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Health effects of Ultra High Magnetic fields (MRI as Case Study)

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Abstract: One of the most rapidly advancing available imaging techniques is Magnetic resonance imaging (MRI). This technique has many side effects can be digested in to main categories:
The first is the High Magnetic field effects: these effects contain personal safeties, electrical induced voltage, forces effects of any none ferromagnetic implant material. The second is the High power Electromagnetic Signal effects, which is needed for atoms Excitation. The useful tools of evaluation such side effect is Specific Absorption Rate (SAR) and the increasing of the body temperature.
In this paper, the first issue of high magnetic field was discussed; simulation of high magnetic time variant achieved using specialized tools, while the non-variant time magnetic effect is out of our scope. These tools used to evaluate the satisfied requirement levels of the magnetic field characteristics with the aid of some useful software such COMSOL Multiphysics and Matlab. The simulation results show a good agreement with the empirical formulas used to calculate the maximum rate of magnetic field charges. New assumption adopted to calculate the overall magnetic field taking in the account the three magnetic gradient components in X, Y and Z directions
The simulation shows that the maximum rate of change in the magnetic field occurs at the edges of the region of interest, while it at lowest level at the isocenter axis. The worst case (more than 50% of the volume beyond the limits) occur at T=100 msec and τ=140 Micro sec (fast imaging case). The generated E field, on the other hand, increased as we far from the center, where a homogenous model was assumed with some none expectable decreasing at the edges. This degradation in the E filed is clearer in non – homogeneous model due to the boundary condition problem.
More studies are required, on the effects of Electromagnetic power used in such equipment such as SAR.

Keywords: Magnetic resonance imaging (MRI), Magnetic field Health effects, Specific Absorption Rate (SAR).

1. INTRODUCTION

Although the Magnetic Resonance Imaging (MRI) device is relatively safe, there is a lot of caution to be considered before testing, during the examination and after completion of the examination.

Compared to magnetic resonance, the CT scan device is a powerful radiation source of ionized radiation, which is dangerous and has cumulative negative effects.

The MRI is generally composed of two main sources of waves [1].

The first is a huge external magnetic field which is used for the alignment of the nucleus (of the liquid) either parallel or perpendicular to the field which called (B0). These nucleus spins have two energy states:

Low energy (Parallel to the Magnetic field) and high-energy state (Perpendicular to the Magnetic field).

The resultant momentum yield a spine at a velocity called Larmor frequency, which is governed by the applied B0 as:

$$\omega_0 = \gamma B0 \qquad ...(1)$$

Where ω_0 is the angular frequency

γ is the gyromagnetic ratio

and B0 is the field strength

The second electromagnetic source RF, (B1) which is used to stimulate the hydrogen nucleus such that some low energy nucleus move to the high energy state and some of the high energy nucleus move to the low energy states. This absorbed energy by the atoms will be emitted shortly after that and collected by a tuned receiver coil.

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The electromagnetic energy required to stimulate these nucleus depends mainly on the strength of the (B_0) field.

$$\Delta E = \gamma h B0/2\pi \quad \ldots(2)$$

Where h is Planck's constant.

Equation 2 states that the energy required to stimulate a nucleus proportional to the main magnetic field B0 and consequently, the new types of MRI devices required relatively high power RF source applied to the human body.

The effect of the high power RF signal on the human body has been Studied deeply in many research [2] and it's out of our scope.

2. MRI MAGNETIC FIELD EFFECTS

The side effect of the huge magnetic field can be classified according to the electrical and magnetic characteristics of the object.

The first types include all Ferro magnetic material intentionally entered the human body such as ferromagnetic aneurysm clips and surgical prostheses , or unintentionally entered the body like bullets, shells or any foreign body. The consequence of being such material in huge magnetic field, either torque forces act on these foreign object yield a movements in any directions, or an eddy current which yields overheating or sometimes burning.

The second type is magnetic Non-ferrous conductive materials such as titanium and its alloys. These materials safe from attraction and torque forces produced by the magnetic field, and still there may be some risks associated with Lenz effect forces specially titanium implants in sensitive areas such as stapes implants in the inner ear. Eddy current and overheating still an issue

The Third type is the Ferro-magnetic Non Conduction materials such as metal-carbon-polystyrene [3].

The fourth type is the None Ferro Nonconductive like the remained isolated material such Teflon and Plastic.

The human body in somehow is an inhomogeneous combination of all above types. The characteristics of the tissue and other parts are depends on the concentration if minors and other chemical contains. Blood, for example, as flow in artery can be considered a finite conducting wire. The brain (which contains high fluids constrains), on the other hand, may act as the third or the forth type. This paper will focus on the Electrical field and its effect on the nerves which is called Peripheral nerve Stimulation PNS [3]

3. ELECTRICAL AND MAGNETIC PROPERTIES OF HUMAN TISSUE

The ability to interaction of a material with electromagnetic energy defined its Electrical properties. This interaction yields from the presence of components within the material that can be affected by the electric and magnetic forces generated by the electromagnetic (EM) fields. The electrical and magnetic characteristics are a direct consequence of its composition and structure.

Senftle, F.E published in 1969 some of the electrical and magnetic properties of the human body [4]. In general, the human body is composed of water; where water is about 72% of the human body and the rest is mostly 99% consists of the four elements, namely hydrogen, carbon, oxygen and nitrogen. Different tissue has different water content and therefore the electrical properties will also vary [5].

The main characteristics, such as the permeability and permittivity of the tissues, depend mainly on the water content as well as the distribution of the four elements that form the tissues, namely hydrogen, oxygen, nitrogen and carbon. Permittivity describes the properties of tissue in terms of loss, as well as the ability to store energy when exposed to an electrical field, as water molecules will try to arrange themselves within that electric field due to the polar nature of water molecules.

The electric and magnetic properties of the of living human tissues have been identified and confirmed by tables of the researcher Gabriel et al at different frequencies [6].

Regarding to susceptibility (χ), material could be classified according as:

Diamagnetic materials ($-1 < \chi < 0$)

Paramagnetic materials ($0 < \chi < 0.01$)

Ferromagnetic materials ($\chi > 0.01$).

Human tissues can be classified as diamagnetic or nearly paramagnetic $-10*10^{-6}$ to 0 [6] as shown in table (1).

Table 1 Susceptibility List of human tissue

Tissue	Susceptibility χ
Soft tissue	-9.0×10^{-6}
Cortical bone	-8.85×10^{-6}
Deoxygenated Red Cells	-6.5×10^{-6}
Liver With heavy Iron	0

In order to study the stimulation of the nerves due to E field generating (y) huge Magnetic field, it is better to review the potential limits which stimulate the human muscles like peripheral, Lung and heart muscles. A lot of studies concludes that the potential difference needed to stimulate the human muscles related to the skeleton around 94 mv negative inside the neuron membrane [7] as shown in Figure (1) below:

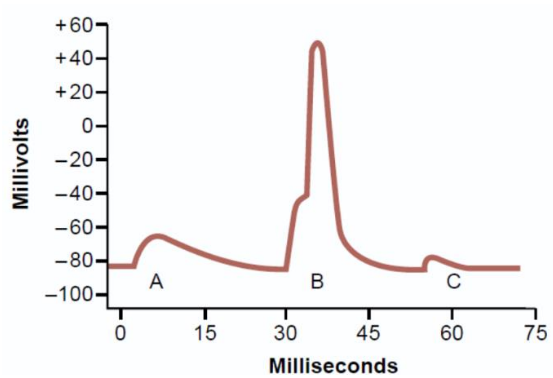

Figure (1) End plate potentials (in millivolts) [7].

A Weakened end plate potential recorded in a curarized muscle, too weak to elicit an action potential. B, Normal end plate potential eliciting a muscle action potential. C, Weakened end plate potential caused by botulinum toxin that decreases end plate release of acetylcholine, again too weak to elicit a muscle action potential.

Heart on the other hand is the most important muscle in human body which also very sensitive for any abnormal electrical activities which called fibrillation: [7] as shown in Figure (2) below

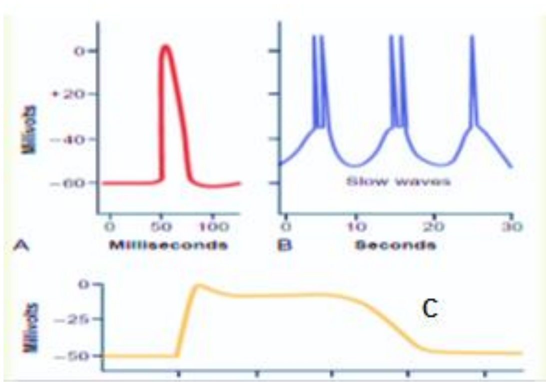

Figure (2) Heart stimulation potential

It is worth mentioning that there are other areas of contemporary research in which electromagnetic induction is successful (and with potential difference). Depression and hallucinations are accompanied by an irregular electrical activity in the brain that helps to inhibit this activity in the relaxation of the condition. The inhibition is done by magnetic stimulation from outside the skull, where a very fast and highly selective magnetic field is placed near the selected sites in the brain. The weak electrical currents are stimulated at specific locations and can lead to the restoration of electrical performance in the brain tissue [8].

As mentioned before, the electrical field is the main consequences of the gradient magnetic field,

The Ferro magnetic material will be excluded from this scenario since it's forbidden to enter any such material to the MRI test room.

The relative transition speed of the object with the B0 field will be very slow hence the body is secured during the test.

4. Induced Electrical field due to time variant Magnetic field

Although the main magnetic field B0 is stationary, there is an addition sources of time varying magnetic field used for encoding the spatial location of the Region of Interest ROI in the three dimensions. This magnetic field is called gradient field generated by the gradient coil.

The gradient switching rate is 100-2000 Hz for normal MRI application or faster for other application (1 KHz to 200 KHz) [9] as shown in Figure (3).

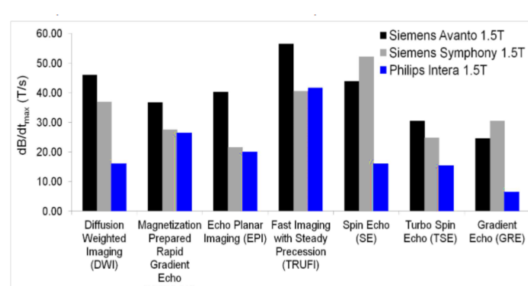

Figure (3) some well-known MRI Gradient switching rate [9].

As show in Figure (3), all commercial MRI scanners have a limit on the maximum slew rate (dB/dt) allowed, preventing the fast gradient switching that causes PNS. While most MRI sequences are well below the slew rate (dB/dt) limit, sequences that utilize echo-planar imaging (fMRI, diffusion) can sometimes result in peripheral nerve stimulation and cause the subject discomfort. In such cases, the subject should notify the operator, and the scan should be aborted.

As Lenz low states, the generated electrical field proportion to rate of change of the applied magnetic field, and this is called slew rate (dB/dt).

The gradient magnetic fields are often switched on and off; and that what called time-variation of the magnetic field ($\partial B/\partial t$) which induces into tissue an electric field ($\vec{E}$), according to the third Maxwell's law

$$\vec{\nabla} \times \vec{E} = -\partial B/\partial t \quad \text{........ (3)}$$

If we take the geometry of the object (or the implant) as a cylindrical with R and axial parallelized to the main Magnet (B0), then the induced Electrical field due to the gradient Z can be calculated as [8]:

$$\oint \vec{E}.\vec{dl} = \iint_S -\frac{\partial \vec{B}}{\partial t}.d\vec{S} \quad \text{.......(4)}$$

Where S is the Cross section area of the cylinder and hence the gradient field is uniform over the area of interest, the above equation can be simplified as:

$$\frac{dB}{dt} = \frac{2.E}{R} \quad \text{...........(5)}$$

Or

$$E = \frac{R.}{2}\frac{dB}{dt} \quad \text{.........(6)}$$

Beside the generated electrical field, an eddy current can be noticeable and sometimes yield a heat the subject.

5. MATERIALS AND METHODS

Two human body models were simulated using Comsol Multiphysics 5.4. The first model assumed to be homogeneous tissue, while the second was assumed to be none homogeneous. A comparison of the result with an empirical model also done. Furthermore, on field questionnaire were achieved in private MRI center to. The main goal of this questionnaire to strengthen the conclusions due to simulation.

5.1MODEL AND SIMULATION

The propose scenarios are based on the properties of the magnetic field of the MRI. The first component is the constant magnetic field (B0) (Time invariant Magnetic field) while the second is the Gradient magnetic field generated the gradient coil which are time variant Magnetic fields.

Figure (4) shows the simulation test bench using Comsol Multiphysics Simulation software. In this scenario, 1.5T B0 field of the MRI ware be simulated, although the available MRI Philips device has 1.5T B0, the up-to-date magnetic fields has 7T, 10T or bigger. The time invariant Magnetic field was modeled as permanent Magnetic field within the Y direction. The human body was assumed as a cylindrical shape with specific susceptibility. The Gradient coils were placed on X, Y and Z direction. Note that the model was assumed to be cylindrical while the Volume of Interest in MRI imaging assumed to be parallelepiped. The main reasons of choosing this shape due to the simplification of reconstruction voxels from the frequency drifts of the received signal by the coils.

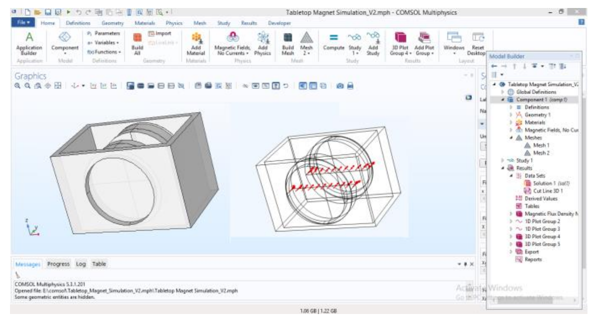

Figure (4) Simulation test bench

The overall magnetic field due to the three gradient (X, Y, and Z) coils is simulated. As shown in figure (5) the edge of the region of interest carries the peak gradient field and the field density decreases moving toward the center. It is obvious that the center of the cube has the lowest magnetic field density and theoretically equal to zero.

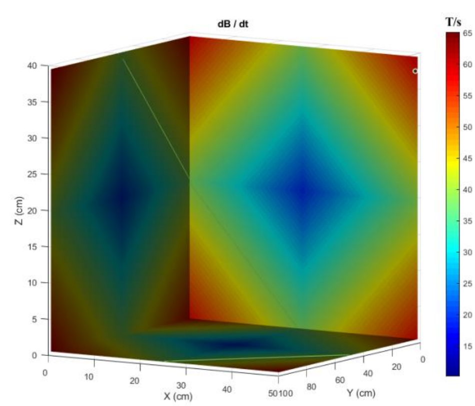

Figure (5) Magnetic field variation distributed in the volume of interest.

The electrical threshold cannot be defined well, some theories and empirical formula ware suggested [9].

Some safety recommendation assumed 40 T/s is the limits [10].

A semi empirical model of nerve stimulation by Reilly [11] as:

$$\left(\frac{dB}{dt}\right)_{Threshold} = 54\left(T/_{sec}\right)\left[1+\frac{132\mu sec}{\tau(\mu sec)}\right] \quad ....(7)$$

Where T is duration

τ Is the total ramp time

Regarding to our work, if we apply the threshold obtained from equation (7) , 7% , 50% and 75% of the volume will considered harmful at the specific values of T and Tau as shown in the figures (6), (7) and (8) respectivly.

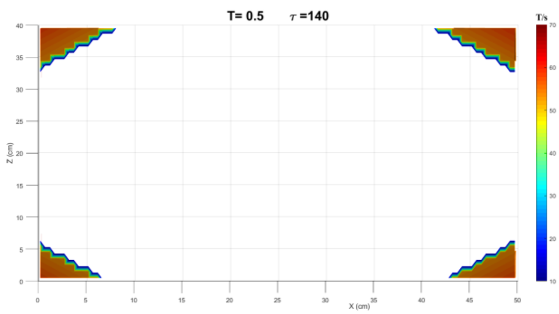

Figure (6) Magnetic field density variation T=.5 sec Tau=140 u sec.

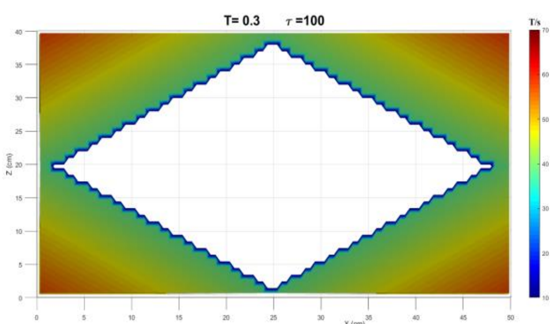

Figure (7) Magnetic field density variation T=.3 sec Tau=100 u sec.

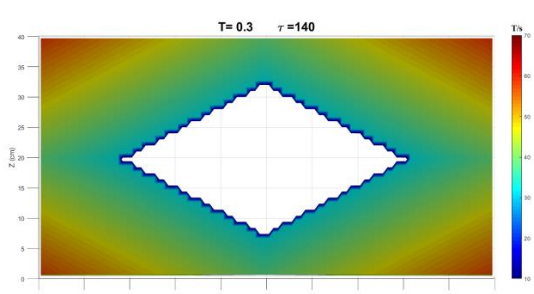

Figure (8) Magnetic field density variation T=.3 sec Tau=140 u sec

For comparison, the simulation results was compared with empirical formula in [9], as shown in the figure (9) below, while the operating frequency compared with the threshold in ref [11] is shown in figure (10)

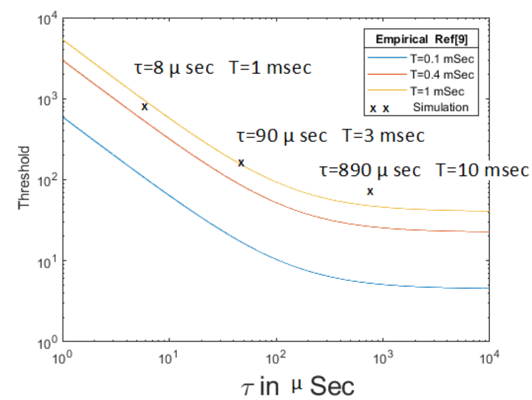

Figure (9) Simulation E threshold compared with empirical values.

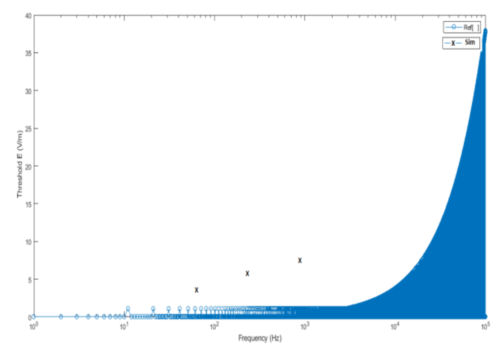

Figure (10) Operating frequency (simulation compared with Empirical formula)

The induced E field due to the gradient magnetic field also simulated. Figure (11) below shows the worst case where the measurements at the extreme ends at the Y axis, the human body was modeled as cylindrical with susceptibility=-2x 10^{-6}

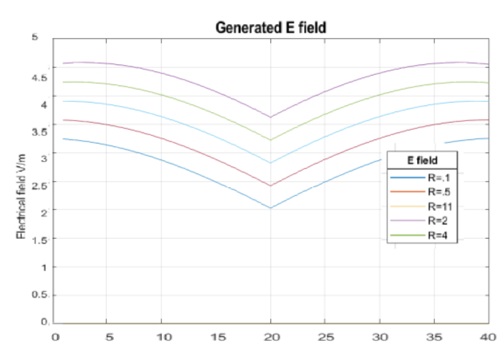

Figure (11) Induced E field at worst case for homogeneous model

A second model where the human body was modeled as two cylindrical, the first R=30 and S= -2 x 10^{-6} and the second R=40 with S=-9 x 10^{-6} and the result as shown in figure (12) below.

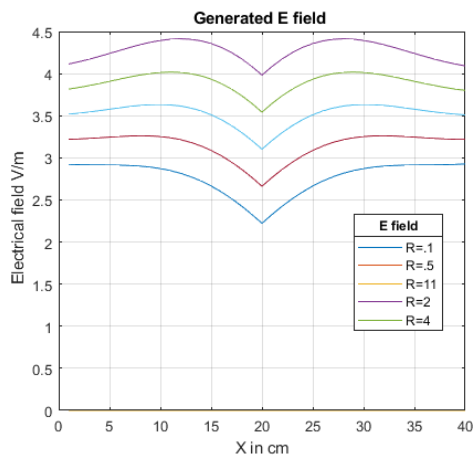

Figure (12) Induced E field at worst case for Non-homogeneous model

Another parameter affect the threshold of rate of change in B is the frequency of change, where the generated E field has a frequency above the response of the human muscles simulation result compared to ref [12]

5.2 FIELD SURVEY AND QUESTIONNAIRE

The study conducted a field survey on the effects that patients find during the examination, including high body temperature, there is a kind of jitter in the limbs, feeling uncomfortable... etc

The sample included more than 100 people who underwent magnetic imaging from the age of 14-60 years. The younger and older patients were excluded because either the patient was a psychedelic and was not able to provide useful information. The Device type of the MRI was Philips Achieva 1.5 T. The used Protocols were:

Diffusion-Weighted Imaging (DWI) with maximum gradient switching rate = 15-25 T/s

Turbo Spin-Echo (TSE) with maximum gradient switching rate = 15-25 T/s

T1-weighted spin-echo (SE)) with maximum gradient switching rate = 25-35 T/s

True Fast Imaging with steady-state free precession (Trufi) with maximum gradient switching rate = 50-60 T/s

The table (2) below shows the results of this questionnaire, which shows cases of discomfort due to high sound, tightness of breath, high body temperature, and several protocols (for several values of magnetic flux change with time (protocol).

Table 2 Questionnaire results

Protocol	No of Patient	Uncomfortable	PNS	Over heat
DWI	25	1	0	0
TSE	25	3	1	0
SE	25	5	0	0
Trufi	25	7	4	2

As shown in the table (2) the feeling of the PNS mainly coherent with the high rate of dB/td, other psychological effect can be reasons

6. CONCLUSIONS & SUGGESTIONS

In this paper, a time variant huge magnetic field effects on human body discussed, the generated electrical fields is mainly related of the rate of change of the Magnetic field. The induced (E) fields sometimes beyond the limits will cause “peripheral nerve stimulation. Limits calculations of such effect depends mainly on the characteristics of the magnetic field (peek rate of changes) and the electromagnetic properties of the human body.

It can be concluded from the results that the huge magnetic field may be harmful if the gradient field fluctuation exceed 40T/sec. of course these variations are not the only factor, the location of the body within the axis, relaxation time, test duration also has major effects. The gradient speed limit varies according the brand of the instrument, the healthcare regulations, and the used protocol. We notice some divergence between the empirical formula and the simulation results. The main reason f this divergence related to the way and the assumptions of the empirical formula that’s neglects the effects of the parameters T and Tau.

Increasing the operating frequency of the gradient coils is neither feasible nor applicable because of the limitation of the relaxation time (principle of MRI operation).

Lowering the operating frequency below 1 Hz also not applicable (the test will takes a tremendous time).

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