

Human Health Risk Assessment of 4-12 GHz Radar Waves using CST STUDIO SUITE Software

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ABSTRACT

Background: The application of radar systems in telecommunications and aerospace science is important. However, engineering department's staff various tissues are always under chronic radiation generated by the radar fields which may affect health.

Objective: This study aims to evaluate the risk of radar wave exposure and to explore the effects and limitations.

Material and Methods: In this simulation study, an adult body model versus 1 watt source with a distance of 50 centimeters exposure has been simulated using the CST STUDIO SUITE. Furthermore, various physical and electrical properties of each tissue and organ for different frequencies and exposure times have been studied. The exposure dose limitations have been considered using the International Commission on Non-Ionizing Radiation Protection (ICNIRP) safety and health guide report.

Results: Total body absorbed doses for 4 GHz, 8 GHz, and 12 GHz frequency, and 6 min, 4 h, and 30 days exposure time, have been calculated as 1.136×10^{-5} , 1.598×10^{-5} , 1.58×10^{-3} , 1.521×10^{-5} , 3.122×10^{-5} , 4.52×10^{-3} , 4.1×10^{-5} , 10^{-4} , and 10^{-2} , respectively.

Conclusion: It has shown that the internal organs of the body and head will be under more risk by reducing radar frequencies from 12 GHz to 4 GHz. On the other hand, the higher frequency can cause a higher risk to the human skin. In addition, the maximum Specific Absorption Rate (SAR) for each case has been calculated. The results show that for this normalized source, the safety criteria have been respected, but for a higher source, the calculations must be repeated.

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Keywords

Human Health; Risk Assessment; CST Studio; SAR; Synapses; Ventricular

Introduction

The electric properties of all tissues have been practically measured and known [1-5]. Radar is a radio frequency wave detector used to observe and measure the distance, angle or velocity of objects. Radar systems have been widely used in navigation, aerospace, communication systems, and meteorology applications. In spite of the many reported hazards, associated with radar radiation exposure, applications of such systems are increasing [6-10]. On the other hand, aging and chronic diseases of the body are the fundamental challenges which affect the quality of human life. Resolving these concerns can have a sig-

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nificant impact on improving people's quality of life [11]. The results of studies about physical and even psychological problems of radar waves on human health have caused great concerns for those who live near the source of these waves or are exposed to these waves in the workplace. In children, some diseases such as cancer, reproductive failure, ocular defects and behavioral changes have been reported based on international safety standards [12-14].

Destructive effects of mobile phone exposure on short-term memory of elementary children have been shown in Movahedi research [15]. Mortazavi with emphasizing mobile waves destructive effects on mice bodies, by conducting practical tests, effective efforts to reduce this effect has proposed [16, 17]. Taheri has shown short-term absorption significant effects of 2.4 GHz Wi-Fi waves on antibiotics sensitivity [18]. The effect of Wi-Fi radiation on sperm count has been reported in Mahmoudi research [19].

Recent research on living organisms, especially about humans, have used passive radars to measure and monitor the health of body accurately. Hence, recognizing these waves and their effects on body activities has become a very important issue that can help to predict and prevent the spread of many chronic diseases [14, 20]. Moreover, according to [21], the use of micro-Doppler radars in a living environment, identifying biological characteristics, and monitoring overall life patterns and human conditions has become a topic of interest in bioscience research [21]. The independency of the Doppler radar from environmental factors such as light, ambient temperature, interfere with other waves in the environment and the fading effect causes it to be a powerful tool for long-term studies of respiratory diagnostics and monitoring and even sleep-related studies [21-23]. In [22], the Doppler radar system was used for monitoring the heart rate and breathing as a cytostatic model. In recent research, monitoring and analysis of respiration

patterns using microwave Doppler radar have been studied [24]. The results of this research have shown that the microwave Doppler radar is a powerful tool that not only applies to respiratory rate measurements but also can be successful in detecting different respiratory patterns.

In some cases, radar waves are used to diagnose the elderly's failures [25]. Different algorithms for analyzing and processing radar signals have been investigated. The radar waves and Doppler effects have been used in the heart rate measurement [26]. However, the issues formulated in standards, such as the IC-NIRP (FCC), have demonstrated undesirable effects of radar waves in exponential and high-power radiation, resulting in many harmful effects on human health. In another research, the effects of a weak magnetic field on biological systems have been studied [27]. The results have demonstrated that the radar signals can effectively reduce the growth rate of cancer cells. In 2016, the blood flow control systems (both virtual and remote) have been considered in the optimization of human biological activities exposed to the magnetic fields [28]. Moreover, in the radio frequency range, the safety and health of the users are of particular importance, because of the widespread use of the radar signals [29, 30].

As used in [31], Specific Absorption Rate (SAR) is an appropriate criterion for radiation biological effect. In this research, biological effects of the 60.42 GHz radar waves have calculated using FDTD method. Results indicate that exposure to low-power radiation around 60 GHz does not cause any significant effect, but about high-power radiations, destructive effect can be seen with considering SAR limits.

In this paper, to study the effects of the radar waves in the range of 4-12 GHz and the absorbed dose of the radiation, the human body model has been made using CST Studio Suite. In this way, it is possible to evaluate different parts of the body tissues in a microwave 3D

environment, and then conclude the final risks on human health.

Material and Methods

Radar features

In this simulation study, an adult body model versus 1 watt source with a distance of 50 centimeters exposure has been simulated using the CST Studio Suite. The radar system has a transmitter emitting radar waves, called radar signals. When these signals collide with a body, they scatter in different directions. But some of them are absorbed in and penetrate into the target. Two of the main concerns are the assessment of the absorption and efficiency of radar signals. When the target object moves toward (or away from) the radar, there is a slight change in the frequency of the wave, called the Doppler effect. Radar receivers are usually in the same place as the transmitter [30].

The concept of specific absorption rates

Based on the discussions in [29, 32], the SAR, is the amount of energy absorbed by the body when exposed to radio beams. This reflects the amount of electromagnetic energy absorbed by the human body from waves whose unit is the watt per kilogram. The higher the SAR leads to the higher the body's energy absorption, and it is the more dangerous for the human body. The specific absorption track is usually measured at an average which can be the average absorption trace on the whole body or a specific amount of tissue. Electromagnetic fields cause the body to warm or increase the temperature of cells. It also changes the function of muscle and nervous systems. Reduction in eyesight and increased stress are also the side effects of these fields, leading to loss of performance of the persons. These are problems that have been documented by various experiments and evidence of the effects of electromagnetic waves on the human body.

A more comprehensive review of these problems has been made in [24]. Here, we use the SAR parameter to investigate the effects of the radar waves.

Study of the basic properties of organs

Theory

The penetration depth (D_p) is defined as the distance in which the microwave power density has decreased to 37% of its initial value at the surface [33]:

$$D_p = \frac{1}{\frac{2\pi f}{v} \sqrt{\epsilon_r' \left[\sqrt{1 + \left(\frac{\epsilon_r''}{\epsilon_r'} \right)^2} - 1 \right]}} = \frac{1}{\frac{2\pi f}{v} \sqrt{\epsilon_r' \left[\frac{\sqrt{1 + (\tan \delta)^2} - 1}{2} \right]}} \quad (1)$$

where ϵ_r'' is the relative dielectric loss factor and v is the speed of microwave (m/s).

The penetration depth of the microwave power is calculated using Eq. (1), which shows how it depends on the dielectric properties of the dielectric material or human body organs.

Due to the increase in the conduction coefficient of the body tissues by the incremental frequency, decreasing the depth of the shell with increasing frequency is predictable. In other words, increasing the frequency (f) will reduce the penetration depth (D_p).

Methodology

To investigate the effect and mode of interaction of radar waves on the human body, it is necessary to have a realistic model of the human body. Voxel models are the second generation of computer models of the human body, using small cubes (voxels) as the smallest constituent elements and making it possible to create the geometric structures of the human body and its internal organs. Figure 1 represents two voxel models, which have been made from the CST Studio Suite software, consist of millions of voxels with dimensions of $2.5 \times 2.5 \times 2.5 \text{ mm}^3$. This voxel size has been chosen because the voxel size should be smaller than one-tenth of the wavelength. Thus,

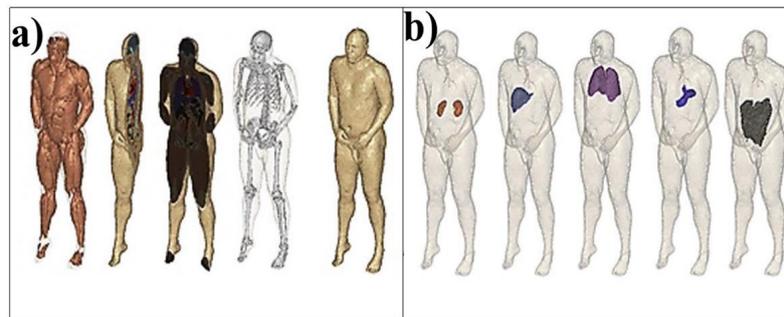


Figure 1: a) Simulated human tissue and skeletal model, b) Simulated some of the body organs

$$f = \frac{C}{\lambda} \xrightarrow{f=4-12\text{GHz}} \lambda = 25 \sim 75 \Rightarrow \text{voxel step } 2.5 \sim 7.5 \text{ (2)}$$

To reduce computational cost with maintaining precision, a similar phantom with 2.5 mm (the dimensions of the body voxel are considered to be 1 tenth of the wavelength) has been selected for the step size of the voxels.

It should be noted that in order to study electromagnetic interactions, in addition to having the geometry and physical structure of the human body, the electrical and physical properties of tissues must also be considered. For this purpose, the electrical and physical properties of the tissues should also be taken into account. Therefore, with the assumption that human tissues are not magnetized ($\mu = 0$), the electrical properties of the body tissues are directly related to the amount of water of which they consist [32]. The higher amount of water in the tissues such as blood or urea causes their conductivity coefficient to increase [34]. On the contrary, the tissue such as bone or fat has a lower conductivity coefficient. The properties of organs have been illustrated in Table 1. The properties of several organs from [35] used in the simulation process have been illustrated in Table 1.

Results

The power deposited in the body

To investigate how radar waves interact with the human body, we used a plane wave with

a vertical polarization to excite the front of the voxel model of the human body. Figure 2 shows the emission of waves transmitted to the body in the range of 4-12 GHz.

Based on the results, due to the propagation of waves at lower frequencies, it is observed that the effects of radiation waves on the human body at frequencies of 4-12 GHz has the highest penetration in the head area and the abdominal cavity. Upside down the head structure, the oral cavity is empty and filled with air. It means that a lesser wavelength can cause deeper effect in the oral cavity and the inner tissues, a bigger wavelength can cause a deeper effect in the inner tissues and organs. The same applies to the wave's collide in the abdominal viscosity with absorption coefficient. In addition to how waves propagate at lower frequencies, investigation of organs reacts versus non-ionization wave with different potential energy range has been done. For this purpose, studied body organs are examined and simulated for the exposure of 6 min and the results are presented in Figure 3a. Excluding the skin, the power loss in the other organs, including the lung, white substance, nervousopticus, pancreas and liver monolithically decreased with frequency increase. However, the pancreas organ has less pronounced the exposure.

To investigate the effect of chronic exposure, despite of the body's natural cooling mechanisms existence, the conservative con-

Table 1: Simulation properties for some of used organs

Voxel	Type	Dispersion coefficient	μ	Density (Kg/m ³)	Thermal conductivity (W/K/m)	Heat capacity (KJ/K/Kg)	Diffusivity (M ² /s)	Blood Flow (W/K/m ³)	Metabolic rate (W/m ³)
Skin	Norm.	Model with the fifth degree approximation	1	1109	0.293	3.5	7.54863×10^{-8}	9100	1620
White matter	Norm.	Model with the sixth degree approximation	1	1041	0.502	3.6	1.33×10^{-7}	17280	7100
Eye	Norm.	Model with the fifth degree approximation	1	1032	0.624	4.178	1.44723×10^{-7}	10300	14250
Bone	Norm.	Model with the sixth degree approximation	1	1908	0.41	1.3	1.65296×10^{-7}	3400	610
Blood	Norm.	Model with the fifth degree approximation	1	1049	0.505	3.9	1.23439×10^{-7}	-	-
Lung	Norm.	Model with the sixth degree approximation	1	394	0.624	3.6	4.39932×10^{-7}	9500	1700

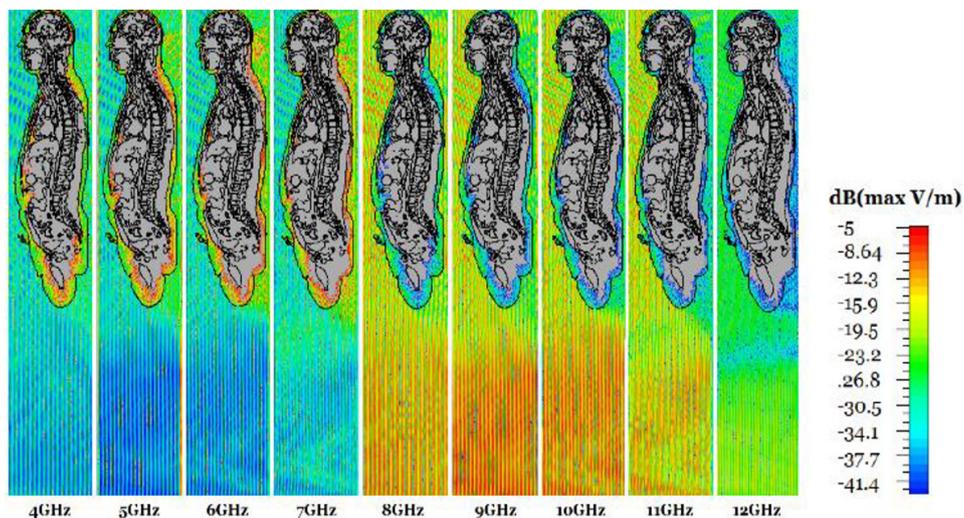


Figure 2: Study of radiation waves and its effects on the human body at frequencies of 4-12 GHz.

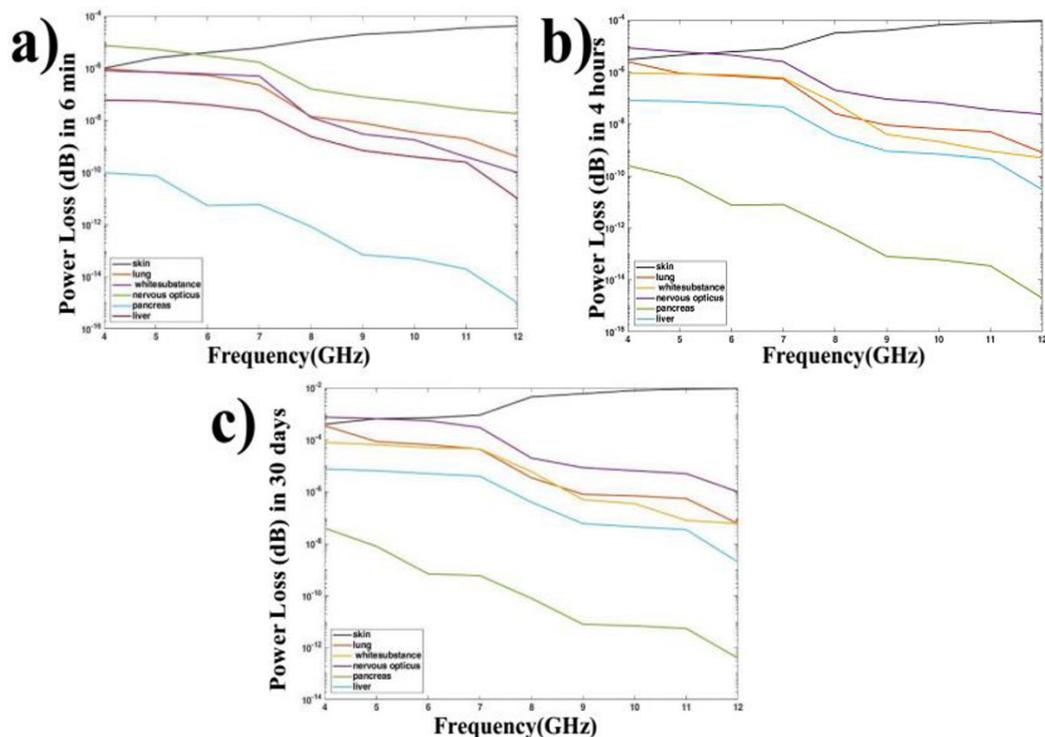


Figure 3: Power lost on the body organs according to frequency variation a) exposure of 6 min b) for 4 h of exposure and c) for 30 days exposure

dition has been chosen and this effect has been neglected. We extracted the results of simulations in two cases of exposure of 4 h and 30 days which are shown in Figures 3b and c, respectively. As seen, the power loss increases by the exposure time, and for 30 days exposure, it has nearly 2 orders of magnitude more absorption at different organs.

Modeling of human organs in CST studio

SAR is an important parameter in the investigation of the thermal effect of a radar field. The SAR in body tissues and at various frequencies is as [36]:

$$SAR = \frac{\sigma}{\rho} |E|^2 \quad (3)$$

Where σ is the sample (tissue) electrical conductivity, E is the effective electric field (RMS), and ρ is the sample's density. SAR is

defined as the power absorbed by the mass of tissue and has the unit of watts per kilogram (W/Kg). SAR is averaged over the whole body or on a small sample size (usually 1 gram or 10 grams of tissue). However, to increase the speed of the simulation, the calculated SAR was calculated as a point using the CST Studio Suite software with the IEEE /IEC 62704-1 standard. ICNIRP defines SAR limits in the human body based on the average SAR of the whole body and the average SAR in 1 gram of the body [37]. Furthermore, it provides the limits for those who work at the workplace interacting with radar waves and those who are exposed to radar energy in general; it is obvious that the first one is more conservative. The SAR limit in the world standards is 0.4 W/Kg for total body weight and 10 W/Kg for 10 g of the upper body part. Similarly, for 1 gram of the upper body part, these limits would be 0.08 W/Kg and 2 W/Kg, respectively, for working

and general environments [38].

Radar waves effect calculation

This section examines the simulation results and the limits defined by the ICNIRP. The maximum SAR calculated in different states is -7 dB, which is equivalent to 0.199 W/Kg. Since our calculations are in grams of a body and according to the standard, the permitted amount for the working environment and the average total body is 0.08 W/kg or similarly -10.96 dB, therefore, the points with SAR more than -10.96 dB, will be harmful to those who regularly have to deal with radar waves in their work environment. We now investigate the SAR parameter at frequencies of 12, 8, and 4 GHz. According to the ICNIRP standard, this study includes different time intervals. Thus, the source radiates on the body of the object and the amount of absorbed radiation is calculated according to the ratio of specific absorption rates. The behavior of the object and the surrounding fields under radiation for 6 min, 4 h, and 30 days at different frequencies are depicted from Figure 4a-c, respectively.

Discussion

As seen, for a reduction in frequencies from 4 GHz to 12 GHz, the signal penetrates the body's internal tissues and is wasted. It is also indicated that the waves have been lost more

in the head area and the abdominal cavity. By increasing the frequency from 4 GHz to 12 GHz, the losses of the waves are concentrated in the tissues near the skin surface. Moreover, based on the results, it can be understood that by increasing the duration of radiation from 6 min to 4 h and 30 days, the intensity of effectiveness and the likelihood of the occurrence of destructive effects increase. However, the problem of various biological complications is very detailed and needs deeper research. Table 2 reports the risk of damage to several body organs extracted from the simulation.

Given the Table 2, one can conclude that the percentage of risk increases from 6 min to 4 h and 30 days for an extended period of exposure. Moreover, the internal organs of the body are more vulnerable to lower frequencies and the reason of which is the increased permeability of the waves into the body for a reduction in frequency. The skin surface is more likely to be damaged for increased frequencies. This is due to the greater inactivity of the waves into the body increasing by incremental frequency, the depth of the waves' penetration which decreases and consequently stops at the surface of the skin. According to the ICNIRP standard, the absorption dose limit is -10.96 dB. Table 3 shows the absorbance dose rate for 6 min, 4 h and 30 days for 4 GHz, 8 GHz, and 12 GHz.

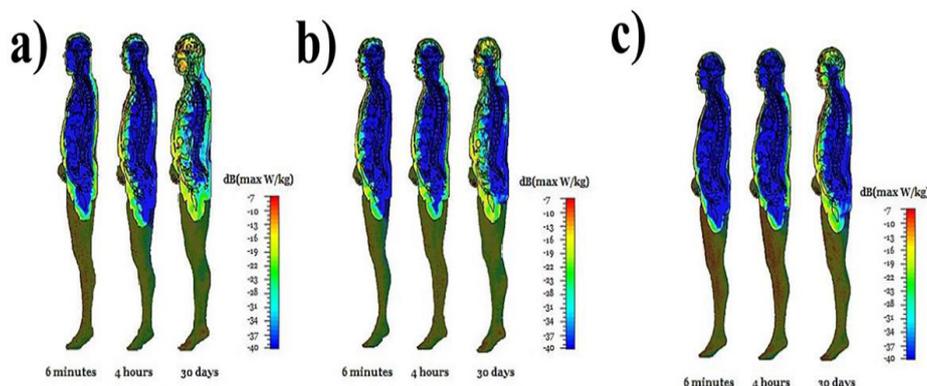


Figure 4: Specific Absorption Rate parameter of the human body at a frequency of a) 4 GHz b) 8 GHz and c) 12 GHz

According to Equation (3), the absorbance rate in decibels is shown in Table 4. Evidently, none of these states has crossed the boundary;

$$A = 10 \log_{10} P_{Absorbed} \quad (4)$$

Consequently, in the event of confrontation with a 1 watt source and a distance of 50 cm, in spite of assessing the risk percentage of or-

gans shown in Table 2, the ICNRIP damage criterion has not been broken.

Thus, this method can be used for each power of source, each distance and criteria, to establish staff risks and estimate environmental humanity condition, for each radar center. This causes an appropriate report for safety condition of each radar center.

Table 2: Assessing the risk percentage of some organs in different time periods.

Type	Frequency range (GHz)	Percentage of damage risk in 6 min radiation (%)	Percentage of damage risk in 4 h radiation (%)	Percentage of damage risk in 30 days radiation (%)
Skin	4	2.238×10^{-2}	5.320×10^{-2}	2.238×10^{-9}
	8	9.645×10^{-1}	8.264×10^{-1}	5.645
	12	1.032×10	1.875×10	4.532×10
Kidney	4	1.343×10^{-6}	2.175×10^{-6}	6.917×10^{-3}
	8	3.532×10^{-9}	5.321×10^{-9}	4.486×10^{-6}
	12	1.728×10^{-2}	2.731×10^{-12}	1.354×10^{-9}
Eye	4	6.127×10^{-5}	8.876×10^{-4}	8.127×10^{-2}
	8	4.652×10^{-6}	7.746×10^{-5}	5.652×10^{-2}
	12	2.138×10^{-7}	6.468×10^{-6}	7.138×10^{-4}
Stomach	4	2.81×10^{-4}	3.218×10^{-3}	6.328×10^{-2}
	8	5.397×10^{-6}	5.683×10^{-5}	3.612×10^{-4}
	12	2.279×10^{-8}	2.135×10^{-7}	1.723×10^{-6}
Pancreas	4	3.296×10^{-2}	3.468×10^{-2}	1.437×10
	8	8.370×10^{-8}	8.632×10^{-8}	6.835×10^{-5}
	12	3.775×10^{-13}	3.854×10^{-13}	4.362×10^{-11}
Bone	4	9.103	1.207×10	3.207×10
	8	4.262	5.867	9.867
	12	1.299	2.755	4.755

Table 3: Total body absorbed dose

Time \ Frequency-	4 GHz	8 GHz	12 GHz
6 min	1.136×10^{-5}	1.521×10^{-5}	4.1×10^{-5}
4 hour	1.598×10^{-5}	3.122×10^{-5}	10^{-4}
30 day	1.58×10^{-3}	4.52×10^{-3}	10^{-2}

Table 4: Total body absorbed dose in decibels

Time \ Frequency-	4 GHz	8 GHz	12 GHz
6 min	-49.446	-48.179	-43.872
4 hour	-47.964	-45.056	-40
30 day	-28.013	-23.449	-20

Conclusion

In this paper, an accurate and comprehensive model of the adult body tissues using the CST Studio Suite software is developed. The effect of EM radiation on the human body was studied for the frequency range of 4 to 12 GHz over a specified period of 6 min, 4 h and 30 days. It can be concluded that the effects are inversely related to the frequency increase. In other words, the longer the wavelength of the electromagnetic field can cause further penetration in the human body and severe effects in the vital organs of the body. The longer exposure time can cause a severe effect. In addition, by examining the pattern of wave propagation in the body, it was seen that in the oral cavities filled with the air, there is a loss of wavelength and the waves tend to fall into the inner tissues which have absorption coefficient. Excluding the body skin, the power loss in the other organs monolithically decreased with frequency increase, and the power loss increases by the exposure time so that for 30 days exposure, it has nearly 2 orders of magnitude more absorption at different organs. The power loss diagram, SAR diagram, and the body organs risk caused by radar waves show the rate of vulnerability of the abdominal cavity and the head. The risk of the body skin disease in the lower frequencies has increased. Furthermore, the skin surface is more vulnerable and the chance of skin complications increases in at higher frequencies up to 12 GHz. It should also be emphasized that for the body of those people whose workplace interact with radar waves exceeding the limit point of -10.96 dB, the critical risk of the body's vital organs increases. As a result, the standard limits should be considered for safety and health of the staff in the radar sites.

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Authors' Contribution

F. Fereidouni conceived the idea. Introduction and manuscript of the paper was written by F. Fereidouni and ST. Mohammadi. V. Faramarzi Shahraki gathers the images and the related literature along with. F. Jahantigh and F. Fereidouni also help with writing of the related works. The method implementation and experimental studies was carried out by F. Jahantigh. Results and Analysis was carried out by F. Jahantigh. The research work was proofread and supervised by ST. Mohammadi and F. Fereidouni help was provided by F. Jahantigh. All the authors read, modified, and approved the final version of the manuscript.

Ethical Approval

The Ethics Committee of Kashan University of Medical Sciences approved the protocol of the study (Ethic cod: IR.KAUMS.NUHEPM.REC.1398.009).

Informed consent

The work was carried out on radar waves and therefore, no participation consent was obtained.

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Conflict of Interest

None

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