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# Electromagnetic Field Effect Simulation over a Realistic Pixeled Phantom Human's Brain

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**Abstract**: The exposition to different types of electromagnetic radiations can produce damages and injures on the people's tissues. The scientist, spend time and resources studying the effects of electromagnetic fields over the organs. Particularly in medical areas, the specialist in imaging methodologist and radiologist treatment, are very worried about no injure there patient. Determination of matter radiation interaction, can be experimental o theoretical is not an easy task anyway. At first case, is not possible make measures inside the patient, then the experimental procedure consist in make measures in human's dummy, however, is not possible see deformations of electromagnetic fields due the organs presence. In the second case, is necessary solve, the Maxwell's equations with the electromagnetic field, crossing a lot of organs and tissues with different electric and magnetic properties each one. One alternative for theoretical solution, is make a computational simulation, however, this option, require an enormous quantity of memory and large computational times. Then, the most simulations are making in 2D or in 3D although using human models approximations, builded with basic geometrical figures, like spheres, cylinders, ellipsoids, etc. Obviously this models just lets obtain a coarse solution of the actually situation. In this work, we propose a novel methodology to build a realistic pixeled phantom of human's organs, and solve the Maxwell´s equations over this models, evidently, the solutions are more approximated to the real behaviour. Additionally, there models results optimized when they are discretised and the finite element method is used to calculate the electromagnetic field and the induced currents.

**Keywords**: Pixeled models; matter radiation interaction; phantoms of human's organs

## 1. Introduction

Nowadays, people are exposed to different types of electromagnetic radiations: sun's rays, microwaves, radio frequencies, electric high tension systems, specially, in medical applications like Magnetic Resonance Imaging, X's rays studios or Computed Tomography Imaging. This radiation energy sources, can injure people that work or walk near there [1].

Make a prediction about the effects of radiation over the tissues and organs require one of two possible previous work. In first place some experimental measures should be making. Since 1960's years, Schwan [2] did investigations to qualify and quantify the effect of not ionizing radiations over biological systems, specially the human's organs, there observations was reported like biophysical parameters in tables. Of course, is not easy neither safety, making measures with living tissues, and is not possible known the electromagnetic field deformation into the body.

Perhaps the second option can give us more practical and useful information. This is a theoretical studio, but an analytical work requires the Maxwell's equations solution [3]. Because is a hard vectorial problem, the most of investigators works in numerical solutions, we know various methodologies, however they require enormous memory resources and large computational times. Almost all simulations are in 2D, some few simulations are in 3D. Authors use organic pixeled phantoms, but there phantoms are building with simple geometrical structures (spheres, cylinders, etc.), Bidinosti et al [4], propose one sphere inside a uniform radiofrequency field, like a pedagogical model to understand the electromagnetic induction problem. There models are designed using data obtained for example from Anatomic Atlas of Human Body [5]. Geometrical models, spend less memory, although have a precision lose.

Our objective in this paper is make an electromagnetic field effect simulation, over a realistic pixeled phantom human's brain. We propose a methodology to design there pixeled anatomical phantoms developed based on a real stack of Magnetic Resonance Imaging (MRI) slices making a 3D rendering image [6]. One time obtained the pixeled

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model we use a commercial computational equation solver, based on Finite Element Method (FEM), to calculate the electric and magnetic fields and the induced current density [7]. This anatomical model, have electric and magnetic properties reported in literature in term of the current frequency [8, 9].

At same time, we show a one possible application of this developed: the effect over subway's drivers, in Boston or in Line A in Mexico City, they have a catenary 2.5 m over the driver's head, this electric line transport 1500A of electrical current, with 750V of voltage.

## 2. Methodology

The origin of this methodology is a clear sequence of steps, since the model building to current intensity calculations.

### 2.1. Develop of Real Pixeled Phantom

We require a 3D stack of MR or CT Imaging, of the body or organ of interest. There imaging are charging in commercial software, like SolidWorks, then, we should be generate the rendering image, this is a 3D optimized model. Figure 1, shows the Real Pixeled Phantom of a head: skin, skull and brain, last both inside.

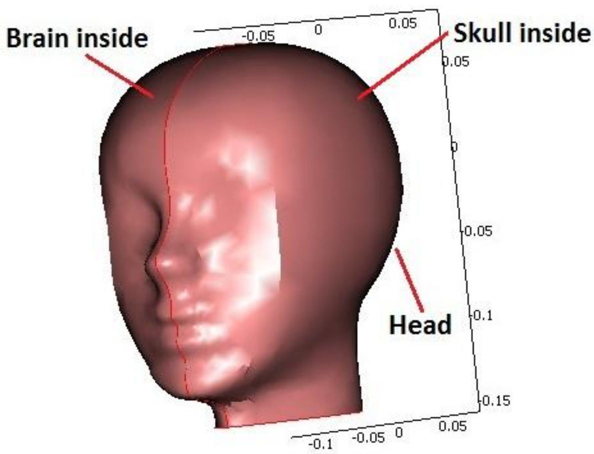


**Figure 1. Pixeled anatomical head/brain phantom model, designed from MR Imaging**

Figure 2, shows the internal structure of Real Pixeled Phantom.

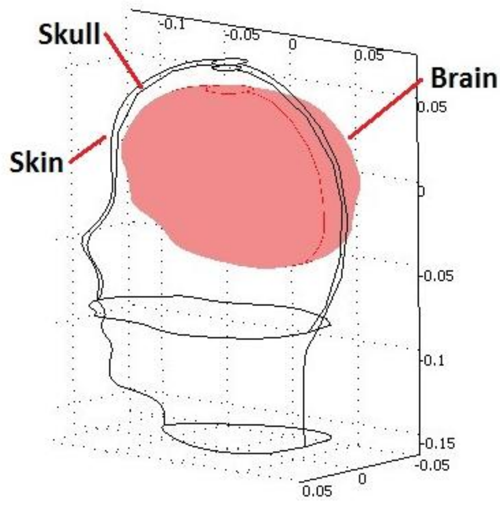


**Figure 2. Real Pixeled Phantom, internal structure**

We can see that with this procedure, we can build a Phantom of any organ, from human or animal body.

### 2.2. Complete Model to Electromagnetic Field Calculations

Once that we have the Pixeled Phantom, we should be generate the complete model system (particular application), to solve the Maxwell's equations, with this objective in mind, we used a commercial software based in FEM, this method require the establishment of a system's boarder, to limit the calculations volume. In first place, FEM makes necessarily a tetrahedrical mesh. One mesh with high density of elements, gave us a more precise and detailed solution, but the memory and calculation time, grow exponentially. When the model is complexes or of great size, is common use a very coarse mesh.

Taken the above considerations, our head model, just conserve skull and brain organs, because the skin-skull interface generate an enormous quantity of mesh elements, beyond of computer memory scopes. The segment bar have 22 cm of large, 1 cm of diameter, represent the catenary (alimentation line) in some subways services, transport 1500 A at 750 V, the current density is 15 x $10^2$ A/$m^2$. This catenary is collocated at 50 cm from the driver's head. Finally the external cylinder marks the system insulated frontier, there dimensions are 24 cm of high and 68 cm of diameter. Figure 3, shows the complete model.

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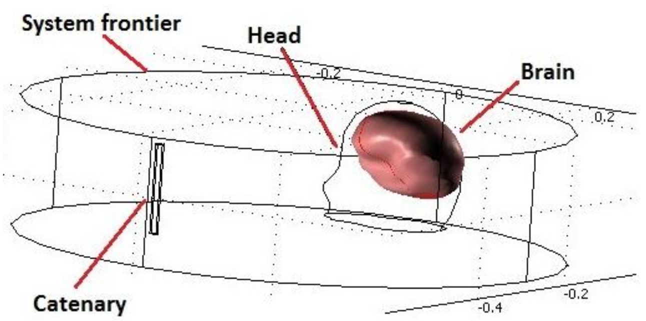


**Figure 3. The brain is into the head model and the catenary is 50cm away from head. The extern cylinder define the system boarders**

Due the complexity and dimensions of the complete model, we choice a very coarse mesh. Then the mesh elements are minimal and let us to no exceed the computer limits.

### 2.3. Mathematical Develop

The mathematical model was derived from Maxwell's equations (1-4). After, this model will be discretized by FEM to be numerically solved.

We used a quasistatic approximation, i.e. the model is limited to low frequencies. This let us make some assumptions to simplify the equation's ensemble.

$$\nabla\times\vec{E}+\frac{\partial\vec{B}}{\partial t}=0 \qquad (1)$$

$$\nabla\times\vec{H}-\frac{\partial\vec{D}}{\partial t}=\vec{J} \qquad (2)$$

$$\nabla\cdot\vec{D}=\rho \qquad (3)$$

$$\nabla\cdot\vec{B}=0 \qquad (4)$$

Considering force/charge rate $\vec{F}/q$ expressed in Lorentz force (5) terms, at a relative speed ($\vec{v}$) of model respect to reference system:

$$\frac{\vec{F}}{q}=\vec{E}+v\times\vec{B} \qquad (5)$$

The current density in a conductor medium, with an external current present is:

$$\vec{J}=\sigma\frac{\vec{F}}{q}+\vec{J}e \qquad (6)$$

Introducing (5) in (6):

$$\vec{J}=\sigma(\vec{E}+v\times\vec{B})+\vec{J}e \qquad (7)$$

Using (7) in (2):

$$\nabla\times\vec{H}-\frac{\partial D}{\partial t}=\vec{J}=\sigma(\vec{E}+v\times\vec{B})+\vec{J}e \qquad (8)$$

When a field oscillate to single frequency, can be expressed like the product of two complex functions, one in position and other one in time:

$$\vec{A}(\vec{r},t)=\mathrm{Re}\left|\vec{A}(\vec{r})e^{-j\omega t}\right| \qquad (9)$$

$\vec{A}(\vec{r},t)$ is a complex quantity called the phasor or magnetic potential vector. Using the magnetic and electric ($V$) potentials, we can rewrite $\vec{B}$ and $\vec{E}$:

$$\vec{B}=\nabla\times\vec{A} \qquad (10)$$

$$\vec{E}=-\nabla V-\frac{\partial\vec{A}}{\partial t} \qquad (11)$$

Taking the complete constitutive equations, for $\vec{B}$ and $\vec{D}$ in isotropic and linear medium:

$$\vec{B}=\mu(\vec{H}+\vec{M}p) \qquad (12)$$

$$\vec{D}=\varepsilon\vec{E}+\vec{P}o \qquad (13)$$

Using the constitutive equations (12) and (13) in (12), we obtain:

$$\nabla\times\left(\frac{\vec{B}}{\mu}\right)-\frac{\partial(\varepsilon\vec{E}+\vec{P}o)}{\partial t}=\sigma(\vec{E}+v\times\vec{B})+\vec{J}e \qquad (14)$$

Using equations (3) and (4), (14) is transformed in:

$$\nabla\times\left(\frac{\nabla\times\vec{A}}{\mu}-\vec{M}p\right)-\frac{\partial\left(\varepsilon\left(-\nabla V-\frac{\partial\vec{A}}{\partial t}\right)+\vec{P}o\right)+\vec{P}o)}{\partial t}=$$
$$\sigma\left(-\nabla V-\frac{\partial\vec{A}}{\partial t}+\vec{v}\times\nabla\times\vec{A}\right)+\vec{J}e \qquad (15)$$

When the medium is not magnetic $\vec{M}p=0$ and no polarized $\vec{P}o=0$. For a static geometry $\vec{v}=0$ and without external electrical potential $V$ = 0. Now we can reorder the equation (15), obtaining:

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$$\sigma \frac{\partial \vec{A}}{\partial t} + \varepsilon \frac{\partial^2 \vec{A}}{\partial t^2} + \nabla \times \left( \frac{\nabla \times \vec{A}}{\mu} \right) = \vec{J}e \qquad (16)$$

If we applied a harmonic in time function, like the magnetic potential function (9), at the equation (16), we obtain:

$$\left( j\omega\sigma - \omega^2 \varepsilon \right) \vec{A} + \nabla \times \left( \mu^{-1} \nabla \times \vec{A} \right) = \vec{J}e \qquad (17)$$

however,

$$\nabla \times \left( \mu^{-1} \nabla \times \vec{A} \right) = \mu^{-1} \left( \nabla \times \nabla \times \vec{A} \right) \qquad (18)$$

appling vectorial algebra in (18):

$$\nabla \times \left( \mu^{-1} \nabla \times \vec{A} \right) = \mu^{-1} \left( \nabla \nabla \cdot \vec{A} - \nabla^2 \vec{A} \right) \qquad (19)$$

because $\vec{A}$ is the magnetical potential:

$$\nabla \cdot \vec{A} = 0 \qquad (20)$$

then the equation (19), can be writing:

$$\nabla \times \left( \mu^{-1} \nabla \times \vec{A} \right) = -\mu^{-1} \nabla^2 \vec{A} \qquad (21)$$

using last result in equation (17), we can write:

$$\left( j\omega\sigma - \omega^2 \varepsilon \right) \vec{A} + \mu^{-1} \nabla^2 \vec{A} = \vec{J}e \qquad (22)$$

or one equivalent form:

$$\left( j\omega\sigma\mu - \omega^2 \varepsilon\mu \right) \vec{A} + \nabla^2 \vec{A} = \mu \vec{J}e \qquad (23)$$

if we want calculate the electrical potential in just one direction, is possible simplify the equation (23), let it in scalar form:

$$\left( j\omega\sigma\mu - \omega^2 \varepsilon\mu \right) A_z + \nabla^2 A_z = \mu Je_z \qquad (24)$$

If we solve this last equation for *Az*, through the equations (10) and (11), we can obtain the magnetic and electric fields. Here we used a commercial software, to discretised the equation and using FEM, that be solved. The solutions are presented in graphical mode (see the result section).

The realistic pixeled models and all simulations, was realized with a Dell's lap top, on Windows 7 platform, double core processor and 3Gb in RAM.

The MRI stacks, was proportioned by Medic Imagenology Centre of Universad Autónoma Metropolitana-Iztapalapa.

Variables list:

$\vec{E}$ Electric field (V/m).
$\vec{B}$ Magnetic field (T).
$\vec{H}$ Magnetic field intensity (A/m).
$\vec{D}$ Electric field intensity (T).
$\vec{J}$ Current density (A/m$^2$).
$t$ Time (s).
r Electric charge density (C/m$^2$)
F Lorentz force (N).
$q$ Electric charge (C).
$v$ Relative velocity (m/s).
e Electric permittivity (F/m).
s Electric conductivity (S/m).
m Magnetic permeability (H/m).
$\vec{A}(\vec{r})$ Phasor or magnetic potential (A/Sm).
$\vec{M}p$ Magnetization (A/m).
$\vec{P}o$ Electric polarization vector (C/m$^2$).

## 3. Results

How we talk above, the final model used at the simulations is showed at Figure 3. Because the simulations, was realized at different frequencies, between 100 Hz to 100 MHz, we should be adjusting the electric conductivity and the relative electric permittivity values, for brain and bone (skull) at each frequency used [8], see Table 1.

**Table 1. Electric Conductivity and Relative Electric Permittivity Values, for Brain and Bone (Skull) at each Frequency Used**

| | Brain | | Bone | |
|---|---|---|---|---|
| Frequency (Hz) | s (S/m) | er | s (S/m) | er |
| 100 | 0.06 | 20E6 | 0.02 | 7000 |
| 1 K | 0.1 | 7E6 | 0.02 | 2000 |
| 100 K | 0.1 | 3000 | 0.02 | 300 |
| 1 M | 0.2 | 700 | 0.02 | 150 |
| 10 M | 0.3 | 300 | 0.04 | 30 |
| 50 M | 0.4 | 200 | 0.03 | 20 |
| 100 M | 0.5 | 80 | 0.08 | 20 |

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We consider one catenary with 100 $mm^2$ of transversal section area, and 1500 A of current intensity, then, the current density is 15 x $10^6$ $A/m^2$.

With all this parameters, we can make the simulations, for example of electric field. Figure 4, shows the electric field simulation like vertical slices, and the effect intensity, are represented with a colour distribution. At same time, the streamlines, represent the magnetic field effect. This run was at 50MHz.

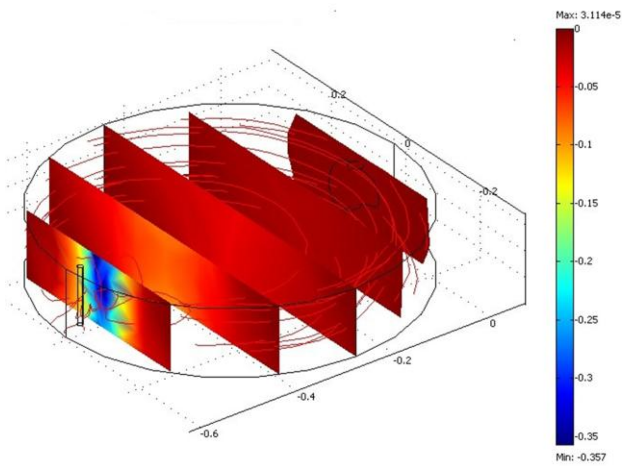


**Figure 4. The slices are the electric field simulation. The streamlines are the magnetic flux density at 50 MHz**

Figure 5, shows the magnetic field in slices at saggital cuts and the same magnetic field in streamlines representation. This computation was at 10 MHz. If we follow the streamlines of both, Figure 4 against Figure 5, we can see the differences of effects about the frequency changes.

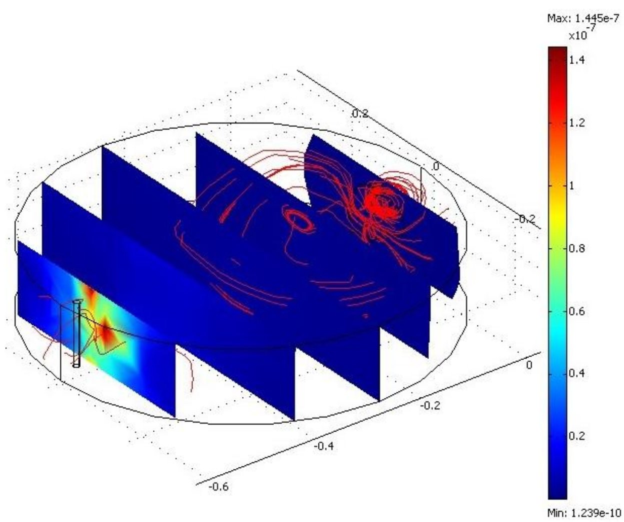


**Figure 5. Magnetic flux density at 10MHz, showed in slices and stream lines**

Figure 6, shows the magnetic flux density just in stream lines at 100MHz:

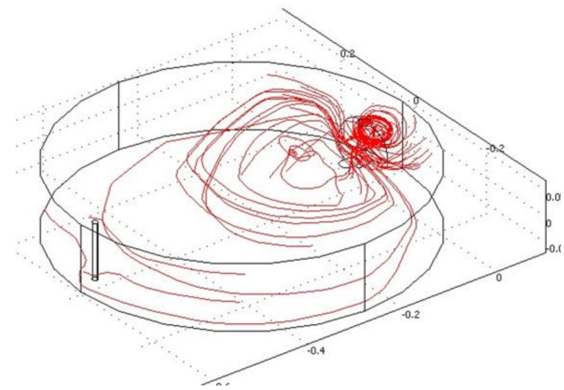

**Figure 6. Magnetic flux density in streamlines at 100MHz**

Another important calculation is the inducted current over the organs and tissues. In this case, we take points along the strike line between the catenary and the head. Figure 7 shows this fact, and Table 2 contains the registers.

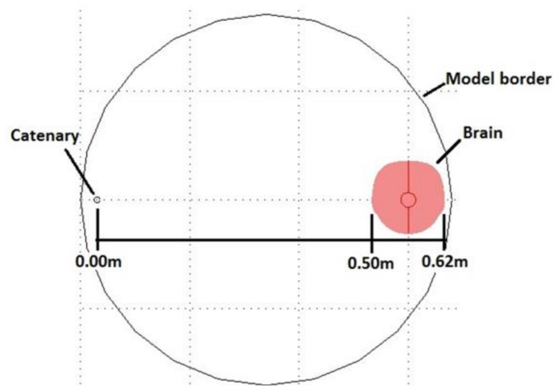


**Figure 7. Line of positions to calculate the inducted current**

**Table 2. Induced current densities over the brain pixeled model, in function of frequency and distance**

| Frequency Hz / Distance m | 100 | 1K | 100K | 1M | 10M | 50M | 100M |
|---|---|---|---|---|---|---|---|
| 0.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.5 | 7.8E-4 | 8.3E-4 | 3.4E-4 | 4.6E-4 | 6.9E-4 | 9.8E-4 | 1.4E-3 |
| 0.53 | 7.2E-4 | 7.5E-4 | 8.4E-5 | 2.0E-4 | 3.1E-4 | 4.3E-4 | 6.1E-4 |
| 0.56 | 4.2E-4 | 4.5E-4 | 5.3E-4 | 1.3E-4 | 1.9E-4 | 2.8E-4 | 4.0E-4 |
| 0.59 | 1.8E-4 | 1.9E-4 | 2.4E-5 | 3.5E-5 | 5.2E-5 | 7.6E-5 | 1.1E-4 |
| 0.62 | 1.1E-4 | 1.1E-4 | 1.7E-5 | 2.7E-5 | 4.1E-5 | 5.9E-5 | 8.4E-5 |
| 0.63 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Obviously, induced current densities in zero, corresponds at positions filled with air, then, the graphic in Figure 8, start in 0.50m, the shorter distance between the catenary and the brain model.

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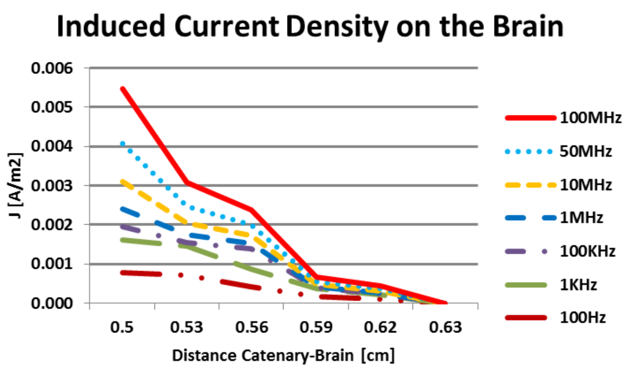


**Figure 8. Induced current density on the brain. The catenary is 50cm of the brain**

The graphic in Figure 8, confirm the result expected, the induced current density, increase when the frequency of radiation grows, and decrease with distance.

For the parameters that we used in this specific case, the induced currents, are very low (few mA). In applications like the Mexican subway, the catenary is 2.5m head away, is clear that a possible damage in brain is not probable.

# 4. Conclusions

This novel methodology to obtain realistic pixeled phantom model, can be applied to any organ or body if it be scanned with a MRI or CT system. There phantoms are optimized to any commercial programs of MATLAB's family, then we can simulate the interaction of one electromagnetic field over the model, obtaining the field modified by de organs, the induced current over any organic surface, so we can determinate possible injures or damages over the organs. All this computational process, results too optimized, because with little memory is possible realise the calculation in very short time lapses. Additionally, the simulation gave us a 3D imaging that we can see in any angle or position and we can see slices in any axes of the organ under study.

The applications of this procedure are unlimited, can be used to help to predict the consequences in the application of a medical procedure, or the effects over a human because he stay, near of a source of one electromagnetic strong field.

The methodology, let us realize different simulations, changing important parameters of radiation like: frequency or intensity, obtaining in just few minutes a whole study of different possible stages.

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