The Effects of High-Altitude Electromagnetic Pulses on human body:

Propagation, Dosimetry (SAR), and Comparative Study

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Abstract – The development of different technologies using electromagnetic waves in various applications (telecommunications, medical, military, etc.) was beneficial for humanity but, on the other hand, created new challenges to human health. The increasingly complicated electromagnetic environment has led to a growing interest in the study of the electromagnetic field's interaction with biological tissues.

The majority of research studies the health effects of mobile phones, but there is less study on the effects of other electromagnetic sources, such as the high-altitude electromagnetic pulse.

The High-altitude Electromagnetic Pulse (H-EMP E1) can cause malfunctions and disorder in electronic equipment and serious damage to electric power systems and communication networks. But we don't know exactly the effects of EMP on biological tissues and the human body.

The work presented in this paper aims to study the propagation of electromagnetic pulses (EMP) and show their predicted effects on a human body in different cases (in open space and in a shielded environment such as a vehicle).

For that, we use two models (simplified and anatomical) in a 3D simulation in order to study dosimetry and show clearly the effects on the human body by calculating the Specific Absorption Rate (SAR), and we compare, interpret, and explain the results between the two models.

Key words - Electromagnetic pulse, SAR, electromagnetic effects, high voltage pulse,human models, electromagnetic wave, electromagnetic compatibility.

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1. Introduction

H-EMP is one of the important damaging effects of high-altitude nuclear explosions and has the characteristics of a large amplitude, a short rise time, a short duration, and a wide exposed area

[3]. HEMP can couple into electronic systems through the gaps and holes on the cable, antenna, and metal shield, causing interference or damage to electronic systems [1]. Therefore, it attracts the attention of researchers.

A very short pulse has maximum wavelengths and a high spectral content, which offer several advantages. This type of phenomenon is represented in nature by lightning [4], which is a brief electrical discharge of the electrostatic energy accumulated between the clouds and the earth, accompanied by electromagnetic effects.

2. Electromagnetic Pulse Signal

The electromagnetic form used in our simulation is the E1 bi-exponential signal as excitation according to MIL-STD-464A [8] and IEC 61000-2-9 standards (Fig. 1). We generate our electromagnetic pulse in a 3D simulation [5].

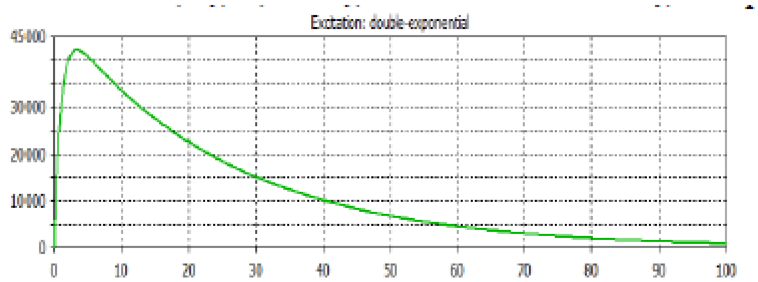


Fig.1. E1 bi-exponential signal

Our example of study is the illumination of the human body by an electromagnetic pulse (EMP) in different situation, in a free space and inside a vehicle (Figure 24), to answer the questions if our generated EMP can

affect the internal organs of the human body, and if the EMP is harmful for the human body?

3. 3d Electromagnetic Simulation

The presented simulation gives an analysis of the SAR values obtained by 3D electromagnetic simulations where our biological model was exposed to the electromagnetic pulse HEMP [6].

- **3d Model Of Simulation**

The right choice of biological model [15] is essential for the reliability of a medical simulation. Generally, in simulation, they use two types of biological human models : homogeneous models and heterogeneous models (Fig. 2).

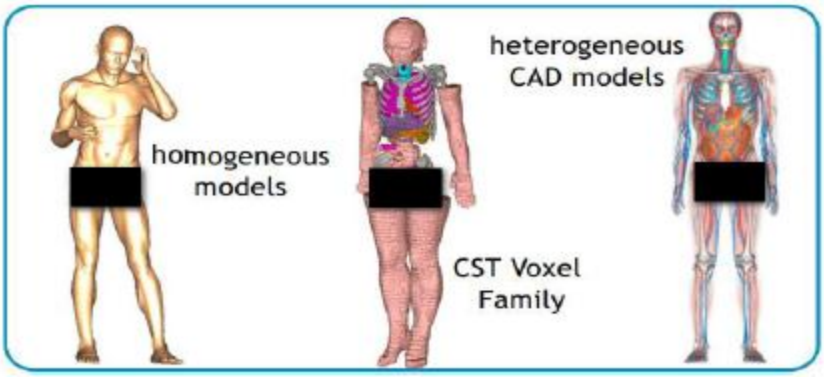
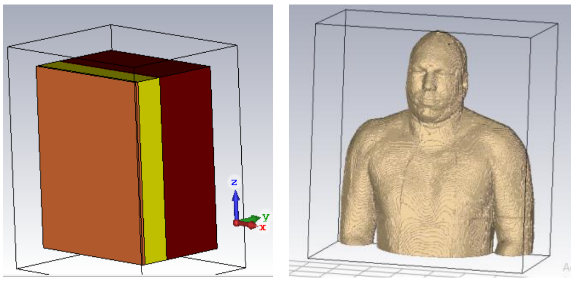


Fig.2. biological model

Homogeneous model and heterogeneous human biological model [17] are both used in scientific research and medical studies [10] to understand the human body and its functions. However, they differ in terms of the level of complexity and diversity they capture. A homogeneous model, also known as an idealized model, assumes that all individuals or parts of a population are identical and have the same attributes. It disregards the variations and differences that exist among individuals and represents an average or generalized human body. This type of model is commonly used in basic research studies where the aim is to understand general trends or principles without considering individual variations. On the other hand, a heterogeneous human biological model takes into account the diversity and complexity of human individuals. It recognizes that individuals may differ in terms of age, sex, genetics, physiology, and other factors and aims to capture this diversity in a more detailed and accurate manner. Heterogeneous models are often used in clinical and translational research as they provide a more realistic representation of how different individuals may respond to diseases, treatments, or interventions. In summary, the main difference between a homogeneous model and a heterogeneous human biological model lies in the level of complexity and diversity they represent. While homogeneous models assume all individuals are identical and disregard variations, heterogeneous models aim to capture the diversity and individual differences that exist within a population.

The choice of the model has a direct impact on the results, which will diverge between homogeneous and heterogeneous models. On the other hand, the calculation time in the heterogeneous model is very long and requires powerful computer machines [15].

In our study, we realized a simplified model (Fig. 3), which, on the one hand, avoided the homogeneity of the homogeneous model and, on the other hand, was simpler with fewer details than the heterogeneous model.



Anatomic model with a pacemaker
Simplified model with a pacemaker

Fig.3. Human body models

In our 3D simulation, we use two models (Fig. 3) : the anatomic human body and the simplified human body.

We will make a comparison between the two models in different cases. In a simplified model, we present the human body in three simple layers (skin, fat, and muscle) and enter the thickness and characteristics of the conductivity and relative permittivity for each layer. We use the simplified model in free space and in a shielded area (a vehicle), where the metal body of the car (Fig. 4) is similar to an electromagnetic cavity with openings, in which our radiation signal is the potential source of external disturbance (Fig. 1). We used a 3D vehicle model in a STEP format with a reel dimension, and we introduced the entire characteristic (permeability, conductivity, etc.) for the metal body of the vehicle.

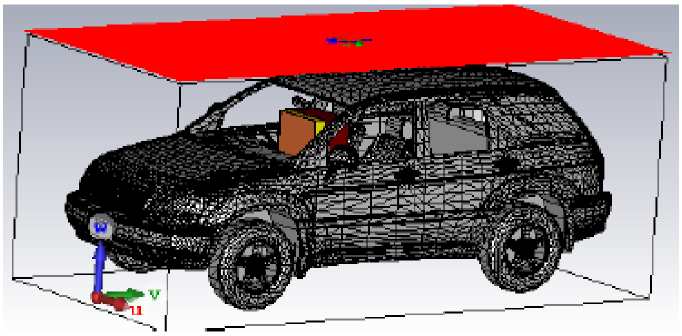


Fig. 4. The 3D vehicle model and EMP signal.

The anatomic model is a professional model; in our case, we can use the Austin and the CST anatomic human models.

An EMP typically contains energy at many frequencies. The shortness of the pulse means that it will always be spread over a range of frequencies. In order to analyze the SAR distribution in the human body resulting from exposure to radiofrequency electromagnetic fields, 3D simulations were performed.

The simulations were performed on a hexahedral mesh using the transient solver. We use the E1 bi-exponential signal as excitation (Fig. 1). The frequency range was between 0.1 and 100.1 MHz, and field monitors were used for electric fields, power losses, and SAR. As a post-processing result, SAR values were obtained according to the IEEE C95.3 standard averaging method.

- **Sar In The Human Body**

Specific Absorption Rate (SAR) is an electromagnetic absorption of a human body that has become an important issue as governments strictly limit it. Due to the extensive spread of mobile handsets and other products, electromagnetic radiation has rapidly received increased attention. The radiation can be evaluated by the specific absorption rate (SAR), which represents the time rate of microwave energy.

When human tissue is subjected to an RF field, part of the field is reflected, and the other enters the body [9]. The radiation produced by this interaction must be quantified because it can cause biological effects. The field that penetrates inside the tissues can be calculated using electromagnetic models, and the energy dose absorbed by transformation into heat is quantified by the power absorbed per unit mass of material biologically exposed. It is defined by the specific absorption rate (SAR).

The heating ability of the particles is quantified by the specific absorption rate (SAR) [9], an extrinsic parameter based on the clinical response characteristic of power delivered per unit mass. Clinically, SAR is used to denote the transfer of energy into the human body by radio-frequency electro-magnetic fields, such as those generated by mobile phone use or exposure to MRI scanners, and also by other means, such as ultrasound. In the clinical context, the SAR refers to the power dissipation per gram of living human tissue. Scientists use the SAR (specific absorption rate) to determine the amount of radiation that human tissue absorbs [10].

- **Wave Propagation And The Human Body**

The body behaves as a lossy dielectric material and absorbs RF power [6]. The kinetic energy inside the human tissue increases as a function of time when the microwave energy is dissipated within. If this energy is sufficiently high, the temperature will linearly increase, and the rate of this rise is determined by the power deposition. If the frequencies of RF from a mobile phone or other electromagnetic sources are close to the resonance frequency of the tissue, then more heat is transmitted to the human body [2], which is mainly composed of water, electrolytes, and complex molecules [3]. Thermal effects such as dielectric heating are the obvious effects of electromagnetic (EM) waves. In our case, we don't study continuous electromagnetic sources but rather transitory sources such as electromagnetic pulses.

- **Sar Standarts**

The growing number of radio systems owned by private individuals and industrialists led to the publication of international standards by ICNIRP and IEEE in order to limit the risk of electromagnetic overexposure for people. Various organizations are involved in standardization and regulation, providing guidelines for measurement and simulation setup as well as defining limits [18].

Two international bodies, ICNIRP (2009) and IEEE (2005), have developed guidelines in which the radiofrequency exposure limits for mobile phone users are expressed in terms of specific absorption rate (SAR). The SAR is defined as a measure of the rate at which energy is absorbed by the body when it is exposed to a radio-frequency electromagnetic field. Usually it is averaged either over the whole body or over a small sample volume (typically 1 g or 10 g of tissue) and can be expressed by the following formula:

$$\mathrm{SAR} = \frac{\iiint \frac{\sigma(r)|E(r)|^2 dV}{\rho(r)}}{V}\left[\frac{W}{kg}\right] \quad (1)$$

σ represents the electrical conductivity, and ρ is the mass density of the sample tissue. The electric field strength E magnitude is given in terms of the root mean square value.

For radiofrequency exposure [7], governments define the maximal allowed exposure in terms of energy absorbed in the head and the limbs. Namely, the FCC in the USA requires an SAR level of maximum 1.6 W kg−1 taken over a volume that contains 1 g of tissue, while CENELEC in Europe requires a maximal SAR value of 2 W kg−1 averaged over 10 g of tissue. The SAR values mentioned previously refer to the maximal value, which may appear in the head, while for the limbs, the maximal SAR value is 4 W kg−1.

	ICNIRP "Health Physics" Avril 1998	CENELEC ENV 50166-2 1995	IEEE C95.1-1991 Etats-Unis
Sector of application	International	Europe	Etats-Unis
Frequency range	100kHz-10GHz	10kHz-300GHz	100kHz-6GHz
Average Whole Body SAR	0,08W/kg	0,08W/kg	0,08W/kg

Local SAR on a mass of reference	2W/kg	2W/kg	1,6W/kg
mass of reference	10g	10g (cube)	1 g (cube)
local SAR for hands, wrists, feet and ankles	4W/kg	4W/kg	4W/kg
mass of reference	10 g	10 g (cube)	10 g (cube)
density of power (W/m2)	f(MHZ)/200	f(MHZ)/200	f(MHZ)/150
Electric field threshold	1 ,375	1 ,375	
Magnetic field threshold	0,0037	0,0037	

Table1. SAR *international standards*

The SAR calculation can be carried out as a post-processing step after the simulation. We obtain by simulation the power loss density, and we calculate the SAR values and fields. We use the FPBA mesh type for SAR simulations.

The Specific Absorption Rate (SAR) is defined as the time derivative of the incremental energy (dW) absorbed by (dissipated in) an incremental mass (dm) contained in a volume element (dV) of a given mass density (p).

$$SAR = \frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{dW}{dm}\right) = \frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{dW}{\rho \cdot dV}\right)$$

$$PLD = \frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{dW}{dV}\right) \qquad (2)$$

$$SAR = \frac{P}{\rho} = \frac{\sigma E^2}{\rho} = \frac{J^2}{\rho\sigma}$$

The SAR value is expressed in units of watts per kilogram (W/kg).

The Power Loss Density (PLD) value is expressed in units of watts per cubic meter (W/m3).

Where σ is the conductivity of human tissue, ρ is the density, and |E| is the norm of the electric field. The SAR value is an average over a region of either 10 g or 1 g of tissue.

- **Sar Calculation And Results:**

Before results, we give a bref definition for different type of SAR:

- Whole-body-averaged SAR: The value is obtained by dividing the total power absorbed in the human body by the full body weight.
- Local SAR: SAR is given as a numerical value per volume element and becomes a space distribution function. For this function, the mass mean value in arbitrary tissue volume is called local SAR.
- Total SAR: The tissue power divided by the tissue mass.

- Point SAR: Local SAR without mass or volume averaging

- Max point SAR: The maximum point SAR of all grid cells. For each grid cell, its point SAR is calculated by its absorbed power divided by its mass.
- Maximum SAR: The maximum of the spatially averaged SAR for the given averaging mass. For point SAR calculations, Mass Averaged SAR (typically 1g or 10g), often different limits for head, trunk and limbs.
- Absorbed power: The total power absorbed in biological tissue and other lossy normal material. The power loss density monitor used to calculate this SAR results.

Human model and tissue properties use the Voxel Data Import for very realistic SAR calculations (in anatomical model) or assign the appropriate material properties to our simplified human models using the material dialog.

The results for the SAR values for the simplified and the anatomical model are presented in figures (Figs. 5–11), where the 3D simulation of SAR in human body for the two models can give us answers and visualize effects:

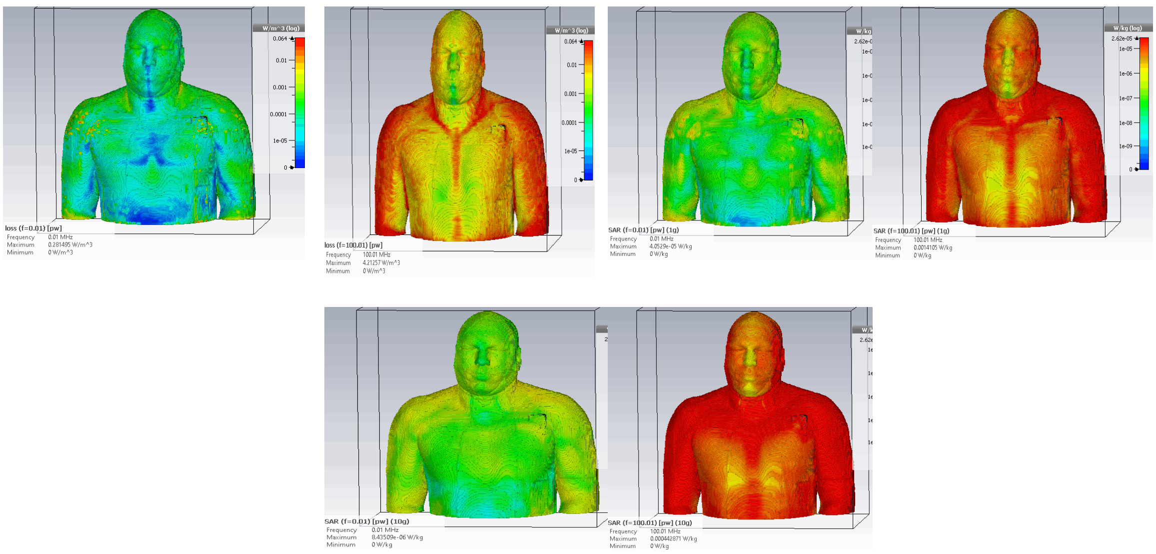


Fig.5 Exterior SAR calculation in anatomic human model

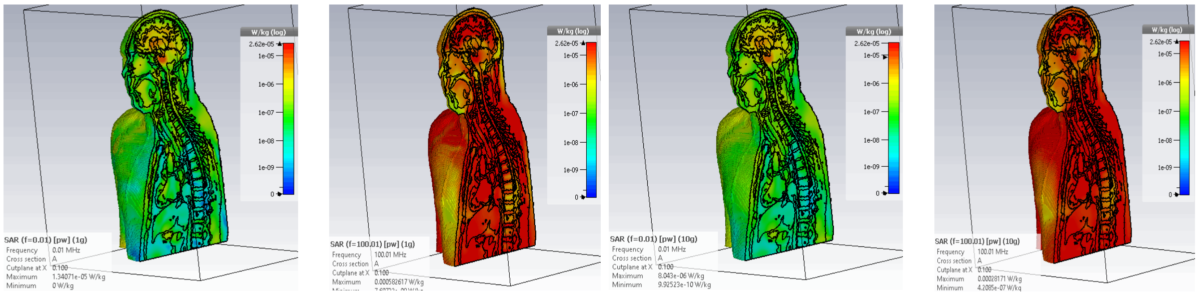


Fig.6 Interior SAR calculation in anatomic human model

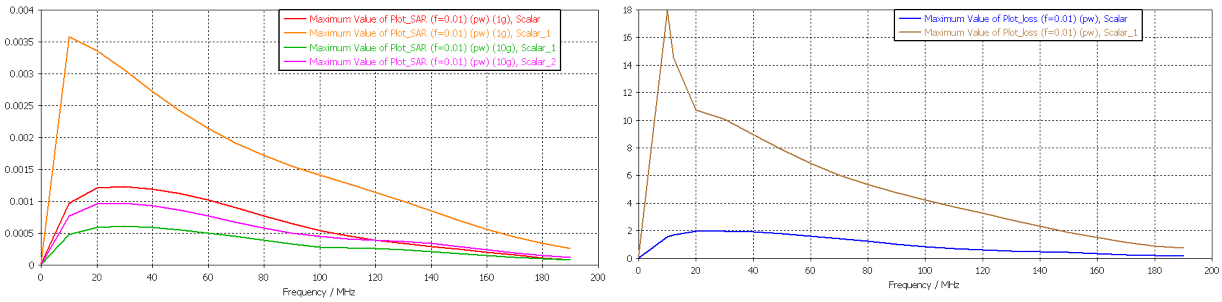


Fig.7. variation of SAR and power loss with frequencies (in anatomic human body model)

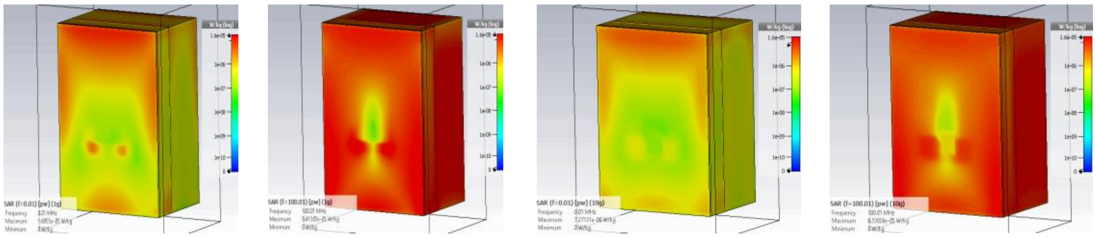


Fig.8. Exterior SAR calculation in simplified human model

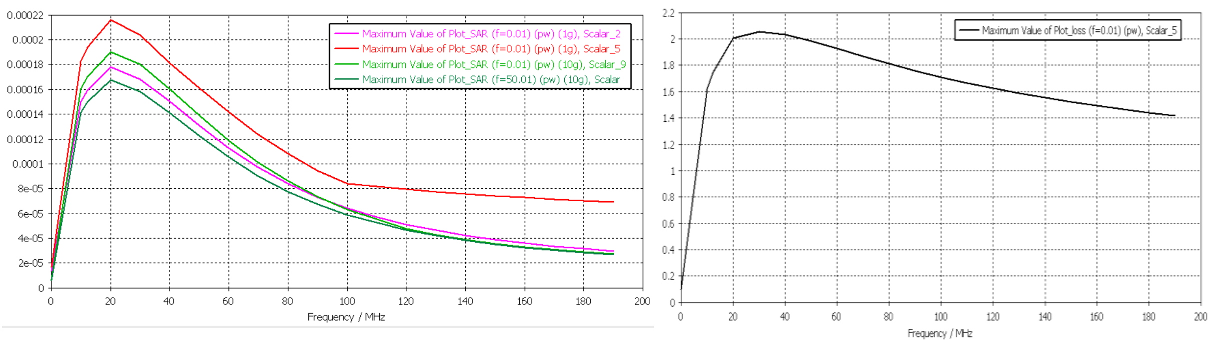


Fig.9. variation of SAR and power loss with frequencies (in simplified human body model)

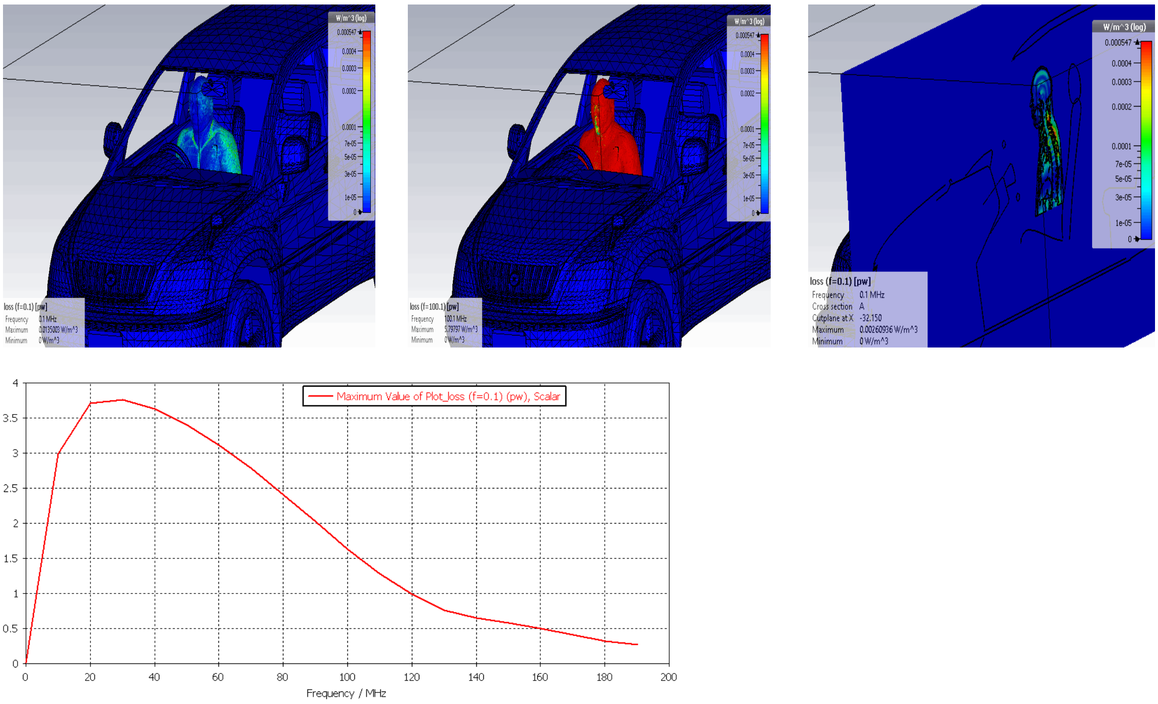


Fig.10. SAR and power loss calculation in anatomic human model inside vehicle

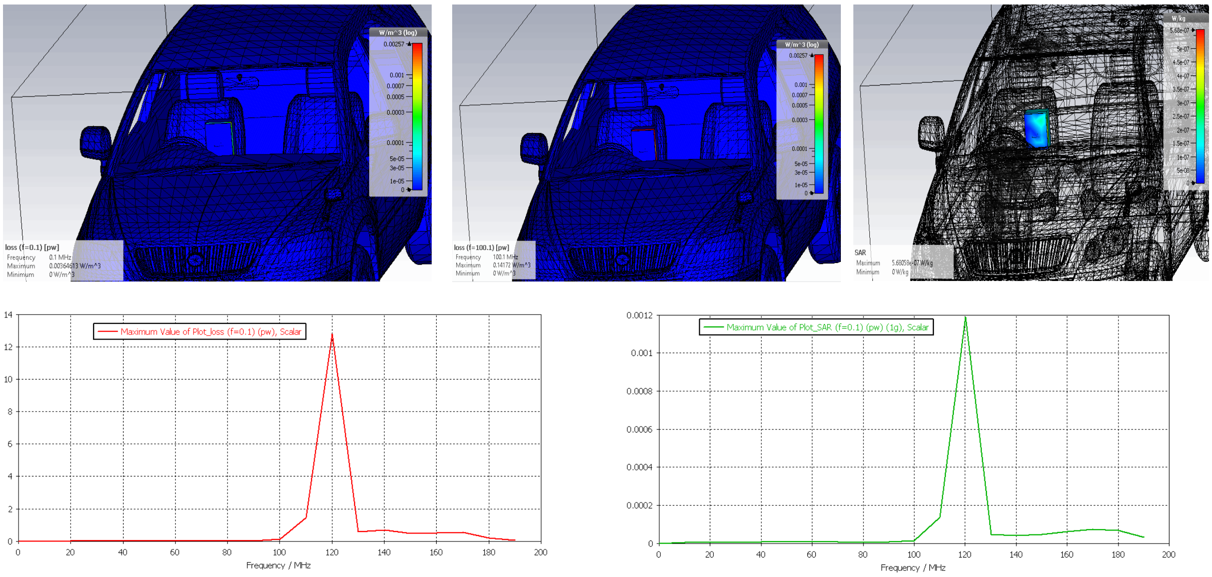


Fig.11. SAR calculation SAR and power loss in simplified human model inside vehicle

There are several parameters that can emerge from the 3D simulation, concerning the SAR and the power loss, surface currents, power flow, etc. In the table 2, we present a comparison of the results obtained from the different values of the SAR and power loss between the anatomical model (AM) and the simplified model (SM):

Parameters	Frequency (MHz)	A.M		S.M	
		FS	V	FS	V

	0.01	100.01	0.1	100.1	0.01	100.1	0.1	100.1
SAR 1g (W/Kg)	$4.05x10^{-5}$	0.00141	/	/	1.69 $x10^{-5}$	$8.41x10^{-5}$	$5.68x10^{-7}$	$1.41x10^{-5}$
SAR 10g (W/Kg)	$8.43x10^{-6}$	0.000442	/	/	7.27 $x10^{-6}$	$6.33x10^{-5}$	$4.89x10^{-7}$	$1.12x10^{-5}$
Power Loss (W/M^3)	0.251	4.21	0.013	5.797	0.097	1.71	0.003	0.14

Table2. *Comparative table of the results between the anatomical model (AM) and the simplified model (SM)*

- **Interpretation and explanations of the results:**

We notice that there is the same distribution of SAR and power loss globally between the two models and between the calculation SAR of 1g and the SAR of 10g, with the same frequency (≈ 20 MHz) of the maximum SAR in figures 5, 6, and 8.

At a frequency of 0.01 MHz in a free space (FS) for the anatomical model (AM), the variation of SAR (1g) is between 0 and SARMAX = 4.05x10-5 (W/Kg), and for the simplified model (SM), it is between 0 and SARMAX =1.69x10-5 (W/Kg).

At a frequency of 0.01 MHz in a free space (FS) for the anatomical model (AM), the variation of SAR (10g) is between 0 and SARMAX = 8.43x10-6 (W/Kg), and for the simplified model (SM), it is between 0 and SARMAX =7.27x10-6 (W/Kg).

At a frequency of 0.01 MHz in a free space (FS), for the anatomical model (AM), the variation of power loss is between 0 and Power Loss MAX = 0.251 (W/M3), and for the simplified model (SM), it is between 0 and Power Loss MAX =0.099 ≈ 0.1 (W/M3).

At a frequency of 100.01 MHz in a free space (FS) for the anatomical model (AM), the variation of SAR (1g) is between 0 and SARMAX =0.00141 (W/Kg), and for the simplified model (SM), it is between 0 and SARMAX =8.41x10-5 (W/Kg).

At a frequency of 100.01 MHz in a free space (FS) for the anatomical model (AM), the variation of SAR (10g) is between 0 and SARMAX =0.000442 (W/Kg), and for the simplified model (SM), it is between 0 and SARMAX =6.33x10-5 (W/Kg).

At a frequency of 100.01 MHz in a free space (FS), for the anatomical model (AM), the variation of Power Loss is between 0 and Power Loss MAX =4.21 (W/M3), and for the simplified model (SM), it is between 0 and Power Loss MAX =1.71 (W/M3).

According to the results, we can say that at lower frequencies, the simplified model gives approximate results with relatively the same variation of Power Loss and SAR on the human body as obtained by the anatomical model (AM).

For higher frequencies, there is a divergence in results between the simplified model and the anatomical model.

By comparison, we can say that the simulation values obtained by the anatomical model and the simplified model are not contradictory and are close. So the values obtained by our simplified model are accepted, but the anatomical model is more accurate and gives more details and precision.

It can be noticed that the maximal SAR value is higher in the realistic anatomical model than in the simplified model. However, this SAR value does not exceed the maximum allowed SAR value in the head prescribed by the FCC, CENELEC, and IEEE C95.1 (Table 1). The anatomical (realistic, inhomogeneous) model allows an accurate analysis of the SAR distribution inside the model. As shown in Fig. 6, the parts of the head that absorb the most energy can be identified. The maximum SAR values occur within the skin and fat tissue, but some increased SAR values occur in the muscles and in the mucous membrane in the nose.

.The plots of the variation of SAR and power loss for different cases are shown in Figures 7, 9, 10, and 11. The results show that in this case, the SAR values in the anatomical human head are less than the ones in the simplified model.

The maximal SAR value in the anatomical head decreases when the body is inside the vehicle (Figs. 10, 11). In this case, the vehicle absorbs a large part of the energy.

The SAR values in the head of the anatomical model, although larger than in the simplified model, as shown in Table 2, did not exceed the limits prescribed in the standards (Table 1). Additionally, a comparison of the results between two scenarios on the anatomical model showed that the presence of a body inside the vehicle leads to a decrease in the maximal SAR value.

It can be concluded that the vehicle has a "protective role", reducing the radio-frequency absorption in the body. The analysis of the maximal SAR values obtained by these simulations leads to the conclusion that the prescribed limits for radiofrequency exposure do not underestimate the SAR values. The simplified model does not have the same precision as the anatomical model given the dielectric characteristics, which are fixed for the entire frequency range. On the contrary, the anatomical model is made in such a way to have variable dielectric characteristics with the frequencies, which is more realistic. Nevertheless, the simplified model has a lack of precision, but the calculations are fast, so the simulation does not take a considerable amount of time like the anatomical model, and it can give us an order of magnitude of the values of SAR and power loss, which give us an overview with speed calculation without needing a machine with high performance; so we can use the simplified model to obtain quickly approximated values and the anatomical model for more accurate results.

4. Conclusion

The objective carried out and presented in this work was visulazing the effects of High-Altitude Electromagnetic Pulses on the Human Body: Propagation, Dosimetry (SAR), and Comparative Study, using 3D numerical method [19], whose results give us a clear concretion of this effect using a simplified and anatomical human model.

All living matter contains electric charges (ions, molecules, etc.) and insulating materials; it is therefore a weakly conducting medium. So human biomass can be considered a dielectric.

The electromagnetic wave that penetrates the tissue depends on the following electrical properties [4]: the permittivity electric ε, the magnetic permeability, and the conductivity electric σ of various tissues, as well as the thickness of the tissue, forward power, and operating frequency. The electrical properties of tissues vary with their content of water; the water content in fatty tissues is much higher than in non-fatty tissues.

SAR is a point quality, and its value varies from one location to the next. Tissue density, conductivity, and, most significantly, the E-Field are key parameters that determine the reliability and accuracy of a given SAR value.

Comparing standards for the maximum mass averaged SAR, it is worth mentioning that the volume of tissue used to define SAR can greatly influence the SAR values. If the absorbed energy is averaged over a defined tissue of 10g, the result may be less strict compared with the 1g averaged SAR. The latter provides a more precise representation of the localized microwave energy absorption and a better measure of SAR distribution inside the head. We can say that the response of the human body subjected to the Electromagnetic Pulse (EMP) effect is a complex problem [1] and very different from that of electronic devices.

The parameters that govern the EM response of the human body tend to also vary significantly with frequency. As frequency increases, the conductivity increases, and the permittivity decreases. This further complicates the reflection process. To account for this, there has to be data available for the frequency dependence of different organs in the human body.

Another complication is that for different human bodies, the water content has a very significant effect on its parameter values, so it may depend upon what the recent weather has been.

Research and debates on the potential harmful effects of electromagnetic waves on the human body [7] give us several studies that highlight potential health risks associated with prolonged exposure to certain electromagnetic fields, such as the BioInitiative Report [20], which is an independent review of over 3,000 scientific studies on the effects of electromagnetic fields (EMFs). The goal of the report is to assess the potential health risks associated with EMF exposure and recommend biologically-based standards for public safety. The BioInitiative Report concluded that long-term exposure to certain EMFs, especially from wireless communication devices and power transmission lines, may have adverse health effects. The report highlighted several concerns, including increased risks of brain tumors, neurodegenerative diseases, cognitive impairments, decreased fertility, and disturbances in the immune system. It was also suggested that EMFs may contribute to the development of certain childhood cancers and cause electromagnetic hypersensitivity in some individuals.

It's important to note that the BioInitiative Report has faced criticism from regulatory agencies and some researchers as it claims adverse health effects at levels below the existing safety guidelines set by governmental organizations such as the World Health Organization (WHO) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP). Critics argue that the report does not adequately consider the overall weight of evidence from the broader scientific community. Other scientific studies conducted so far do not provide conclusive evidence that electromagnetic radiation poses significant harm to human health.

We can say that daily and excessive exposure to electromagnetic sources that exceed the norms and standards of safety can be harmful for the human body and especially the brain, because the human brain is the most important and sensitive part, which contains more neurons and consequently the electrical system and an internal electrical field.

By using the 3D simulation and the obtained results of SAR compared to the standards [9], we visualize effects and confirm that we don't have the same harmful effects obtained in electronic devices. The values obtained do not exceed the safety values imposed by the different standards. The effect of an electromagnetic field that lasts over time has a greater impact on the human body than the effect of an electromagnetic pulse, even if this pulse is powerful. Electromagnetic pulses (EMPs) are rapid bursts of electromagnetic radiation [16] that can disrupt or damage electronic devices [11]. While EMPs can harm electronic systems, they don't directly affect the human body for several reasons: EMPs generate high-intensity electromagnetic fields that induce voltage surges in electronic circuits. Electronic devices are designed to operate within specific voltage and current limits. The high-intensity electromagnetic fields generated by an EMP exceed those limits and interfere with the normal functioning of electronic components, leading to malfunctions or permanent damage. However, the human body largely operates on chemical and biochemical processes, which are not directly affected by EMPs. In most cases, even if a person is in close proximity to an EMP source, the intensity of the electromagnetic radiation decreases rapidly with distance. Additionally, natural materials, such as buildings and other structures, or even just air, can provide some level of shielding against the effects of EMPs. This further reduces the likelihood of electromagnetic radiation reaching and affecting the human body.

The human body acts as a natural shield against electromagnetic waves to some extent. Our skin acts as a protective barrier, limiting the penetration of electromagnetic waves and reducing their potential harmful effects on internal organs. Additionally, the fluids, tissues, and bones in the body provide a certain level of resistance to the flow of electric currents induced by EMPs, further minimizing the potential damage.

Electronic devices are designed to operate within specific frequency ranges, and an EMP generally emits energy at a wide range of frequencies [14]. This energy can affect and overload electronic circuits, causing damage. In contrast, the human body is not sensitive to the same frequencies and is not equipped with electronic circuits that can be disrupted in this way [12] [13].

Electronic devices, being made of inorganic materials, can efficiently absorb and conduct electromagnetic energy, which makes them susceptible to damage. In contrast, the human body is primarily composed of organic matter, such as water and carbon-based molecules, which do not conduct electromagnetic energy as efficiently. As a result, the energy from an EMP is less likely to cause harm to the human body.

However, it is important to note that EMPs can indirectly affect human health and safety by disrupting critical infrastructure such as power grids, communication systems, and medical equipment, which in turn can have serious consequences. While the EMP itself does not directly harm the human body, it can lead to cascading effects that may impact various aspects of our lives.

It is important to note that extremely high-intensity EMPs, such as those generated by nuclear explosions or large-scale solar flares, can induce electrical currents in the human body, potentially causing minor physiological effects like tingling sensations or interference with implanted medical devices. However, these effects are still not comparable to the extensive damage often experienced by electronic devices.

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