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Original Article

Sizing the Neural Transmission Line: UWB Antenna Effects on Action Potentials Across Nerve Diameters

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Abstract *- Wireless communication devices emit Electromagnetic (EMT) radiation, which is now widely present in modern society. This has led to worries over its impact on human physiology, specifically the interaction between EMT and the human nervous system. The assessment of the influence of Ultra-Wideband (UWB) technology on neural signaling poses distinct issues. This study examines the impact of UWB technology on Action Potentials (APs) in nerve fibers, taking into account the transmission line characteristics of different nerve diameters in uniform human arm models across three age groups (7, 26, and 38 years old). Both flat and cylindrical geometric layouts were examined, encompassing nerve fiber sizes ranging from 0.2 to 1.0 mm. A UWB Coplanar Waveguide (CPW)-fed circular patch antenna was incorporated into the arm models at different positions and orientations. AP signals, produced utilizing Izhikevich's neuron model in MATLAB and simulated in CST software, exhibited notable disparities in AP signal distortion between flat and cylindrical models. The results indicate an inverse relationship between the diameter of nerve fibers and their susceptibility to UWB interference. Smaller diameter fibers show more substantial distortions in action potentials across all age groups, with younger individuals demonstrating greater susceptibility to UWB influence. Additionally, larger areas of exposure led to greater amplitudes of spike interference. The findings underscore the importance of employing accurate anatomical models when evaluating the effectiveness and safety of UWB devices in biomedical contexts. They offer valuable insights into the impact of neural transmission line sizing on UWB radiation interaction and stress the significance of taking into account the diversity of nerve fibers and age-related factors in future assessments of electromagnetic compatibility.*

Keywords *- UWB interference, Neural transmission lines, Action potential distortion, Nerve fiber diameter, Electromagnetic bioeffects.*

1. Introduction

Ultra-Wideband (UWB) technology is a significant advancement in wireless communications, providing fast data speeds and accurate localization capabilities across a broad frequency spectrum, typically ranging from 3.1 to 10.6 GHz [1], [2]. This technique is utilized in several domains, including medical imaging, radar systems, and Internet of Things (IoT) devices. Concurrently with these technological breakthroughs, our comprehension of the human neurological system has progressed.

Neural signaling, which forms the basis of human physiology, depends on the transmission of Action Potentials (APs) along nerve fibers. The fibers, which range in diameter from less than 1 μm to over 20 μm, operate similarly to biological transmission lines, where their size affects the speed and accuracy of signal transmission [3]–[5]. The widespread use of UWB devices has caused worries over the possible electromagnetic interference to biological systems, specifically the human nervous system [6]–[9]. The difficulty lies in comprehending the intricate interplay between UWB radiation and nerve fibers of varying sizes. Recent research indicates that non-ionizing electromagnetic waves have the potential to cause minor alterations in cellular function and neuronal activity [10]–[13]. Nevertheless, the precise impact of UWB on neuronal communication is still uncertain, particularly when taking into account the varying dimensions of nerve fibers throughout the human body.

The presence of uncertainty in this situation has the potential to create concerns for human health and safety. There is a shortage of comprehensive studies examining the precise impacts of UWB radiation on nerve fibers with varying diameters among different age cohorts. Therefore, it is necessary to conduct a comprehensive examination of the impact of UWB radiation on the transmission of action potentials via nerve fibers with different diameters.

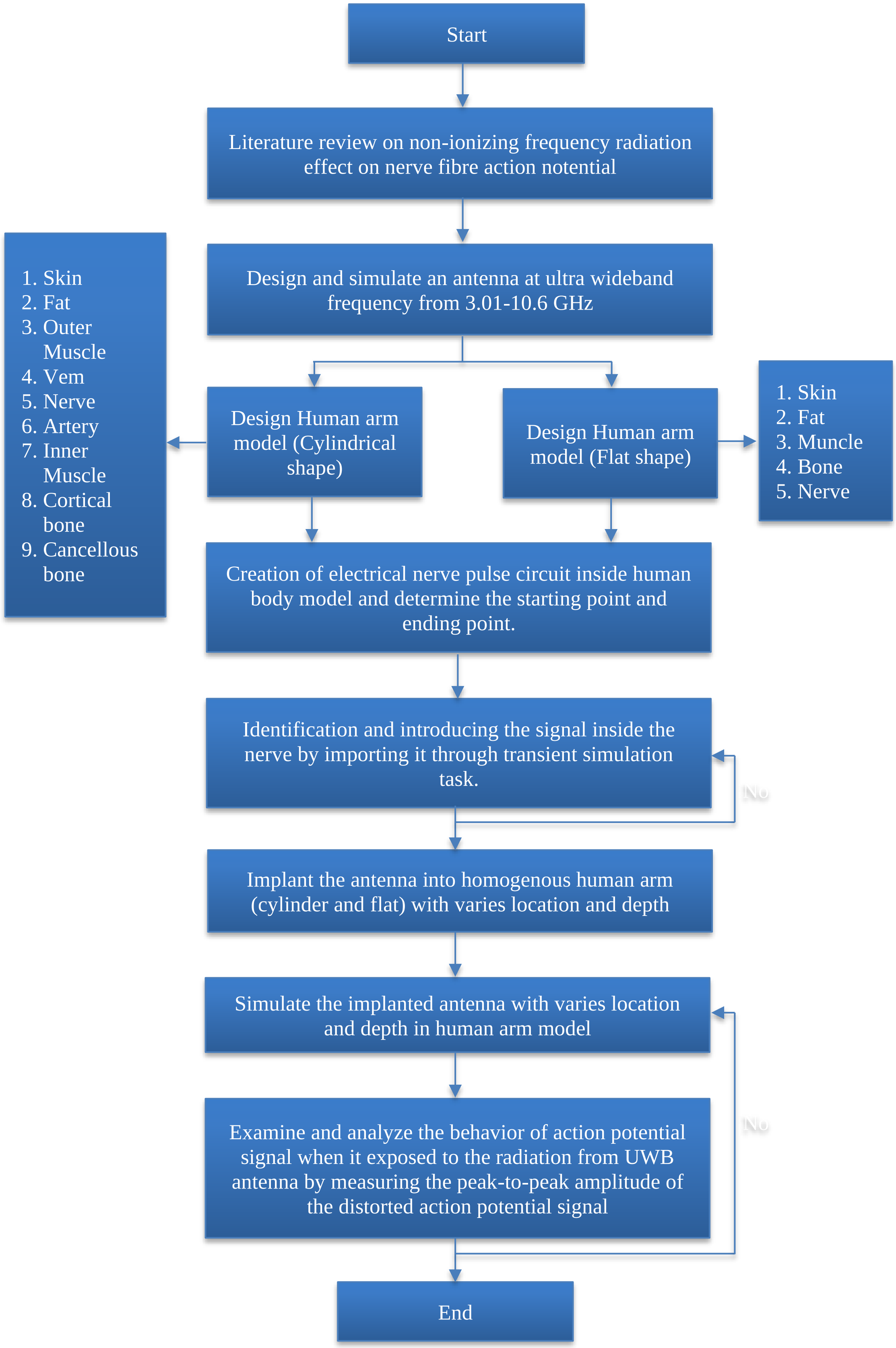


Fig. 1 Flow chart of the overall process of UWB antenna effect on action potential

An extensive investigation has been carried out to examine the impact of electromagnetic radiation on biological tissues, specifically nerves. Research has shown that non-ionizing radiation can have heat changes and potentially change cellular processes, such as ion channel activity and membrane potential [14]–[17]. Regarding UWB, research has demonstrated its capability to influence brain activity both in laboratory settings (in vitro) and in living organisms (in vivo). Nevertheless, there is still a substantial lack of comprehension of the precise interaction between UWB and nerve fibers of different sizes. The majority of previous research has mostly examined the effects of single frequency exposures or general tissue responses, resulting in a limited understanding of the precise influence of UWB on brain transmission lines of varying widths [18]. The presence of this gap is of utmost importance, as the size of nerve fibers is a key factor in defining their electrical characteristics and, consequently, their vulnerability to electromagnetic interference.

This work seeks to fill the previously noted gap in research by conducting a comprehensive investigation into how UWB antenna radiation affects action potentials in nerve fibers of different sizes. The study employs sophisticated computational modeling methods to predict the effects of UWB radiation on nerve fibers in several age groups (7, 26, and 38 years old) and whose nerve sizes range between 0.2 and 1.0 mm. The present work adds to the understanding of how the "sizing" of brain transmission lines affects their vulnerability to UWB interference. It does so by examining the changes in action potential properties, such as signal distortion and amplitude modulation.

The results enhance our comprehension of the possible physiological impacts of UWB technology, which is essential for formulating well-informed safety protocols regarding its usage in close proximity to human tissue. Moreover, this research establishes the foundation for future investigations into the enduring consequences of UWB exposure on neuronal function and overall human health.

2. Design Methodology

Figure 1 shows the flow chart of the overall process of UWB antenna radiation on nerve fiber action potential signal. The main process includes antenna design, human arm modeling, creation of electrical nerve pulse, the introduction of the signal inside the nerve, antenna implantation in the human arm and analysis of the behaviour action potential signal.

As illustrated in Figure 2, the research made use of a UWB Coplanar Waveguide (CPW)-fed circular patch antenna that was tailored to function within the 2.9367-19.032 GHz frequency range. An antenna with a relative permittivity of 2.8 and a loss tangent of 0.04 was made on a biocompatible substrate of polymethyl methacrylate.

The circular patch design was selected due to its extensive bandwidth possibilities, while the CPW feed provided benefits such as seamless integration with active circuits and minimized radiation loss. The antenna dimensions were adjusted using parametric calculations, resulting in a small size of 36 mm x 38 mm. This size is acceptable for on-body applications. Additionally, three strategic truncations were made to the patch edge to increase bandwidth and impedance matching across the UWB spectrum. Table 1 shows the dimensions of the element in the antenna.

Two homogenous human arm models were created: a nine-layered cylindrical model (Figure 3(a)) for precise anatomical representation and a five-layered flat mode (Figure 3(b)) for improved computational efficiency. Both models were specifically created to accommodate three distinct age groups (7, 26, and 38 years) in order to consider the differences in tissue properties that occur with age. In terms of the complicated permittivity that pertains to the propagation of electromagnetic waves, each layer is a lossy dielectric with a specified thickness. The models utilized CST Microwave Studio's bio-tissue database to guarantee precise depiction of electrical properties that rely on frequency.

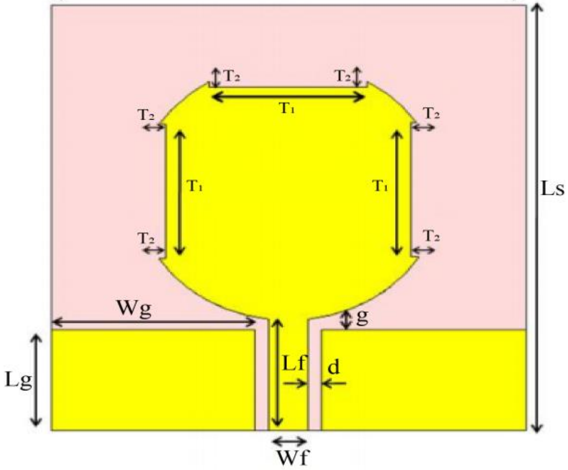


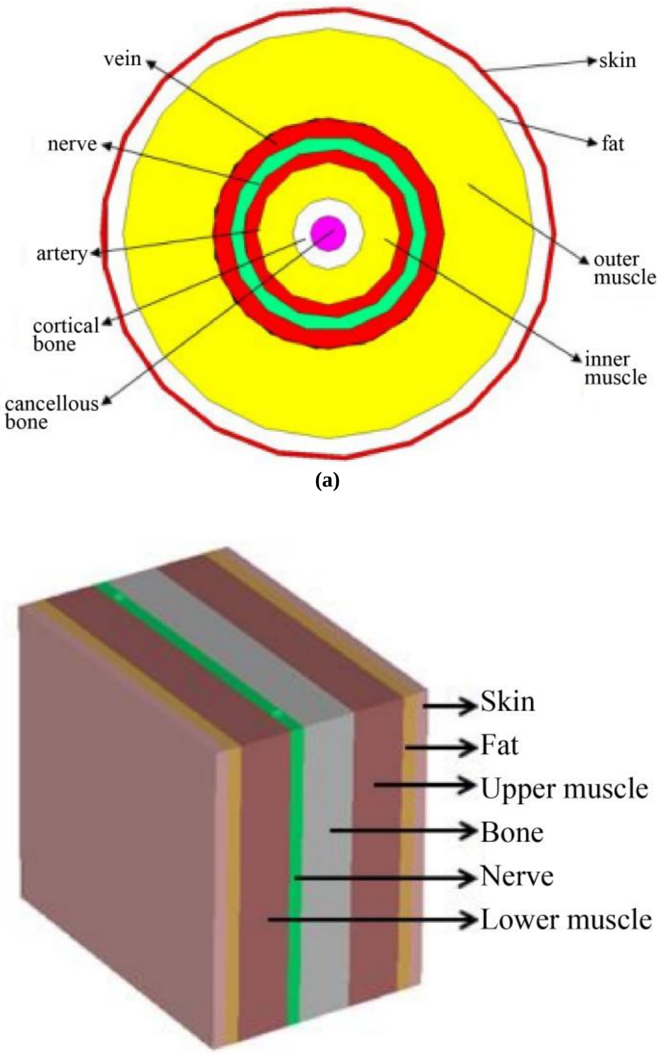
Fig. 2 Front perspective of design antenna

Table 1. UWB CPW-fed circular patch antenna dimension

Element	Dimension (mm)
Substrate width, *Ws*	36
Substrate length, *Ls*	38
Radius, *r*	11.5
Ground plane width, *Wg*	15.5
Ground plane length, *Lg*	9
Feed line width, W_f	3
Feed line length, L_f	10
Feed space, *d*	1
Feed height, *g*	1
Ground slot, *gs*	12
Truncate Length, T_1	12
Truncate Length, T_2	2

The utilization of multiple models and age groups facilitated a thorough examination of the impact of UWB radiation on various anatomical structures and phases of development. After consulting Table 2, the electrical properties of the human arm's organs and tissues were applied to the model of a cylinder representing the arm. Tabulated in Table 3 are the electrical characteristics of a flat human arm model for a child aged seven.

The intriguing parallels between electrical and biological systems are highlighted by viewing the nervous system as a wiring system. The brain is located in the nervous system, and both systems rely on electric charges. The brain is like the control center of a circuit. A model has been built to describe the human arm as an electrical system.

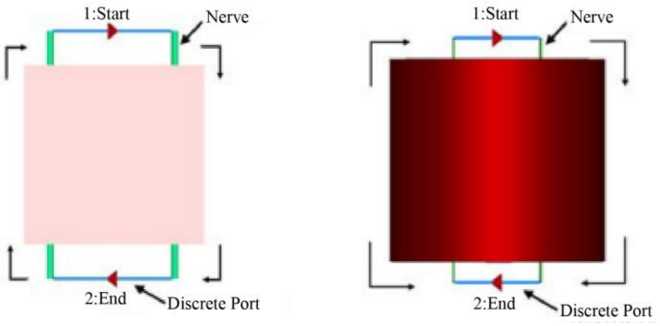


(a)

(b)

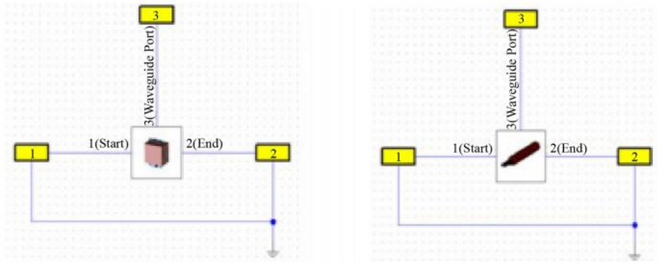
Fig. 3 Cylindrical model (b) Flat model

This model was chosen because it accurately reflects the common occurrence of arm exposure to microwave radiation during daily activities. This model highlights the pivotal role of neurons in arm movement, transmitting Action Potential (AP) signals from the brain to arm muscles to regulate the process of contraction and extension. The action potentials are depicted as voltage sources in the circuit. The depicted model in Figure 4 demonstrates the uniform arm in both flat and cylindrical arrangements, completely merged with an electrical circuit system. This illustration demonstrates the similarities between the nervous system and an electrical network, highlighting the electrical nature of brain communication and its effects on human physiology. It showcases how the nervous system, consisting of nerve fibers, acts as a bio-electrical system. Figure 5 is a diagram of the nervous system circuitry in a human arm model constructed with CST software utilizing interconnected simulation blocks to represent different components of the nervous system.



(a) **(b)**

Fig. 4 (a) Cylindrical model (b) Flat model as an electrical circuit system



(a) **(b)**

Fig. 5 Neuronal network diagram (a) Flat model (b) Cylindrical model

The UWB antenna was carefully placed within the arm models to replicate realistic exposure circumstances, with several orientations and depths of implantation investigated. By employing a systematic methodology, it was possible to pinpoint crucial locations where UWB radiation could have a substantial impact on the transmission of nerve signals. The comparison of surface-mounted (flat model) and embedded (cylindrical model) configurations yielded valuable information about the protective properties of various tissue layers. Figure 6 shows the position of the antenna in the human arm model (vertical orientation).

Izhikevich's neuron model was employed in MATLAB to generate action potential signals because of its computational efficiency and capability to produce biophysically realistic waveforms. The signals were included in CST software as piecewise linear voltage, enabling precise depiction of neuronal activity within the intricate electromagnetic environment of the arm models. Figure 7 shows the creation of an action potential signal.

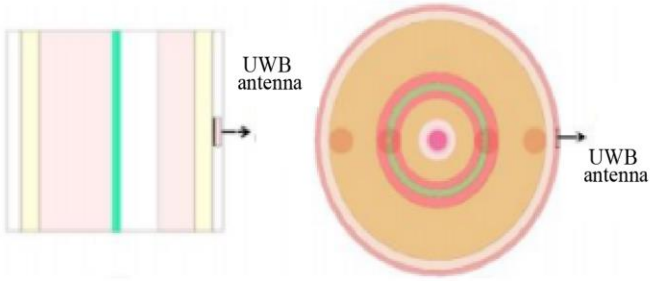
Table 2. The cylindrical human arm model's electrical characteristics at 3.9 GHz

Organs	Thickness (mm)	Relative permittivity (ε_{r1}) at 3.9 GHz	Conductivity at 3.9 GHz (S/m)
Skin	1	40.972	2.6204
Fat	4	5.1346	0.1773
Outer Muscle	20	50.9460	2.9207
Vein	4	40.725	2.5205
Nerve	3	28.825	1.7841
Artery	3	40.725	2.5205
Inner Muscle	8	50.9460	2.9207
Cortical Bone	4	10.583	0.7046
Cancellous Bone	4	17.040	1.3584

Table 3. Anatomical and physiological characteristics of the human arm at age 7 (flat human arm model) in terms of electrical conductivity

Tissue	Width (mm)	Relative Permittivity (ε_{r1}) at 3.9 GHz	Relative Permittivity (ε_{r2}) 5.27 GHz
Skin	2	38.077	33.1299
Fat	2	5.6540	5.1160
Upper muscle	8	51.822	44.3977
Bone	15	51.822	44.3977
Nerve	8	10.581	8.2924
Lower muscle	2	30.132	25.4113

The primary emphasis of the investigation was on the transmission line characteristics of nerve fibers with diverse diameters (ranging from 0.2 to 1.0 mm) among different age groups, acknowledging nerves as biological conduits for transmitting signals. The examined characteristics included signal attenuation, propagation velocity, waveform distortion, frequency-dependent effects, and age-related variations. The study employed CST Microwave Studio's transient solver to observe the propagation of electromagnetic waves in the time domain, specifically under UWB exposure. This thorough approach yielded valuable data on the correlation between nerve fiber diameter, age, and susceptibility to electromagnetic interference. These findings can be used to evaluate the safety and effectiveness of UWB devices when used near human tissue.



(a) **(b)**

Fig. 6 Antenna position in human arm model (vertical orientation) (a) Flat model (b) Cylindrical model

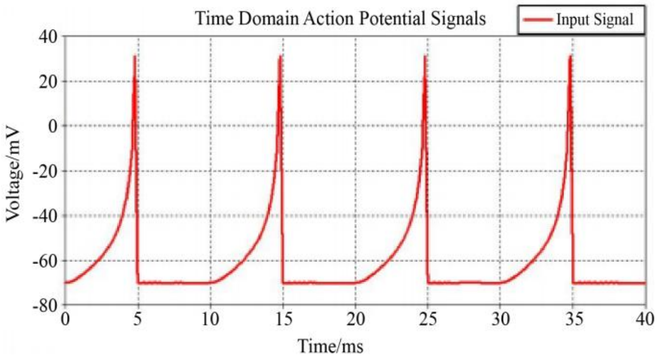


Fig. 7 Creation of action potential signal

3. Results and Discussion

The suggested UWB antenna performs well from 2.930 GHz to 19.032 GHz. The antenna has a large operational range, with a total bandwidth of 16 GHz.

This allows it to work over several frequencies. The antenna's almost omnidirectional radiation pattern makes it ideal for many UWB applications.

The examination of the return loss indicates the presence of three clearly identifiable resonant frequencies (fr): 3.90 GHz, 10.26 GHz, and 15.83 GHz. The presence of many resonance spots enhances the antenna's wideband performance and adaptability. This antenna possesses a mix of wide bandwidth, radiation in all directions, and many frequencies at which it resonates.

Figure 8 displays the return loss (S_{11}) outcomes of a UWB antenna in several settings, such as free space and near-human arm models representing ages 7, 26, and 38 years. The investigation of the S_{11} indicates that the antenna's performance is subpar while in close proximity to biological tissue.

This is mainly attributed to the intricate and non-uniform characteristics of this medium, which is known for its high level of electrical loss. The surrounding tissue's dielectric constant lowers the antenna's resonance frequency, while the human arm's conductive properties change impedance matching, affecting return loss.

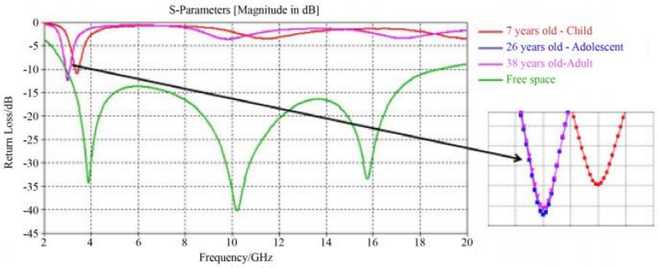


Fig. 8 Antenna return loss in free space compared to a model of a homogenous human arm (with a cylindrical shape)

The presence of significant tissue attenuation causes losses that contribute to a decrease in antenna gain. The diagram clearly illustrates the significant influence of the closeness of the human arm on radiation properties. This is consistent with the existing understanding that when the human body is close to an antenna, it decreases the antenna's effectiveness, changes the way it emits radiation, and affects its electrical characteristics. Moreover, when the antenna is positioned close to the arm, there is a slight change in frequency at lower frequencies. This change can be explained by the influence of the biological tissue on the antenna, known as the dielectric loading effect. These findings emphasize the crucial significance of taking into account the interactions between biological tissues when designing and implementing UWB antennas for wearable or implantable applications.

This study examined the impact of UWB antenna radiation on Action Potential (AP) signals. The study manipulated the diameter of nerve fiber transmission lines in individuals from three different age groups (7, 26, 38). The study analyzed four different diameter configurations: 1.0 mm-0.2 mm, 1.0 mm-0.4 mm, 1.0 mm-0.6 mm, and 1.0 mm-0.8 mm.

The importance of these differences lies in their direct impact on the pace at which action potentials propagate, which is critical for transmitting information along nerve fibers. Increased diameter of fibers generally results in faster action potential transmission by reducing electrical resistance and increasing membrane capacitance. Figures 9, 10, and 11 illustrate UWB antenna AP signal degradation of 7, 26, and 38-year-old flat arm models with varying nerve transmission line diameters.

Table 4 contains comprehensive assessments of the Action Potential (AP) data for three distinct age groups. It displayed the duration (in milliseconds) and magnitude (in millivolts) of distortion signals in Action Potential (AP) signals caused by UWB antenna radiation with different nerve sizes. The findings revealed a direct relationship between the size of the nerve and the strength of the AP signal. The 7-year-old model had the highest signal strength at 13.37 mV, followed by the 26-year-old model at 13.31 mV and the 38-year-old model at 11.86 mV.

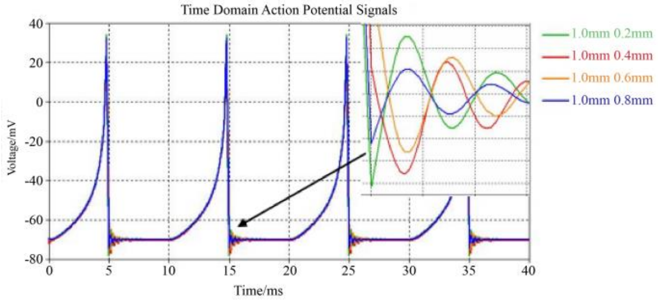


Fig. 9 7-year-old flat model AP signal degradation with nerve transmission line diameter difference

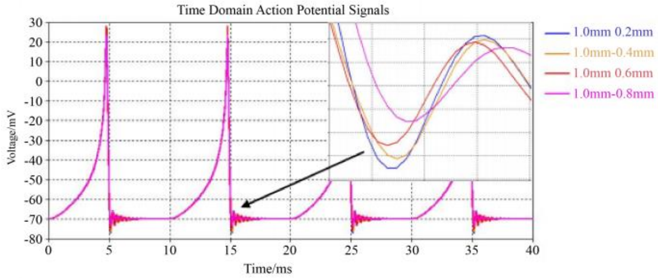


Fig. 10 26-year-old flat model AP signal degradation with nerve transmission line diameter difference

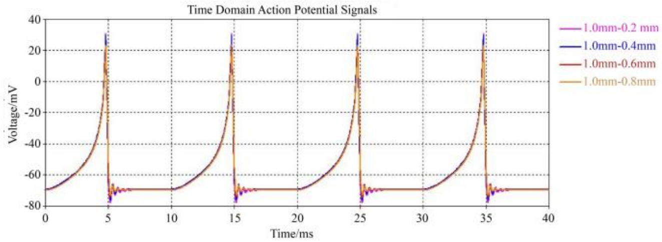


Fig. 11 38-year-old flat model AP signal degradation with nerve transmission line diameter difference

This indicates that susceptibility to UWB antenna interference varies with age. The study also found that the size of the area exposed to the radiation source was important in determining the effects of Electromagnetic (EM) radiation. Larger nerve fiber models showed higher spike interference amplitudes on the AP signal. These data emphasized the significance of taking into account both the diameter of the nerves and the region of exposure when evaluating the impact of UWB antenna radiation on neural signaling.

The discovered modified AP signals have generated concerns regarding potential disturbances to typical human arm functions, which could potentially result in harmful health consequences.

This study yielded significant findings regarding the intricate connections between UWB antenna radiation and neural signaling in various age groups and anatomical structures. These results emphasize the necessity for additional research on the potential long-term effects of UWB antenna radiation on biological systems.

Table 4. Comparison of time duration for the distorted signal and its maximum and minimum amplitudes in difference diameter of nerve transmission (flat model)

Human homogenous arm model	Diameter of nerve (mm)	Time duration of distorted signal (ms)	Maximum-to-minimum amplitude (mV)
7 years old	1.0 – 0.2	5.00 – 7.87	13.37
	1.0 – 0.4	5.00 – 7.85	11.37
	1.0 – 0.6	5.00 – 7.67	10.22
	1.0 – 0.8	5.00 – 8.52	8.88
26 years old	1.0 – 0.2	5.00 – 7.49	13.31
	1.0 – 0.4	5.00 – 7.49	9.99
	1.0 – 0.6	5.00 – 7.41	8.43
	1.0 – 0.8	5.00 – 6.90	6.62
38 years old	1.0 – 0.2	5.00 – 7.03	11.86
	1.0 – 0.4	5.00 – 6.83	10.18
	1.0 – 0.6	5.00 – 7.02	7.51
	1.0 – 0.8	5.00 – 6.99	6.32

After being subjected to the UWB antenna, different nerve diameters showed a comparison in Table 5 of the time duration of distorted signal and maximum to minimum amplitude. The study was conducted on a 26-year-old model employing a cylindrical design. The findings revealed a direct relationship between the size of the nerve diameter and the amplitude of the action potential signal. The nerve diameter of 1.0 mm-0.2 mm had the maximum amplitude of 12.50 mV, followed by 12.31 mV for 1.0 mm-0.4 mm, 12.14 mV for 1.0 mm-0.6 mm, and the lowest interference spike of 11.38 mV for 1.0 mm-0.8 mm. The observed pattern suggests that UWB antenna interference has a stronger impact on narrower nerve fibers, as the amplitude of AP signals increases when the nerve diameter decreases.

Table 5. Comparison of time duration for the distorted signal and its maximum and minimum amplitudes in difference diameter of nerve transmission (Cylindrical model, 26 years old)

Diameter of nerve (mm)	Time duration of distorted signal (ms	Maximum-to-minimum amplitude (mV)
1.0 – 0.2	5.00 – 8.22	12.50
1.0 – 0.4	5.00 – 8.43	12.31
1.0 – 0.6	5.00 – 8.26	12.14
1.0 – 0.8	5.00 – 8.08	11.38

The findings offered useful insights into the correlation between the shape of nerve fibers and the interactions with electromagnetic fields in young adults. This contributes to our comprehension of the possible biological impacts of UWB radiation on neural signaling. Considering the significant variance in the diameters of nerve fibers and anatomical differences among persons and species, it is important to examine how this can affect the applicability of the findings. Conducting further research that includes a wider variety of nerve fiber diameters and anatomical configurations would offer useful empirical information to either support or improve the existing findings. Alternatively, one may create a thorough theoretical framework to clarify how these elements might impact the observed events. This paradigm should take into account the influence of fiber size on signal propagation, the consequences of anatomical variations on network structure and connectivity, and the possible compensating mechanisms that may emerge in different brain architectures. By taking these factors into account, scientists can improve the durability and relevance of their discoveries in various nervous system setups, thereby reinforcing the wider significance and potential practical applications of the research.

The study offers vital insights into the interference caused by UWB on human arm models. However, it is crucial to accept the study's limitations and identify areas that require more research. Applying the findings to the entire human body requires careful evaluation of nerve fiber sizes and anatomical changes in different locations. Future research should further investigate this topic by doing simulations on various anatomical regions or developing theoretical frameworks to evaluate the applicability of the findings. Furthermore, it is necessary to expand the existing emphasis on direct UWB interference effects to include consideration of ambient factors and biological variability among individuals. These parameters, such as temperature, humidity, stress levels, and hydration state, have the potential to affect susceptibility to UWB interference. For future research, it is advisable to include these factors in the simulation models or perform sensitivity analysis to assess their influence. This comprehensive method will improve the strength and practicality of the findings, offering a more detailed understanding of UWB interference in various situations and populations.

Overall, this work outperformed current methodologies by using a more comprehensive approach to estimating the impact of UWB radiation on nerve fibers. Prior research has predominantly concentrated on single-frequency exposures or generalized tissue models, which fail to accurately depict the intricate interactions between UWB signals and nerve fibers of different sizes and ages. Our technique combines powerful computational models with comprehensive anatomical representations to consider these variances, leading to more precise predictions of action potential aberrations. Moreover, the integration of Izhikevich's neuron model with CST Microwave Studio facilitated accurate simulations that closely resemble real-world physiological settings, surpassing the existing literature. The methodological changes we have made immediately lead to the observed increases in the accuracy of the signal and the identification of important elements that affect the vulnerability of brain systems to UWB interference. This places our study at the forefront of research in this field.

4. Conclusion

In this study, Action Potential (AP) signals from human arm models with different nerve sizes were subjected to UWB antenna radiation. Comparisons across different age groups in the flat arm model showed that younger participants had greater peak-to-peak AP signal amplitudes when exposed to UWB antenna B2 radiation. More precisely, the model that was 7 years old demonstrated the greatest amplitude, with the 26-year-old and 38-year-old models following closely behind. This indicates that younger individuals are more prone to being affected by UWB influence. The examination of the cylindrical arm model specifically examined a case from 26 years ago. The results showed a distinct inverse correlation between the diameter of the nerves and the amplitude of the AP signal. The nerve with the smallest diameter (1.0- 0.2 mm) had the highest peak-to-peak amplitude, measuring 13.31 mV. Conversely, the nerve with the largest diameter (1.0-0.8 mm) had the lowest amplitude, measuring 6.62 mV. This trend emphasizes the importance of nerve geometry in interactions with UWB radiation. Furthermore, the research discovered that bigger areas of exposure led to greater amplitudes of spike interference, highlighting the need to take into account both the diameter of the nerves and the area of exposure when evaluating the impacts of the UWB antenna. The results highlight the possibility of UWB antenna radiation interfering with regular brain communication, potentially affecting the functioning of the arm.

Further research in this domain should prioritize enhancing our comprehension of UWB interference with neuronal action potentials by tackling many crucial aspects. An extensive examination of anatomical and biological variability is necessary to consider individual variations and their influence on research results. Further investigation should examine the impact of environmental factors and physiological conditions on vulnerability to UWB. In order to strengthen the reliability of results, it is necessary to create and utilize sophisticated statistical techniques specifically designed for bio-electromagnetic research. It is imperative to conduct a comprehensive examination of ethical considerations related to UWB exposure.

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