Non-Invasive Detection of Compartment Syndrome Using Radio Frequency Wave

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Abstract—Development of Compartment Syndrome (CS) could affect blood flow to muscles, nerves, and as a result could causes permanent damage to tissues and nerves with risk of amputations and even death. The lack of non-invasive clinical diagnosis of compartment syndrome has led to thousands of permanent nerve and tissue damages. This paper aims to present a novel method, design concept, and numerical realization of non-invasive Radio Frequency (RF) based detection of compartment syndrome. The proposed method uses electromagnetic waves, produced by a small printed antenna at frequency of 300 MHz for identifying compartment syndrome. The effects of compartment syndrome and changes on tissue electrical properties are taken into account, since the ways in which electrical properties differences between normal and injured tissue should aid diagnosis on injured area by RF-wave radiation. We used a numerical leg model to identify inter-compartmental edema size of the lower leg, the most commonly effected area for patients. Because the antenna can be made very small, RF-based detection of compartment syndrome applications can be extended to small-scale devices. Numerical studies show that compartment syndrome as small as 5 ml can be detected with this method. We hope that our novel method will improve both diagnosis and overall patient care for compartment syndrome. Moreover, this detection system is intended to provide a safe, economical, and less distressing method to monitor compartment syndrome.

1. INTRODUCTION

Compartment Syndrome (CS) is a condition that involves increased pressure on muscle tissues, blood vessels, and nerves within a fascial compartment. Compartment syndromes can arise in any area of the body that has little or no capacity for tissue expansion. However, the most commonly affected areas of the body are the lower leg and forearm. Physical signs such as pain, pallor, and paralysis may often be hard in the early stages [1]. If left untreated, compartment syndrome can lead to permanent nerve damage, amputation of affected body parts, and even death.

In arms and legs, there are thick layers of tissue called fascia. The space inside the fascia layer is called compartment. Compartment contains blood vessels, nerves, and muscle tissues. Injuries in arms or legs could cause swelling in a compartment that will lead to increasing pressure in the compartment. However, fascia does not expand, hence, pressure will rise and put pressure on blood vessels, nerves, and muscles tissues [2].

Compartment Syndrome can develop in patients from wide range of activities and injuries, such as rigorous exercise, car accident, a motorcycle fall, or even during a football match. This condition is well known among specialists, emergency and rescue units, as it can develop in a short period as short as eight hours. Studies have shown that without immediate treatment via fasciotomy, permanent tissue damage within 4 hours and serious consequence of permanent tissue damage with irreversible changes

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in the nerves, and risk of amputation are possible after 8 hours of high compartmental pressure [3]. The average annual report occurrence of acute compartment syndrome is estimated from 1 to 7.3 per 100,000 [4].

Detection of compartment syndrome is based on physical examination and then by inserting compartment pressure testing needle into the injured area for measuring tissue pressure and hence confirmation of diagnosis. According to the World Health Organization (WHO) if signs and symptoms persist, management of the condition and treatment should be done immediately. Even short delays will increase the extent of irreversible muscle necrosis, so timing is very significant to the successful treatment [5]. A common method involves physical examination and use of invasive needle pressure monitoring. However, most clinicians do not prefer the invasive device since it needs multiple entrances to the body tissues that causes additional swelling.

Using devices such Computed Tomography (CT) or Magnetic Resonance Imaging (MRI) scans has the advantages of being noninvasive, highly specific, and very sensitive. However, they are bulky, require significant operating energy, and are expensive. Hence, they are generally limited to hospitals. There is need for a portable, noninvasive and inexpensive device that can provide rapid and reliable detection of compartment syndrome. Therefore, it can be used not only in hospitals but also in the crush site or disaster area.

In healthcare, numerous modern technologies are based on electromagnetics and Radio Frequency (RF), and in the current time of medical diagnosis, RF-wave detection is in high demand because of its widespread applications, easy usage, and having small form factor operating system due to advances in microelectronic and RF devices. Technology advances such as RF detection could provide noninvasive diagnosis and detections for a number of conditions, such as compartment syndrome.

A small form factor printed antenna is proposed here for noninvasive RF-wave detection of compartment syndrome. The operation frequency of 300 MHz provides sufficient penetration depth to body tissues. Transfer coefficient can be used to identify any edema inside the tissue by RF-wave of transmitting antenna that is getting pass through the tissue and measured at the other side of tissue by the receiving antenna. Therefore, in-depth understanding of interaction of RF-wave and body tissue is vital for the design of RF-wave based detection of compartment syndrome.

Due to its simplicity, ease of fabrication and production, and low cost, this method is an attractive way for the next generation of compartment syndrome detection. To the best of our knowledge, no such work has been reported previously.

The rest of this paper is organized as follows. Section 2 describes the electromagnetic wave and antenna design. Numerical analysis and results are presented in Section 3. Section 4 provides RF exposure and safety regulation. Finally, conclusions and future works are presented in Section 5.

2. ELECTROMAGNETIC WAVE AND ANTENNA

The principal of RF-wave detection of compartment syndrome is the satisfaction of the electromagnetic wave passing through the biological tissues. Therefore, condition is dependent on electrical properties of the materials forming between transmitter and receiver units, which are highly frequency dependent.

An electromagnetic wave from a transmitter is incident on the surface of skin, and a portion of wave will be reflected upon interface. The unreflected part propagates into the skin, fat, and muscle, then passes into skin again, until being captured by the receiver unit on the other side as shown in Fig. 1.

At frequency of 300 MHz, wavelength will be 100 cm. Knowing that the dimension of a resonant antenna is strongly associated with the wavelength of the operating frequency, end result will be an antenna with bulky size at this frequency. However, miniaturization techniques can be used to reduce the antenna size. A multi-turn wire structure such as meander line antenna is quite appropriate for this purpose. Meander line antenna is a structure with multiple foldings and bendings which gives a designer flexibility to reduce the antenna size, with a structure such as monopole and dipole [6–9].

There are many possible forms of meander line antennas with respect to the applications that require electrically small planer antennas [10, 11]. The proposed antenna is shown in Fig. 2, with total dimension of 17.3 mm × 17.4 mm × 2.536 mm. The antenna is a three-layer structure; substrate, single side metalized and superstrate. The antenna has been constructed on a Rogers TMM-10 (tm)
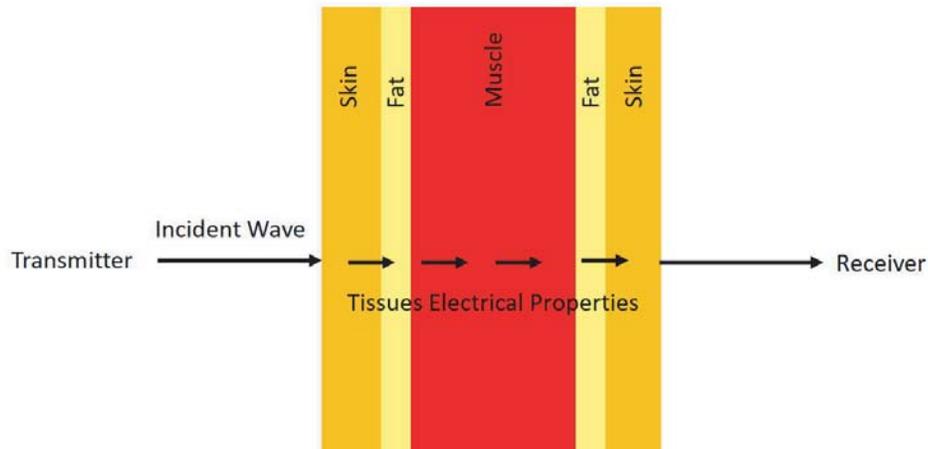
Figure 1. Principal of RF-wave detection.
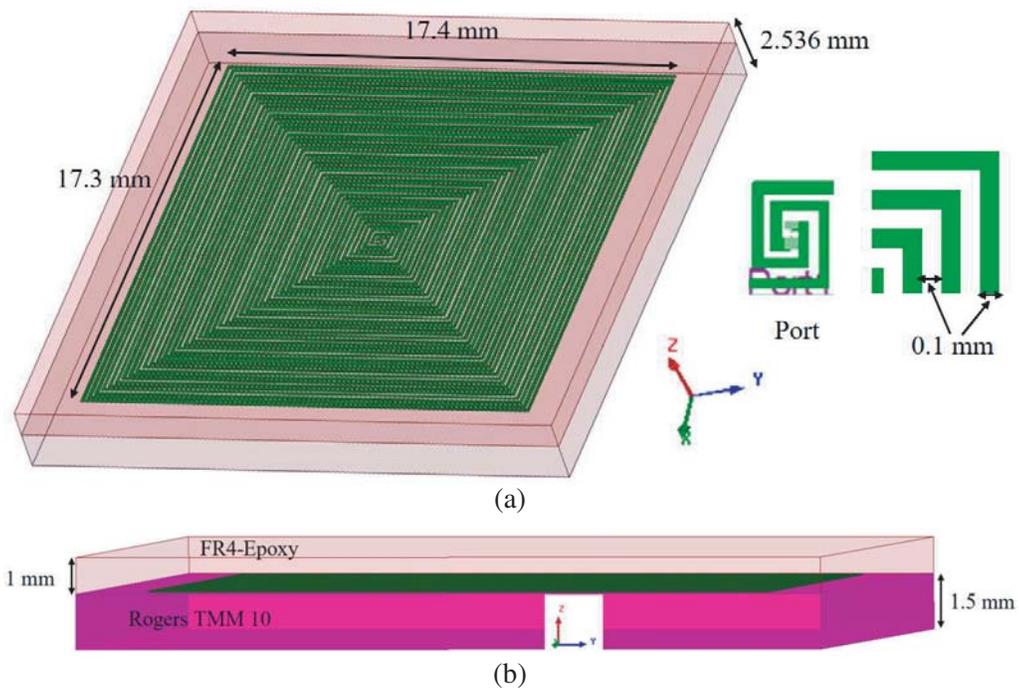
Figure 2. Antenna configuration and dimensions, (a) top view, (b) side view.

substrate with thickness of 1.5 mm that has relative permittivity of $\varepsilon_r = 9.2$ and dielectric loss tangent of $\tan \delta = 0.0022$. The copper cladding, radiating element, has thickness of 0.036 mm. The antenna is covered with a FR4-Epoxy superstrate layer with thickness of 1 mm that has relative permittivity of $\varepsilon_r = 4.4$ and dielectric loss tangent of $\tan \delta = 0.02$.

The proposed antenna is designed in free space and then in the present of a bulk muscle tissue to avoid any mismatch that could affect the antenna performance. The antenna characteristics in close proximity to the leg tissue model are studied, to make sure that antenna resonates at required frequency bandwidth, as leg tissue close to the antenna might affect the input impedance of antenna and therefore disturb antenna scattering parameters.

The return loss of antenna in close proximity to the leg tissue is presented in Fig. 3. It shows that the antenna has an impedance bandwidth of -10 dB in the frequency range of 293.2 to 304 MHz. The transmitting and receiving antennas are identical; hence, they have the same impedance bandwidth.
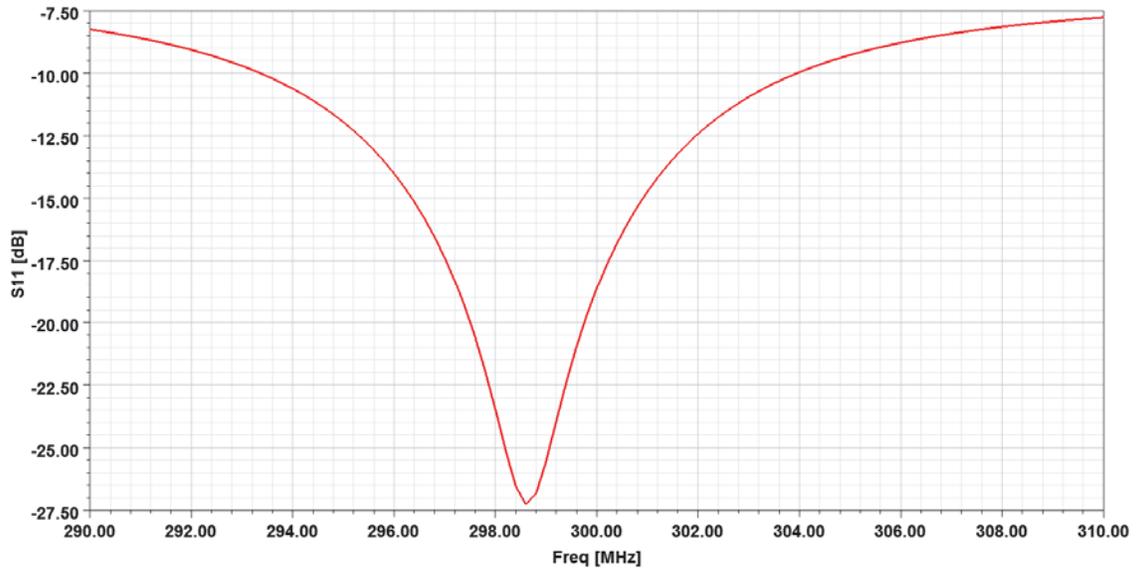
Figure 3. Antenna return loss while on touch to the leg tissue model.
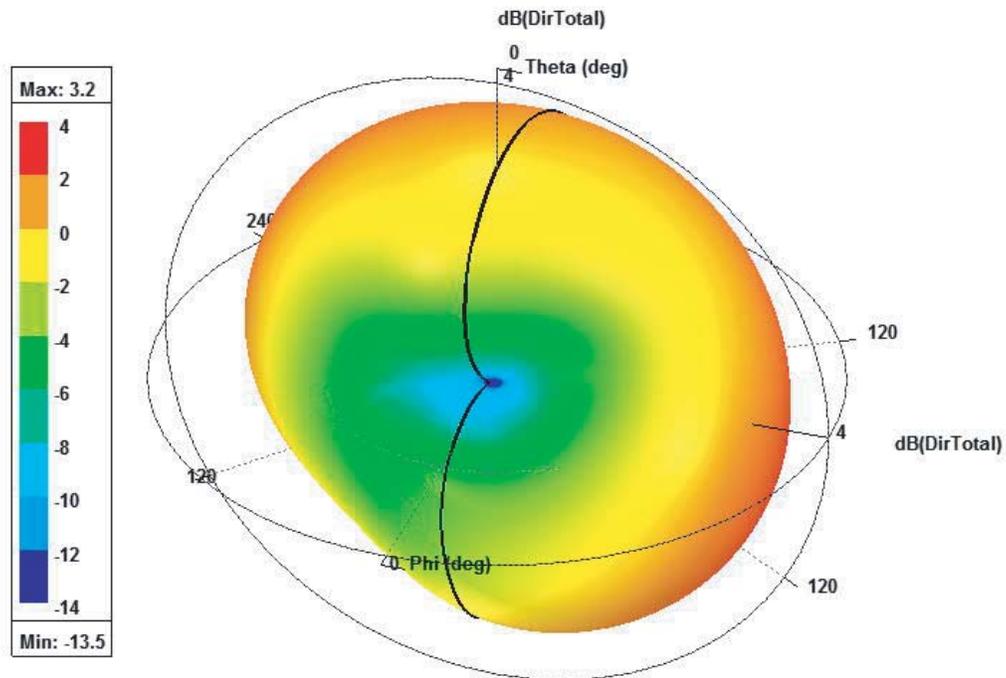
Figure 4. The 3D total directive gain pattern of antenna at 300 MHz.

The 3D total directive gain pattern of antenna at frequency of 300 MHz when antenna port is excited with 500 mW magnitude of power as an input source is shown in Fig. 4.

3. NUMERICAL ANALYSIS AND RESULTS

Numerical simulations were conducted using High Frequency Structure Simulator (HFSS), based on the Finite Element Method (FEM) from ANSYS electronic desktop (2019 R2) [12]. The simulations were

Table 1. Electrical properties of tissues at 300 MHz.

	Relative Permittivity	Conductivity (S/m)	Loss Tangent
Skin	49.821	0.641	0.771
Fat	5.634	0.039	0.420
Muscle	58.201	0.770	0.793
Bone	13.439	0.082	0.368
CSF	72.734	2.224	1.832

performed when the antenna was in touch with tissue layer with distance gap of 1 mm due to superstrate thickness and radiating directly towards the leg tissue. The layered structure of leg and its electrical properties have significant effect on RF wave, as leg tissue properties will control the propagation, reflection, and attenuation of RF fields. The leg model consists of skin, fat, bone, and muscle. The electrical properties of human tissues are frequency dependent. The electrical properties of human body tissues found by Gabriel et al. [13, 14] are used for all the computational analysis in this paper. Table 1 shows the electrical properties, i.e., relative permittivity (ε_r), conductivity (σ), and loss tangent ($\tan\delta$), of different tissues, i.e., skin, fat, muscle, bone, and Cerebrospinal Fluid (CSF) at frequency of 300 MHz. Skin is the only tissue for which the dielectric data are available for both dry and moist conditions [15]. However, for this study we use data for dry skin. The fluid inside the edema is a combination of blood and bodily fluids; hence, we modeled the edema using the electrical properties of CSF.

In [16], a simple cylinder muscle tissue created as a leg model is used. However, in order to achieve accurate RF field characteristics studies and RF-wave absorption, a realistic 3D geometry model of the human leg is needed. Fig. 5 shows the leg model with 2 mm resolution that has been used in this study [17]. We have considered four scenarios; no edema (0 ml), 5 ml edema, 10 ml edema, and 15 ml edema. The volume of 5 ml edema corresponds to the sphere with radius of 10.06 mm, 10 ml with radius of 13.365 mm, and 15 ml with radius of 15.295 mm.
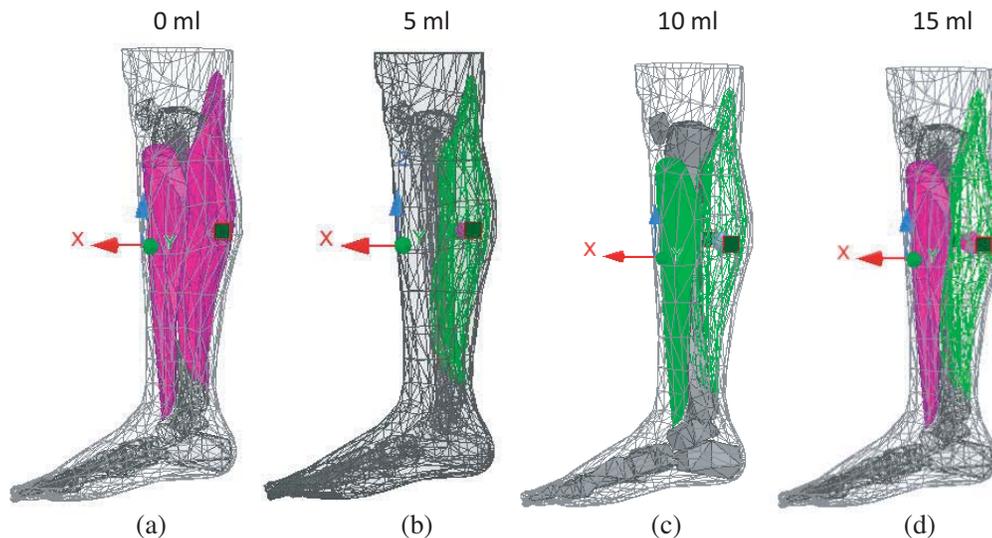
Figure 5. Leg model for compartment syndrome studies with (a) no edema, (b) 5 ml edema, (c) 10 ml edema, and (d) 15 ml edema, placed inside the calf muscle.

Computational models can simulate the amount of RF energy transmitted to the biological tissues and provide its details on each tissue layer. We calculate the transfer function while both antennas, i.e., transmitter and receiver, have an input impedance of 50 Ω, and transmitting antenna is fed with 500 mW input power.

To make this analysis, a transmitter sends a small amount of RF radiation toward the suspected area. The RF radiation attenuates as it passes through tissues, and then it is detected by the receiver. With 5 ml of edema in the muscle tissue, there is a change in amplitude of transfer coefficient (S_{21}) compared to the muscle tissue without edema, as shown in Table 2. Development of compartment syndrome from its early stage and size to a bigger one will happen within first few hours, hence, with increasing the volume of edema to 10 ml and then 15 ml, one can see that at 15 ml there is a significant change in the amplitude of S_{21} associated with the muscle tissue devoid of compartment syndrome. The results demonstrate that our method has the potential to detect the onset and progression of compartment syndrome.

Table 2. Transfer coefficient for different scenarios at 300 MHz.

	0 ml	5 ml	10 ml	15 ml
S_{21} [dB]	−85.781	−86.092	−86.574	−87.048
Pressure [mmHg]	0	1.479	1.965	2.249

Table 2 also provides approximate values of rise in pressure with respect to the edemas diameter. We use CFS density at temperature of 37°C from [18] with values of 1.000529 (g/ml) to calculate pressure correspond to the amount of liquid in the edema. With 5 ml of liquid formation in the tissue, there will not be a complaint of pain and just slightly discomfort. However, this method can detect a very tiny edema of 5 ml.

4. RF EXPOSURE AND SAFETY

The proposed method will be used in very close proximity to the human body tissues. Hence, the Electromagnetic Field (EMF) compliance assessments will be necessary. RF-wave produces heat in the biological tissues, and it can cause thermal damage if temperature goes high enough for a period of time. The effect generally depends on the frequency, intensity, and shape of wave. Many of the biological effects of exposure to electromagnetic fields are consistent with responses to induced heating, resulting in rises in either tissue or body temperature. Therefore, EMF compliance assessments are necessary for all the devices emitting radio waves in general and for medical devices in particular due to close contact with body tissues and usage time.

To ensure that wireless devices do not pose health hazards due to exposure to the electromagnetic waves radiated by these devices, standards have been developed by organizations [19–21] as a common regulation for determining the Specific Absorption Rate (SAR), which is a measure of the amount of RF energy absorbed by the human body.

The Finite Element Method (FEM) has been used to compute the electromagnetic fields from the proposed antenna and to determine the SAR distribution within a model of the human leg placed in proximity to the antenna. Since the antenna is very close to the body tissue, reflection and diffraction of transmitted power could be produced in the formation of constructive/destructive electric field. Furthermore, the RF energy induced in the body is scattered and absorbed at various tissue interfaces; therefore, the internal field and hence the SAR distribution is nonuniform [19]. The best estimation of SAR for approximating thermal effects would probably be that obtained by averaging over all regions.

The SAR distribution is observed in the different parts of leg tissues, i.e., edema, calf, and shin, using 3D human leg model. Fig. 6 depicts SAR in a 1-g of mass (expressed as $SAR_{1\,g}$) and 10-g mass (expressed as $SAR_{10\,g}$), while antenna has input power of 500 mW. The SAR limit is 1.6 W/kg in countries, e.g., USA, that set the limit averaged over 1 gram of tissue and 2.0 W/kg in countries, e.g., European Union, that set the limit averaged over 10 grams of tissue. However, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) basic restriction for the general public in the limbs is 4.0 W/kg. Table 3 shows the comparison of the $SAR_{1\,g}$ and $SAR_{10\,g}$ with the basic restrictions. It can be seen that for all the cases SAR values from this study (Table 3 shows the maximum values) are much below the basic restrictions.
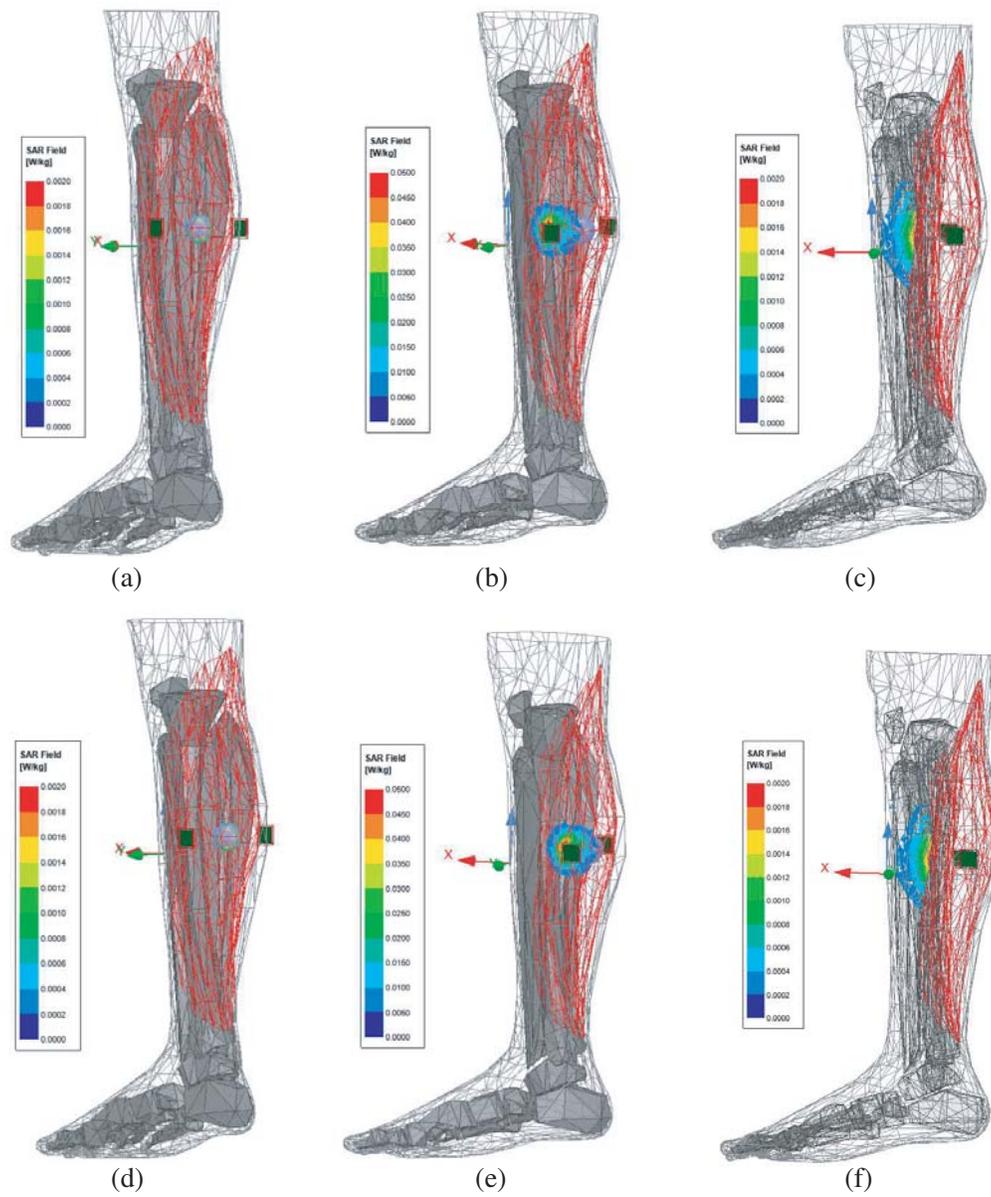
Figure 6. Averaged SAR in the leg tissues for 1-g of mass (a) edema, (b) calf, and (c) shin, and 10-g mass for (d) edema, (e) calf, and (f) shin.

Table 3. Comparison of SAR, current study and limits provided for 1-g and 10-g of tissues. The antenna input power for this study is 500 mW.

	This Study $SAR_{1\text{-}g}$ (W/kg)	This Study $SAR_{10\text{-}g}$ (W/kg)	$SAR_{1\text{-}g}$ (W/kg) Reference	$SAR_{10\text{-}g}$ (W/kg) Reference
Calf	0.05	0.05	1.6	2
Edema	0.002	0.002	1.6	2
Shin	0.002	0.002	1.6	2

5. CONCLUSIONS AND FUTURE WORKS

High pressure in body tissues due to compartment syndrome is a serious condition, and hence importance of timely detection of CS cannot be overemphasized. Therefore, there are studies and efforts to improve diagnosis and henceforth, and reduce the risk of tissue damage.

The current study and work introduces an entirely noninvasive CS detection, capable of continually monitoring the progress of CS within the leg tissues using radio frequency wave technology at frequency of 300 MHz. Application of RF-wave technology for compartment syndrome detection has been studied in a realistic human leg model having electrical properties of human body tissues at frequency of 300 MHz. Computational analysis shows that this method can successfully identify a compartment syndrome with volume of 5 ml of fluid. On RF exposure and safety guidance, the calculated SAR is in the range limit for 1 gram and 10 grams of mass tissue.

Significant and essential factors such as noninvasive procedure, simplicity, low cost, and ease of manufacture make the proposed method more attractive than current available methods. The results suggest that inflammation in tissues can be identified by electrical properties of medium.

In future works, this approach needs to be validated by experiments. Therefore, experimental studies will be set up with liquid and solid phantoms for practical measurements and if possible with animal studies. Moreover, there is need of an algorithm to transfer the magnitude of transfer function to a pressure scale.

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