زانكۆی سەلاحەدین - هەولێر
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Specific Absorption Rate in The Human Brain

Research Project

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Chapter 1

1.1 Introduction

Researchers utilize the Specific Absorption Rate (SAR), a critical measurement, to quantify the extent of radiation that is absorbed by human tissues. This evaluation is particularly significant in the context of mobile telephones, which emit radiation near the brain. Through detailed studies, scientists examine the process by which a human head absorbs electromagnetic waves emitted by an antenna. Additionally, these studies delve into understanding the subsequent increase in temperature within the tissues, a direct consequence of the radiation absorbed. This comprehensive approach allows for a deeper insight into the potential impacts of mobile phone usage on human health, emphasizing the importance of SAR values in ensuring safety standards are met.

The widespread use of wireless devices has resulted in an increase in the amount of radiation to which human bodies are subjected, leading to a greater focus on reducing radiation exposure, particularly to the brain. There is a continuous academic discussion regarding the possible dangers posed by such radiation exposure. It is widely agreed upon that reducing radiation levels is of paramount importance. The Specific Absorption Rate (SAR) value stands out as a commonly employed measure for determining the energy absorbed by a material, which is determined by a specific calculation.

$$E_{\mathrm{SAR}} = \sigma \frac{|\mathbf{E}|^2}{\rho}$$

In this context, the symbol σ represents the conductivity of human brain tissue, ρ denotes the density, and |E| signifies the norm of the electric field (root mean square). The Specific Absorption Rate (SAR) serves as a critical metric for gauging the rate at which radiofrequency (RF) energy is absorbed by human tissue, calculated over a specific volume that typically encompasses either 10 grams or 1 gram of brain tissue. This measurement varies according to the regulatory standards of different countries. This discourse particularly highlights the local SAR values, which are noted for exhibiting peak absorption rates significantly higher than the overall maximum SAR values, thus providing a more detailed insight into localized exposure levels. In the realm of scientific investigation, there has been a concerted effort to accurately measure the levels of RF electromagnetic fields (RF-EMF) and their corresponding SAR values across a variety of human tissues and organs. These studies have unveiled a nuanced understanding that exposure levels and SAR values are not uniform across all demographics but show notable variations based on age and the specific tissue types involved. Notably, research indicates that children's heads may absorb RF energy at higher rates than adults', underscoring a critical area for further exploration and concern.

Despite certain studies suggesting that RF-EMF exposure levels fall within internationally recognized safety limits, the imperative to thoroughly assess the doses absorbed by the human body cannot be overstated. This is particularly crucial given the ongoing debate and emerging evidence regarding the potential health implications of prolonged RF-EMF exposure. A comprehensive understanding of electromagnetic pollution and its quantification through SAR values is indispensable for performing accurate risk assessments, formulating safety guidelines, propelling technological advancements, and elevating public awareness regarding these issues. The academic literature on this subject presents a spectrum of SAR values, with variability often attributed to the methodological approaches of different studies, including the use of simplified versus complex human models. This variability, influenced by factors such as age, gender, and anatomical differences, highlights a significant gap in the existing research that necessitates further detailed investigations. The study under consideration aims to deepen the understanding of the various factors that influence SAR values, including but not limited to age, gender, tissue type, the frequency of RF-EMF exposure, and the intensity of RF-EMF levels. By employing sophisticated laboratory measurements and simulations, which take into account electric field values across a range of frequencies and utilize computational models that accurately represent the diverse tissues and organs within the human head, this research endeavors to shed light on the complex interactions that determine SAR values. This meticulous approach to studying SAR and its determinants is expected to yield valuable insights that could inform the development of more nuanced and protective safety guidelines, tailored to accommodate the specific vulnerabilities of different population segments. The ongoing pursuit of knowledge in this field is vital for ensuring that the advancement and utilization of communication technologies proceed in a manner that conscientiously addresses and minimizes the potential health risks associated with RF-EMF exposure, thereby safeguarding public health in the digital age.

2. Material & Method

2.1. Model definition

The geometry of the human head utilized in SAR (Specific Absorption Rate) value measurements adheres strictly to the standardized model known as the SAM Phantom. This model is the result of collaborative efforts and guidelines set forth by prominent international bodies, including the IEEE (Institute of Electrical and Electronics Engineers), IEC (International Electrotechnical Commission), and

CENELEC (European Committee for Electrotechnical Standardization). These organizations have meticulously defined the specifications for SAR assessments to ensure uniformity and accuracy in radiation exposure evaluations across various devices and scenarios. The original SAM Phantom geometry, a critical component in these evaluations, was seamlessly integrated into the COMSOL Multiphysics software following minor modifications to ensure its compatibility with the simulation environment. This adjustment was essential for preserving the integrity of the standard while accommodating the specific requirements of the simulation tool. Further enhancing the model's sophistication, the COMSOL Multiphysics software incorporates a unique approach to simulating the complex internal structure of the human head. Through the application of a volumetric interpolation function, the model is capable of simulating variations in tissue type within the head with remarkable precision. This function relies on source data meticulously extracted from a file named sar_in_human_head_interp.txt, a comprehensive dataset derived from an intricate analysis of magnetic resonance imaging (MRI) scans of a human head. The MRI data, encapsulating 109 individual slices each composed of 256-by-256 voxels, provides an exceptionally detailed representation of the head's internal structures. Each slice contributes to a three-dimensional matrix that captures the nuances of different tissue types, from the dense bony structures of the skull to the soft tissues of the brain. This data-rich foundation allows for an unprecedented level of detail in SAR simulations, enabling researchers to approximate the electromagnetic field distribution and absorption rates within the head with a high degree of accuracy. The meticulous calibration of the model based on real human anatomical data underscores the commitment to ensuring that SAR evaluations closely mirror the true biological impact of RF exposure. As such, the model not only serves as a cornerstone for understanding the potential health implications of electromagnetic radiation but also as a pivotal tool in the development and refinement of safety standards and guidelines. By leveraging advanced imaging technology and sophisticated computational modeling, researchers continue to advance our understanding of SAR values and their significance in protecting human health in an increasingly wireless world. The application of the data variation from the mentioned file to alter the tissue material parameters in the human head model specifically addressing conductivity, permittivity, and perfusion rates based on the spatial location within the head-is a methodological choice made for illustrative purposes. This approach is not rooted in a scientific hypothesis but serves as a practical example to demonstrate how changes in these physical properties can influence the SAR values across different regions of the head. The visualization of such variations, as depicted in Figure 2.1, provides a clear representation of how electromagnetic fields interact with biological tissues, emphasizing the importance of considering spatial heterogeneity in tissue properties when assessing SAR. To accommodate computational limitations and optimize the simulation process, the model strategically reduces the resolution of the volumetric data derived from the MRI scans to a grid of 55-by-50-by-50 interpolation points. This reduction is carefully calibrated to align with the density of the mesh elements used to represent the head's internal structure in the COMSOL Multiphysics environment. Such a measure ensures that the simulation remains computationally feasible while still capturing the essential variations in tissue properties throughout the head. The preparation of the MRI data for integration into the SAR model involved a series of preprocessing steps, including scaling, translating, and rotating the three-dimensional MRI datasets. These adjustments were meticulously performed to ensure that the MRI-derived data closely matched the imported head geometry specified by the SAM Phantom standard in COMSOL Multiphysics. This process underscores the complex interplay between the high-resolution anatomical data obtained from MRI scans and the geometric and physical constraints of computational models. Through this intricate preprocessing and data manipulation, the model achieves a realistic approximation of the head's internal structure, allowing for a nuanced analysis of SAR distribution. This methodological approach highlights the challenges and considerations involved in bridging the gap between detailed anatomical data and the requirements of electromagnetic simulation models. It also illustrates the potential of computational modeling to explore the effects of variable tissue properties on the absorption of electromagnetic energy, providing valuable insights that could inform safety standards and public health policies. Moreover, this example emphasizes the evolving nature of computational simulations in assessing electromagnetic exposure and their critical role in understanding the interaction between RF energy and biological tissues. As technology and modeling techniques continue to advance, the fidelity and accuracy of these simulations are expected to improve, offering more precise tools for evaluating the potential health implications of exposure to electromagnetic fields.

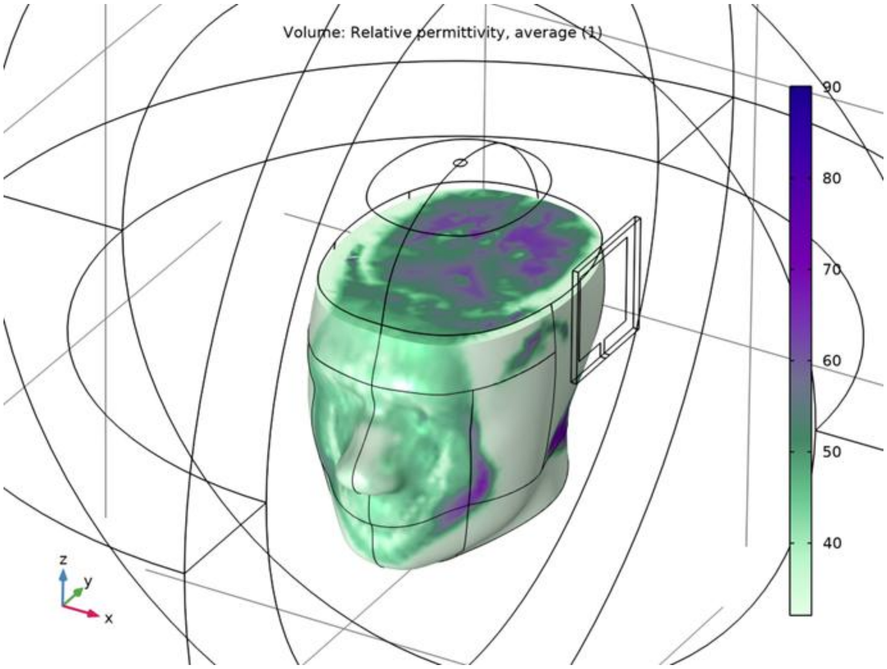

Figure 2.1: This plot shows how the average relative permittivity varies inside the head. The permittivity is calculated from the imported MRI image data.

2.2. Wave Propagation

In this advanced simulation setup, the source of radiation is a patch antenna strategically positioned on the left side of the head, designed to mimic the typical scenario of a mobile phone in use. The patch antenna is activated by a lumped port, a specific type of boundary condition used in electromagnetic simulations to model the energy input from the antenna into the surrounding space in a controlled manner. This method allows for precise control over the power and phase characteristics of the signal emanating from the antenna, thereby enabling a realistic simulation of how a mobile phone would interact with human tissue during a call. To address the challenge of simulating the infinite nature of space and to prevent artificial reflections that could distort the results, the model incorporates a Perfectly Matched Layer (PML). The PML is a sophisticated absorbing boundary condition specifically designed to absorb electromagnetic waves approaching the boundary of the simulation domain from any angle of incidence without reflection. This technique is detailed in the "Perfectly Matched Layer" section of the COMSOL Multiphysics Reference Manual, which explains its theoretical foundation and practical implementation in simulations. By employing a PML, the model ensures that the scattered radiation from the antenna is absorbed as it would be in an open environment, thus maintaining the accuracy of the simulation's portrayal of electromagnetic wave propagation and absorption. Within this simulated environment, the model solves the vector-Helmholtz equation across the entire domain for a specified frequency. The vector-Helmholtz equation is fundamental to the study of electromagnetic fields, describing how waves propagate in a medium. By solving this equation, the simulation can accurately depict the distribution and intensity of electromagnetic fields within the head and around the antenna, capturing the complex interactions between the radiated energy and the biological tissues. This includes the visualization of how electromagnetic waves penetrate, reflect, and get absorbed by different tissues, providing insights into the distribution of SAR values within the head. The frequency chosen for the simulation is critical, as it must reflect the operating frequencies of mobile phones to ensure the relevance of the results to real-world scenarios. By meticulously setting up the simulation parameters to mirror the conditions under which people typically use mobile phones, the study aims to generate meaningful data on the potential exposure levels and health implications of mobile phone radiation. This comprehensive approach, combining a realistic antenna model with sophisticated boundary conditions and a rigorous solution of the vector-Helmholtz equation, exemplifies the cutting-edge techniques used in computational physics to understand and evaluate the safety of wireless devices. The insights gained from such simulations are invaluable for informing regulatory standards, guiding the design of safer telecommunications equipment, and enhancing public awareness about the potential health impacts of electromagnetic radiation:

$$\boldsymbol{\nabla} \times \frac{\mathbf{1}}{\boldsymbol{\mu_r}} \boldsymbol{\nabla} \times \mathbf{E} - \boldsymbol{k_0^2} \boldsymbol{\varepsilon_r} \mathbf{E} = \mathbf{0}$$

where μ_r is the relative permeability, k_0 is the free-space wave vector, and □r is the permittivity. In the realm of simulating wave-propagation phenomena, especially those pertaining to electromagnetic fields as in the case of assessing the impact of radiation from mobile devices on human tissue, the discretization of the simulation domain via meshing is of paramount importance. This discretization process involves dividing the simulation space into finite elements over which the governing equations, such as the vector-Helmholtz equation mentioned earlier, are solved numerically. A crucial criterion for the meshing process in such simulations is the relationship between the mesh size and the wavelength of the propagating wave, particularly the minimum wavelength presents in the problem. The guideline that the mesh size should be limited according to the problem's minimum wavelength is rooted in the need to accurately capture the wave's characteristics, including its propagation, reflection, and absorption within the simulated domain. To properly resolve the wave, and thus ensure that the simulation accurately reflects the physical phenomena involved, it is generally recommended to have about five elements per wavelength. This recommendation ensures that the numerical solution can adequately represent the wave's spatial variations, avoiding numerical dispersion errors that can lead to inaccuracies in predicting how electromagnetic waves interact with human tissues. The requirement for approximately five elements per wavelength serves as a balance between computational efficiency and accuracy. While increasing the number of elements per wavelength can enhance the resolution of the wave's behavior, it also significantly increases the computational resources required, including both processing time and memory. Conversely, reducing the number of elements per wavelength to save on computational resources risks losing critical details about the wave's interaction with the tissues, potentially leading to underestimations of SAR values and, by extension, the biological effects of the radiation. In practice, determining the optimal mesh size for a given simulation involves considering the specific frequencies of interest-corresponding to the operating frequencies of the mobile device in question and the electromagnetic properties of the simulated tissues, both of which influence the wavelength of the waves within the biological medium. The simulation must then be meticulously calibrated, possibly through a series of iterative refinements, to ensure that the mesh is fine enough to capture the essential physics of wave propagation while remaining computationally manageable. This meticulous approach to meshing in wave-propagation simulations underscores the complexity of accurately modeling the interactions between electromagnetic fields and human tissues. It highlights the sophisticated computational techniques employed in contemporary research to evaluate the safety of wireless communication devices, contributing to the ongoing efforts to understand and mitigate the potential health impacts of exposure to electromagnetic radiation. This illustration sources material characteristics of the human brain from a presentation by G. Schmid. The subsequent table examines various frequency-dependent attributes highlighted in this publication. An interpolation function utilizes these values to generate a realistic fluctuation.

Parameter	**Frequency**	**Value**	**Description**
□	835 MHz	1.15 S/m	Conductivity
□*r*	835 MHz	58.13	Relative permittivity

2.3. Heating of the Head

The bioheat equation serves as a mathematical representation of the thermal dynamics within the head, accounting for the increase in temperature resulting from electromagnetic radiation exposure, while also considering the cooling effect brought about by blood flow. This cooling mechanism is influenced by several factors, including the heat capacity and density of the blood, as well as the rate at which blood perfuses through tissues, known as the blood perfusion rate. It's important to note that the perfusion rate is not uniform throughout the human body, exhibiting considerable variation across different tissues and organs. The significance of the bioheat equation in this context lies in its ability to simulate the complex interplay between heat generation due to electromagnetic energy absorption and heat dissipation through blood circulation. This equation incorporates the physiological response of the body to heat, modeling how efficiently heat is removed from tissues by the circulating blood. The parameters for heat capacity and density of the blood provide a quantitative measure of the blood's ability to carry heat, while the perfusion rate reflects the effectiveness of blood flow in different areas of the body at distributing or removing this heat. The variability in perfusion rates among different body parts is crucial for accurately modeling thermal effects in tissues, as areas with higher perfusion rates can dissipate heat more effectively, potentially mitigating the thermal impact of RF exposure. Conversely, regions with lower perfusion rates may experience higher temperature increases under the same exposure conditions, indicating a greater risk of thermal damage. To accurately assess the thermal response of the head to electromagnetic radiation, the bioheat equation utilizes specific values for these parameters, as outlined in the table provided. These values are essential for creating a detailed and physiologically relevant model of heat distribution and dissipation in the head. By understanding these dynamics, researchers can better predict the potential health implications of RF exposure, including the risk of tissue damage or other adverse effects resulting from elevated tissue temperatures. This understanding is instrumental in the development of safety standards and guidelines aimed at protecting public health in the face of increasing exposure to electromagnetic fields.

PART	PERFUSION RATE

Brain	2·10-3 (ml/s)/ml
Bone	3·10-4 (ml/s)/ml
Skin	3·10-4 (ml/s)/ml

The interpolation function applied to model electrical properties is similarly employed to depict variations in perfusion rate between the brain's internal tissues and the external layers of skin and bone. It's important to emphasize that the application of this interpolation function is not based on physical principles but is utilized merely to demonstrate the realistic impact of changing material parameters.

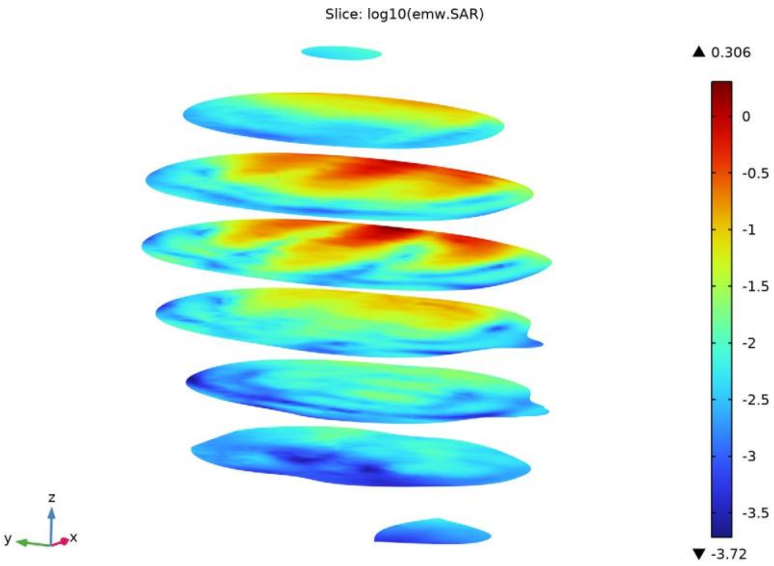

Figure 2: Log-scale slice plot of the local SAR value.

3. *Results and Discussion*

The model conducts an in-depth analysis of the localized Specific Absorption Rate (SAR) within the head, utilizing the previously discussed formula, specifically targeting the frequency of 835 MHz. This examination reveals that the SAR values are predominantly elevated near the head's surface that directly faces the incoming electromagnetic wave. This pattern highlights the intensity of energy absorption where the radiation initially contacts the body, indicating a significant interaction between the electromagnetic field and the tissues at this interface. To further elucidate the impact of varying electrical properties across different areas within the head, the model advocates for the plotting of localized SAR values on a logarithmic scale, as depicted in Figure 3.1. Employing a logarithmic scale allows for a more nuanced visualization of SAR distribution, especially in showcasing the stark contrasts in absorption rates across the head's different regions. This method effectively accentuates the differences in electrical properties, which might otherwise be less discernible on a linear scale. Such disparities in SAR values can be attributed to the heterogeneous nature of the head's composition, including variations in tissue conductivity and permittivity, which influence how different areas absorb and dissipate electromagnetic energy. This detailed approach to modeling and visualizing SAR values serves multiple purposes. Firstly, it provides critical insights into the spatial variation of electromagnetic energy absorption within biological tissues, offering a clearer understanding of potential exposure risks associated with radiofrequency radiation. Secondly, it underscores the importance of considering the head's complex geometry and varied material properties when assessing the safety and health implications of mobile phone usage or exposure to similar devices. Lastly, the findings from such analyses can inform the development of more effective guidelines and standards for limiting human exposure to electromagnetic fields, thereby enhancing public health protection in an era increasingly dominated by wireless technologies. The bioheat equation, a critical tool in understanding thermal effects within biological tissues, similarly generates a plot that maps the heating pattern within the head, emphasizing the thermal impact closest to the antenna where the heat concentration is highest. This heating effect is quantified as a maximum temperature rise of approximately 0.15 ºC from the normal body temperature of 37 ºC. Notably, this increase in temperature diminishes rapidly as one moves further into the interior of the head, illustrating the localized nature of the thermal effect induced by electromagnetic radiation. This temperature gradient is significant for several reasons. Firstly, it provides empirical evidence of how electromagnetic energy, when absorbed by biological tissues, converts to thermal energy, leading to an increase in temperature. The sharp decline in temperature increase with distance from the antenna highlights the effectiveness of the body's thermal regulation mechanisms, as well as the insulating properties of biological tissues, which help in dissipating the heat away from the source. Moreover, the bioheat equation's role in mapping these temperature changes is instrumental in evaluating the potential biological effects of prolonged exposure to electromagnetic fields, particularly those emitted by devices such as mobile phones. By quantifying the temperature rise and its spatial distribution within the head, researchers can assess the extent to which such exposure might influence cellular and tissue functions, potentially contributing to health risks. Additionally, the findings from the application of the bioheat equation have broader implications for the design and safety standards of wireless devices. Understanding the thermal dynamics within human tissues in response to RF exposure can guide the development of technologies that minimize thermal effects, thereby enhancing user safety. It also informs regulatory guidelines and public health advisories regarding safe levels of exposure to electromagnetic radiation. Furthermore, the bioheat equation's insights into thermal effects complement the SAR value analysis, offering a comprehensive view of both the electromagnetic and thermal interactions between wireless devices and human tissues. Together, these analyses form a foundation for ongoing research and debate concerning the safety of wireless technology, driving advancements in both scientific understanding and technological innovation to mitigate potential health impacts.

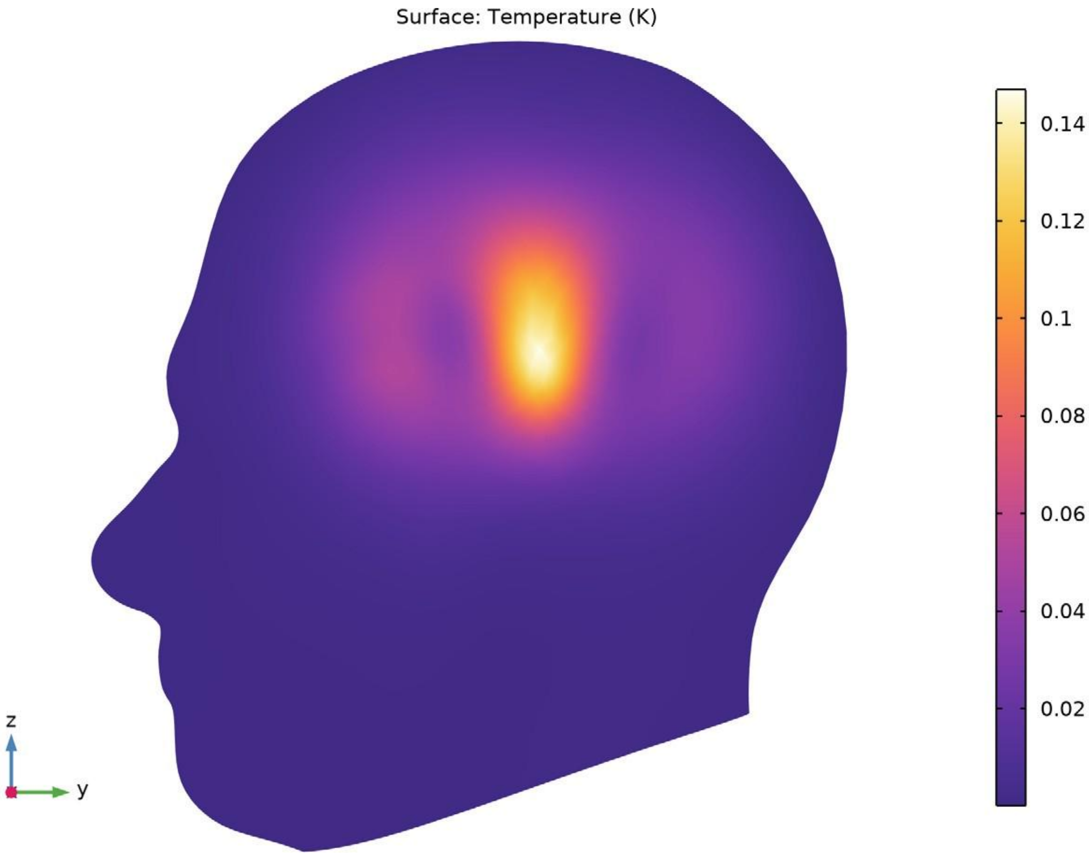

Figure 3.1: The local increase in temperature at the surface has the maximum right beneath the antenna.

4. Conclusion

In conclusion, the study of Specific Absorption Rate (SAR) values plays a crucial role in understanding the interaction between electromagnetic radiation from wireless devices and human tissues. Through meticulous modeling and simulation, including the application of the bioheat equation, researchers have been able to quantify the extent of radiation absorbed by the human body, particularly in the head, when exposed to frequencies typical of mobile phone usage. The findings reveal that SAR values are highest near the surface of the head facing the incident wave, indicating a localized concentration of energy absorption that diminishes rapidly with depth. These insights are not only fundamental to assessing potential health risks associated with prolonged exposure to electromagnetic fields but also instrumental in guiding the development of safety standards and regulations. By identifying the conditions under which SAR values exceed recommended thresholds, regulatory bodies can recommend safer use practices and influence the design of wireless devices to minimize exposure. Furthermore, the temperature increase in the head, as modeled by the bioheat equation, underscores the thermal effects of RF exposure, complementing SAR analysis by highlighting the physiological response to absorbed electromagnetic energy. Although the observed temperature rises are modest, the importance of understanding these effects cannot be overstated, especially considering varying individual susceptibilities and long-term exposure scenarios. Moving forward, continuous research and refinement of SAR measurement and modeling techniques are essential. This includes exploring the variability of SAR values across different populations, including children, and understanding the cumulative effects of exposure from multiple devices. Additionally, advancing technology calls for updated and more comprehensive safety guidelines that reflect the latest scientific findings and technological developments.

5. References