for all combinations of magnets and body motions induced current . In general, the levels of peak current density increase for increasing static field strength and decrease than predicted when the magnet is actively shielded as per the 1T magnet . averaged current densities for most combinations of magnets and motions can be larger than the threshold of 56.57 mAm^2 – peak defined in the ICNIRP and EU Directive 2004/40EC guidelines [11],[12],[17].

The statistical analysis shows a high significance $p < 0.01$ and $R^2 = 24.5\%$ which demonstrates the increase in induced fields as the field strength of the main magnet is increased. Whereas the 1 Tesla magnet results shows a significant decrease of induced current intensities in respect to the 0.5 Tesla magnet due to active shielding as this type of MRI scanner have active shielding against stray magnetic fields. Active shielding is a series of electromagnetic coils that act like a magnetic girdle counteracting the natural 'spread' of the principle magnetic field. In essence, active shielding squeezes the fringing magnetic field of the magnet into a much smaller footprint which is demonstrated in fig 2.

There is many factors that can affect the induced current due to the MRI workers in a static magnetic field , the magnet strength is a factor that affect significantly the induced current results and are expressed by the equation (6) , as well different motion speed has a significant effect of the induced current [3] . The static magnetic field strength effects on the induced current due the body motion can be controlled by the active shielding.

V. CONCLUSION

There are many gaps in knowledge of biological effects and interaction mechanisms of MRI-emitted electromagnetic fields with tissues. High priority research needs cover the studies to fill important gaps in knowledge focused on health risk assessment that are needed to significantly reduce the uncertainty in the current scientific information. In the case of very specific occupational situation of medical staff operating MRI scanners, additional attention should take notice of the occupational exposure to static magnetic field in relationship to the motion speed of the workers Further investigations should provide knowledge for current scientific gaps, but also to allow verification of the protection level from exposure limitations published by various international and national bodies. Such needs indicate that exposure assessment should allow multi-level analysis of exposure pattern, harmonized with exposure limitations. The most important topics for exposure assessment from MRI scanners should include static and gradient fields exposure, exposure results from workers movement in the area of spatially heterogeneous fields, medical staff, technicians, cleaners and other possible exposed workers groups, open and close magnets, low and high field magnets, diagnostic and interventional use, various types of medical procedures, availability of technical staff for the reduction of exposure level and duration. In summary, a detailed exposure assessment protocol with the biomedical research results will be of high importance for combined analysis of various studies and for determination of the groups of workers who are highly exposed .

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