زانكۆی سەلاحەدین ـ هەولێر
Salahaddin University-Erbil

# *Specific Absorption Rate in The Human Brain*

**Research Project**

**Submitted to the department of Physics in partial fulfillment of the requirements for the degree of BSc. in Physics**


***BY:***

***PARINAZ OMAR RAMAZAN***

***Supervised By:***

***MR. KADHIM Q. JABBAR***


**APR – 2023**

# Chapter 1

## 1.1 Introduction

Scientists measure the amount of radiation absorbed by human tissues using the Specific Absorption Rate (SAR), a key indicator, especially relevant to the use of mobile phones that emit radiation close to the brain. Through comprehensive research, they explore how the human head absorbs electromagnetic waves from an antenna and investigate the rise in tissue temperature resulting from this absorption. Such in-depth analysis provides critical insights into how mobile phone use might affect human health, highlighting the significance of SAR values in adhering to safety standards. With the increasing prevalence of wireless devices, humans are exposed to more radiation, leading to heightened efforts to minimize exposure to the brain. The academic community continues to debate the potential risks of radiation exposure, with a consensus on the critical need to lower radiation levels (Seetharaman et al., 2022). 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) (Wessapan et al., 2011). The Specific Absorption Rate (SAR) is an essential measurement for determining how much radiofrequency (RF) energy is absorbed by human tissue, calculated over a specified mass of either 10 grams or 1 gram of brain tissue, depending on the country's regulatory guidelines. This discussion focuses on local SAR values, which reveal peak absorption rates that are considerably higher than the maximum overall SAR values, offering deeper insight into the extent of localized exposure. In scientific research, there has been a dedicated push to accurately assess RF electromagnetic field (RF-EMF) levels and their corresponding SAR values in various human tissues and organs. Such studies have led to a sophisticated understanding that exposure levels and SAR values differ significantly among different groups, influenced by factors like age and specific tissue types. Research has particularly highlighted that children's heads may absorb RF energy more readily than adults', pointing to an important area for further investigation and concern. While some research indicates that RF-EMF exposure levels are within global safety limits, the critical need for detailed analysis of the absorption rates by the human body is undeniable, especially in light of continuing debates and new findings about the potential health risks of extended RF-EMF exposure (Turgut & Engiz, 2023). Achieving a detailed understanding of electromagnetic pollution and accurately measuring it through SAR values is essential for conducting precise risk assessments, developing safety standards, driving technological progress, and enhancing public awareness of these concerns. The scholarly work on this topic shows a range of SAR values, with differences often stemming from the research methodologies employed, such as the use of simplified or complex human models. This variation, influenced by age, gender, and bodily differences, underscores a significant research gap that calls for more thorough investigations. The study in question seeks to enrich our comprehension of the factors affecting SAR values, encompassing age, gender, tissue type, frequency, and intensity of RF-EMF exposure. Through advanced laboratory measurements and simulations that consider electric field values across various frequencies and employ computational models reflecting the diverse tissues and organs of the human head, this research aims to illuminate the intricate factors that influence SAR values. This detailed examination of SAR and its influencing factors is anticipated to provide insights leading to the creation of more refined and protective safety standards, considering the particular susceptibilities of different demographic groups. The continuous quest for knowledge in this domain is crucial for ensuring that the growth and use of communication technologies are pursued with a mindful approach to mitigating the health risks associated with RF-EMF exposure, thus protecting public health in the era of digital technology (Jamshed et al., 2020).

## 2. Material & Method

### 2.1. Model definition

The measurement of the Specific Absorption Rate (SAR) values, used to assess radiation absorption in the human head, strictly uses the standardized SAM Phantom model. This model is the outcome of collaborative efforts and standards established by leading international organizations, such as the Institute of Electrical and Electronics Engineers (IEEE), the International Electrotechnical Commission (IEC), and the European Committee for Electrotechnical Standardization (CENELEC) (Cleveland & Athey, 1989). These bodies have detailed specifications for SAR evaluations to maintain consistency and precision in assessing radiation exposure from various devices and under different conditions. The SAM Phantom's design, essential for these assessments, was integrated into the COMSOL Multiphysics software with slight adjustments for compatibility, ensuring the standard's integrity within the simulation framework. Moreover, COMSOL Multiphysics enhances the model's detail by employing a volumetric interpolation function. This feature allows for the accurate simulation of the human head's complex internal structure, capturing variations in tissue types with exceptional accuracy.

This process utilizes data meticulously gathered from a file named "sar_in_human_head_interp.txt," which is a detailed dataset obtained from complex analysis of magnetic resonance imaging (MRI) scans of a human head. The MRI data, comprising 109 individual slices, each made up of 256-by-256 voxels, offers an exceptionally detailed view of the internal structures of the head. Each slice contributes to a three-dimensional matrix that accurately reflects the various tissue types within the head, ranging from the dense bony structures of the skull to the soft tissues of the brain. This rich dataset provides a foundation for SAR simulations that is unparalleled in detail, allowing researchers to estimate the distribution and absorption rates of electromagnetic fields within the head with high precision (Zhao et al., 2016). The careful calibration of the model with actual human anatomical data emphasizes the dedication to ensuring SAR evaluations accurately reflect the true biological effects of RF exposure. Thus, the model is crucial not only for assessing potential health impacts of electromagnetic radiation but also for guiding the development and enhancement of safety standards and practices. Through the use of advanced imaging techniques and sophisticated computational modeling, the research community is pushing forward our understanding of SAR values and their importance in safeguarding human health amidst the proliferation of wireless technologies. The utilization of data variation from the specified file to modify tissue material parameters in the human head model specifically targeting conductivity, permittivity, and perfusion rates based on their spatial location within the head is a methodological decision chosen for demonstration purposes. This strategy is not based on a scientific theory but is employed to exemplify how variations in these physical properties can impact SAR values in different areas of the head. The illustration of these variations, as shown in Figure 1, effectively highlights how electromagnetic fields interact with biological tissues, underlining the significance of acknowledging spatial diversity in tissue properties for SAR assessments. To manage computational demands and streamline the simulation workflow, the model judiciously downscales the resolution of the volumetric data from MRI scans to a simplified grid of 55-by-50-by-50 interpolation points. This scaling is precisely adjusted to match the mesh density required to accurately depict the internal structure of the head in the COMSOL Multiphysics software, ensuring the simulation's computational viability without compromising the essential representation of tissue property variations across the head. The integration of MRI data into the SAR model necessitated several preprocessing steps, such as scaling, translating, and rotating the three-dimensional MRI datasets. These manipulations were carefully executed to align the MRI-derived data with the head geometry defined by the SAM Phantom standard within the COMSOL Multiphysics software. This procedure highlights the intricate balance between the detailed anatomical information provided by MRI scans and the geometric and physical requirements of computational modeling. By undergoing this detailed preprocessing and data adjustment, the model is able to closely mimic the internal structure of the human head, facilitating a detailed analysis of SAR distribution. This approach illuminates the complexities and necessary considerations for merging in-depth anatomical data with the demands of electromagnetic simulation models (Zhao et al., 2016). It showcases the potential of computational modeling to examine how varying tissue properties affect electromagnetic energy absorption, offering insights that could shape safety standards and public health guidelines. Additionally, this example underscores the dynamic nature of computational simulations in evaluating electromagnetic exposure and their essential role in dissecting the interactions between RF energy and biological tissues. With ongoing advancements in technology and modeling techniques, the precision and accuracy of these simulations are poised to enhance, providing increasingly accurate tools for assessing the health impacts of electromagnetic field exposure (Singh & Kapoor, 2014).

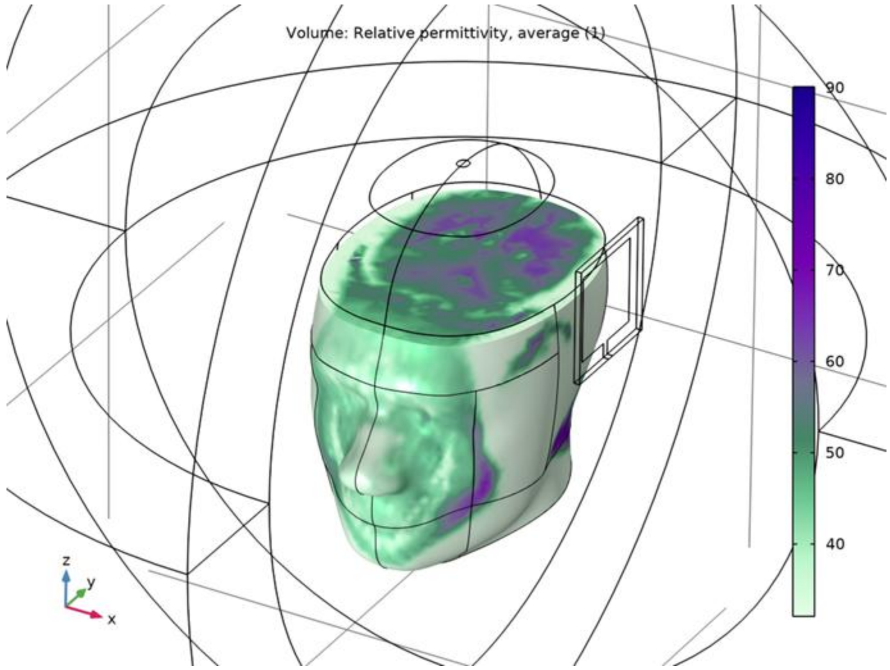


*Figure 2.1: This plot shows how the average relative permittivity varies inside the head. The permittivity is calculated from the imported MRI image data.*

## 2.2. Wave Propagation

In the sophisticated simulation setup, the radiation source is a patch antenna, thoughtfully placed on the left side of the head to replicate the common use case of a mobile phone. This antenna is powered by a lumped port, a particular boundary condition in electromagnetic simulations that models the injection of energy from the antenna into the adjacent space with accuracy. This approach facilitates meticulous management of the signal's power and phase attributes emitted by the antenna, thus enabling an authentic representation of how a mobile phone would engage with human tissue during a call. This strategy ensures that the simulation closely mirrors real-world mobile phone usage, providing valuable insights into the interaction between electromagnetic fields and biological tissues, crucial for assessing safety and health implications (Jensen & Rahmat-Samii, 1994).

To overcome the challenge of simulating the boundless nature of space and to avoid artificial reflections that could skew the outcomes, the model integrates a Perfectly Matched Layer (PML). This PML is an advanced absorbing boundary condition crafted to soak up electromagnetic waves hitting the simulation domain's boundary from any direction, effectively preventing any reflections. The "Perfectly Matched Layer" section of the COMSOL Multiphysics Reference Manual delves into the PML's theoretical basis and its application in simulations. Through the use of a PML, the model mimics the natural absorption of scattered radiation from the antenna as it would occur in an unbounded environment, preserving the fidelity of the simulation's depiction of electromagnetic wave behavior and absorption. This setup effectively simulates an open environment, ensuring the realism of the simulation by preventing the artificial reflections that could otherwise impact the accuracy of the results. In this simulated context, the model addresses the vector-Helmholtz equation throughout the domain for a chosen frequency. The vector-Helmholtz equation, a cornerstone in electromagnetic field studies, describes the propagation of waves in a medium. Solving this equation allows for an accurate representation of electromagnetic field distribution and intensity within the head and in the vicinity of the antenna, capturing the intricate dynamics of how the energy interacts with biological tissues. This includes visualizing the penetration, reflection, and absorption of electromagnetic waves by different tissues, thus offering insights into the SAR distribution within the head. The selection of the simulation frequency is pivotal, mirroring the operational frequencies of mobile phones to align the results with actual usage scenarios. By carefully calibrating the simulation parameters to reflect typical mobile phone use conditions, the research aims to produce valuable data concerning potential radiation exposure levels and their health impacts. This detailed methodology, which combines a realistic antenna configuration with sophisticated boundary conditions and a thorough application of the vector-Helmholtz equation, demonstrates the advanced techniques employed in computational physics to assess and ensure the safety of wireless communication 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 (Pasik et al., 1999):

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

where $\mu_r$ is the relative permeability, $k_0$ is the free-space wave vector, and □r is the permittivity. In simulating wave-propagation phenomena, particularly for assessing electromagnetic field impacts from mobile devices on human tissue, discretizing the simulation domain via meshing is crucial. This process involves dividing the simulation space into finite elements to solve governing equations like the vector-Helmholtz equation numerically. A key aspect of meshing in such simulations is ensuring the mesh size is appropriately related to the wave's wavelength, especially the minimum wavelength present. This is vital for accurately capturing the wave's behavior, including its propagation, reflection, and absorption within the domain. To accurately resolve the wave and reflect the physical phenomena accurately, the mesh should have about five elements per wavelength. This standard helps to ensure that the numerical solution can effectively represent the wave's spatial variations, minimizing numerical dispersion errors that could skew the simulation's predictions of electromagnetic wave interactions with human tissues. Balancing about five elements per wavelength achieves a compromise between computational efficiency and accuracy. Increasing the elements per wavelength improves the resolution but also raises the computational demands significantly. Conversely, reducing the elements per wavelength to conserve computational resources may overlook crucial details of the wave's interaction with tissues, potentially underestimating SAR values and the associated biological effects. Determining the optimal mesh size involves considering the frequencies of interest, which correspond to the operating frequencies of the mobile device, and the electromagnetic properties of the tissues, influencing the wave's wavelength in the medium. The simulation requires careful calibration, possibly through iterative refinements, to ensure the mesh is detailed enough to capture essential wave propagation physics while remaining computationally feasible. This detailed meshing approach in wave-propagation simulations highlights the complexity of accurately modeling electromagnetic fields' interactions with human tissues and showcases the advanced computational techniques used in modern research. These efforts are key to evaluating the safety of wireless devices and addressing the potential health impacts of electromagnetic radiation exposure (Tchikaya et al., 2011).

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** |
|---|---|---|---|
| $\sigma$ | **835 MHz** | **1.15 S/m** | **Conductivity** |

| | | | |
|---|---|---|---|
| $\boldsymbol{\varepsilon_r}$ | **835 MHz** | **58.13** | **Relative permittivity** |

## 2.3. Heating of the Head

The bioheat equation is a crucial mathematical tool for understanding the thermal dynamics within the head, particularly how temperature increases due to electromagnetic radiation exposure are moderated by the cooling effects of blood flow. This equation takes into account various factors, such as the heat capacity and density of the blood, along with the blood perfusion rate, which is the speed at which blood moves through tissues. Notably, the perfusion rate varies significantly across different tissues and organs within the human body. This equation's significance lies in its ability to model the intricate balance between the generation of heat from absorbed electromagnetic energy and the removal of this heat via blood circulation, factoring in the physiological mechanisms of heat dispersion. The parameters concerning the blood's heat capacity and density quantify the blood's heat carriage capabilities, whereas the perfusion rate indicates how efficiently blood flow can distribute or eliminate heat across various body regions. The diversity in perfusion rates is critical for accurately simulating thermal effects in tissues. For instance, areas with high perfusion rates are better equipped to dissipate heat, potentially reducing the thermal impact of RF exposure. On the other hand, regions with lower perfusion rates may see more significant temperature rises under identical exposure scenarios, highlighting a higher susceptibility to thermal damage. To effectively evaluate the head's thermal response to electromagnetic radiation, the bioheat equation employs specific parameter values, critical for developing a physiologically accurate model of heat distribution and mitigation in the head. Grasping these thermal dynamics enables researchers to more precisely forecast the potential health risks associated with RF exposure, such as tissue damage or other adverse outcomes stemming from increased 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 (Aijaz & Dar, 2017).

| **PART** | **PERFUSION RATE** |
|---|---|
| Brain | $2 \times 10^{-3}$ (ml/s)/ml |
| Bone | $2 \times 10^{-3}$ (ml/s)/ml |
| Skin | $2 \times 10^{-3}$ (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.

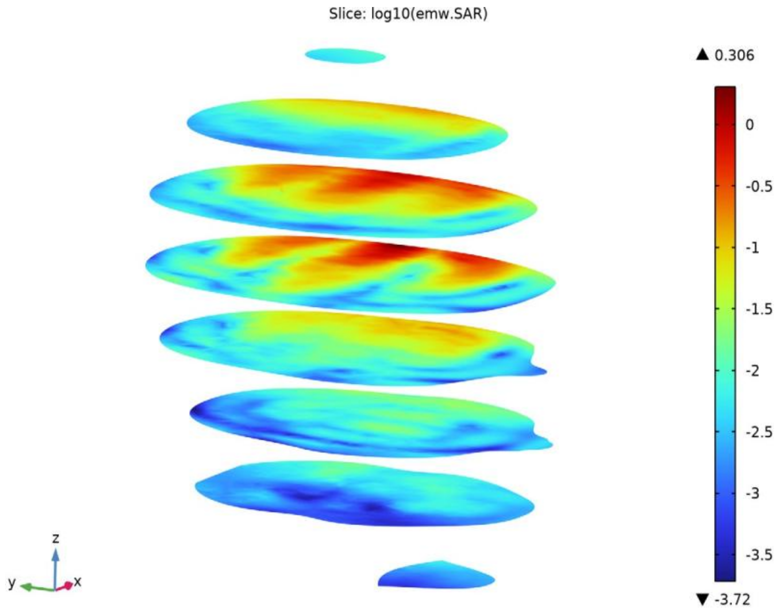


Figure 2.2: Log-scale slice plot of the local SAR value.

## 3. Results and Discussion

The model provides a thorough examination of localized Specific Absorption Rate (SAR) values within the head at a frequency of 835 MHz. This analysis shows that SAR values are notably higher near the surface of the head that is directly exposed to the incoming electromagnetic wave, underscoring a pronounced interaction between the electromagnetic field and the tissues at this boundary. To better understand the impact of the head's varying electrical properties on SAR distribution, the model suggests plotting localized SAR values using a logarithmic scale, as illustrated in Figure 3.1. Utilizing a logarithmic scale enhances the visualization of SAR distribution by highlighting the significant differences in absorption rates across various regions of the head, which might not be as apparent on a linear scale. These variations in SAR values reflect the head's heterogeneous composition, with differences in tissue conductivity and permittivity affecting how various areas absorb and dissipate electromagnetic energy. This meticulous approach to modeling and visualizing SAR values fulfills several objectives.

Firstly, it offers valuable insights into the spatial variation of electromagnetic energy absorption in biological tissues, enhancing our understanding of the potential exposure risks from radiofrequency radiation. Secondly, it emphasizes the need to account for the head's complex geometry and diverse material properties when evaluating the safety and health impacts of using mobile phones or exposure to similar devices. Lastly, the insights gained from such analyses can contribute to the creation of more stringent guidelines and standards aimed at minimizing human exposure to electromagnetic fields, thereby improving public health protections in a world increasingly reliant on wireless technology. The bioheat equation, essential for assessing thermal dynamics in biological tissues, produces a plot that demonstrates the heating pattern within the head, with the greatest thermal impact observed near the antenna where heat concentration peaks. This effect is quantified as a maximum temperature increase of about 0.15 ºC above the normal body temperature of 37 ºC. This rise in temperature quickly decreases as one moves away from the antenna, showcasing the localized nature of the thermal effects caused by electromagnetic radiation. This temperature gradient is significant for several reasons. Firstly, it offers concrete evidence of the conversion of absorbed electromagnetic energy into thermal energy within biological tissues, causing a temperature increase. The rapid decrease in temperature further from the antenna underscores the efficiency of the body's thermal regulation mechanisms and the insulating capabilities of biological tissues, which aid in heat dissipation from the source. Furthermore, utilizing the bioheat equation to map these temperature changes is crucial in understanding the potential biological impacts of extended electromagnetic field exposure, especially from devices like mobile phones. By detailing the temperature rise and its distribution within the head, it allows for an evaluation of how such exposure might affect cellular and tissue functionality, possibly leading to health risks.

Moreover, the insights gained from applying the bioheat equation have wider implications for the design and safety standards of wireless devices. Knowledge of thermal dynamics in response to RF exposure can inform the development of technology designed to minimize thermal effects, improving safety for users. It also contributes to establishing regulatory guidelines and public health recommendations on safe exposure levels to electromagnetic radiation. Additionally, the findings from the bioheat equation analysis enhance the understanding gained from SAR value studies, providing a fuller picture of the interactions between wireless devices and human tissues in terms of both electromagnetic and thermal effects. These combined analyses lay the groundwork for continued research and discussion on wireless technology safety, spurring scientific and technological progress to address potential health concerns.

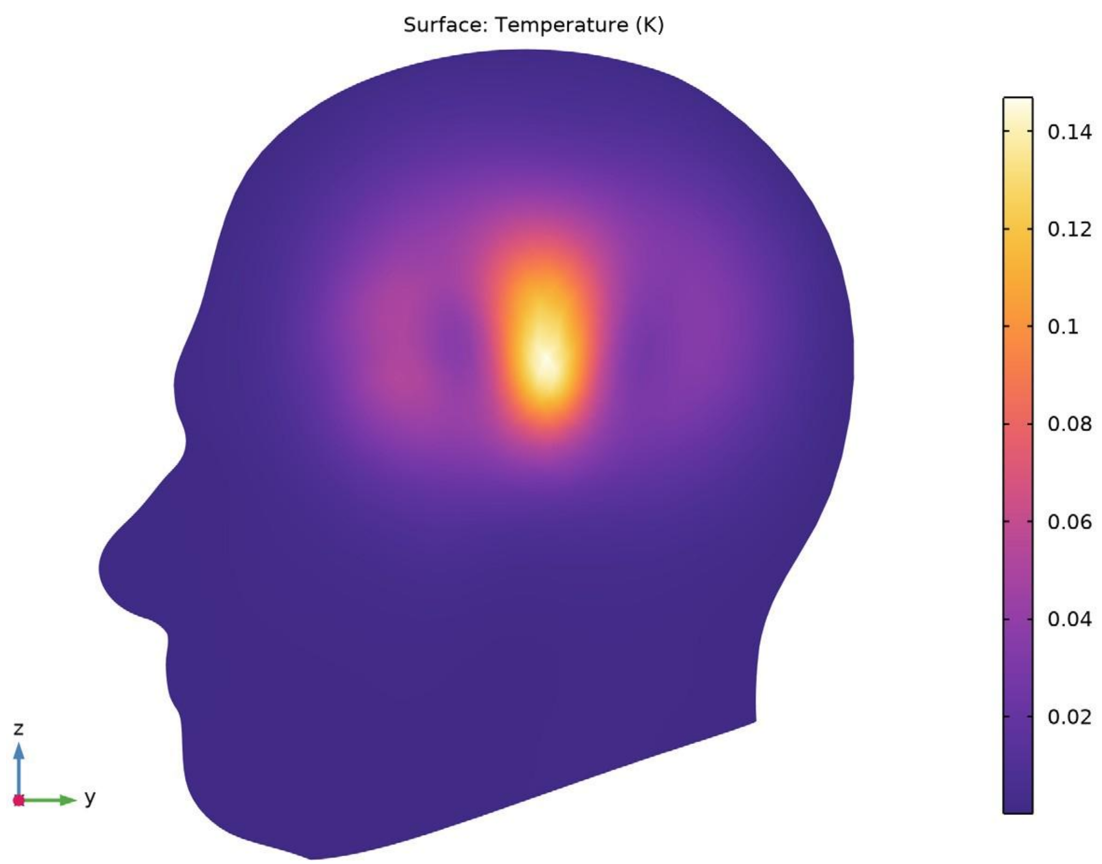

Figure 3.1: The local increase in temperature at the surface has the maximum right beneath the antenna.

## 4. Conclusion

In summary, the investigation of Specific Absorption Rate (SAR) values is pivotal for deciphering how electromagnetic radiation from wireless devices interacts with human tissues. Through detailed modeling and simulations, which include leveraging the bioheat equation, researchers can quantify the radiation absorbed by the body, notably in the head, during exposure to frequencies common in mobile phone use. The research indicates that SAR values peak near the head's surface that faces the incoming wave, showing a localized spike in energy absorption that quickly lessens with increased depth. These findings are critical not only for evaluating potential health risks from long-term electromagnetic field exposure but also for shaping safety standards and regulatory policies. By pinpointing scenarios where SAR values surpass advised limits, regulatory agencies can propose guidelines for safer device use and influence wireless device design to reduce exposure. Additionally, the thermal impact modeled by the bioheat equation highlights the physiological effects of RF exposure, providing a complementary perspective to SAR analyses by shedding light on the body's response to absorbed electromagnetic energy. While the temperature increases observed are slight, recognizing these effects is crucial, particularly in light of individual differences in susceptibility and extended exposure periods. As technology progresses, ongoing research and the enhancement of SAR assessment and modeling methods remain vital. This includes examining SAR value variability among different demographic groups, such as children, and assessing the combined exposure impacts from various devices. Furthermore, the evolution of technology necessitates revised and more encompassing safety guidelines that accurately reflect the most recent scientific discoveries and technological advancements.

## 5. References


Seetharaman, R., Tharun, M., Gayathri, S., Mole, S., & Anandan, K. (2022). Analysis of specific absorption rate and heat transfer in human head due to mobile phones. *Materials Today: Proceedings*, *51*, 2365–2374. https://doi.org/10.1016/j.matpr.2021.11.582

Wessapan, T., Srisawatdhisukul, S., & Rattanadecho, P. (2011, January 31). Numerical Analysis of Specific Absorption Rate and Heat Transfer in the Human Body Exposed to Leakage Electromagnetic Field at 915 MHz and 2450 MHz. *Journal of Heat Transfer*, *133*(5). https://doi.org/10.1115/1.4003115

Turgut, A., & Engiz, B. K. (2023, June 9). Analyzing the SAR in Human Head Tissues under Different Exposure Scenarios. *Applied Sciences*, *13*(12), 6971. https://doi.org/10.3390/app13126971

Jamshed, M. A., Heliot, F., & Brown, T. W. C. (2020, March). A Survey on Electromagnetic Risk Assessment and Evaluation Mechanism for Future Wireless Communication Systems. *IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology*, *4*(1), 24–36. https://doi.org/10.1109/jerm.2019.2917766

Cleveland, R. F., & Athey, T. W. (1989, January). Specific absorption rate (SAR) in models of the human head exposed to hand-held UHF portable radios. *Bioelectromagnetics*, *10*(2), 173–186. https://doi.org/10.1002/bem.2250100206

Zhao, L., Ye, Q., Wu, K. L., Chen, G., & Yu, W. (2016, October). A New High-Resolution Electromagnetic Human Head Model: A useful resource for a new specific-absorption-rate assessment model. *IEEE Antennas and Propagation Magazine*, *58*(5), 32–42. https://doi.org/10.1109/map.2016.2593966

Beard, B., Kainz, W., Onishi, T., Iyama, T., Watanabe, S., Fujiwara, O., Wang, J., Bit-Babik, G., Faraone, A., Wiart, J., Christ, A., Kuster, N., Lee, A. K., Kroeze, H., Siegbahn, M., Keshvari, J., Abrishamkar, H., Simon, W., Manteuffel, D., & Nikoloski, N. (2006, May). Comparisons of Computed Mobile Phone Induced SAR in the SAM Phantom to That in Anatomically Correct Models of the Human Head. *IEEE Transactions on Electromagnetic Compatibility*, *48*(2), 397–407. https://doi.org/10.1109/temc.2006.873870

Singh, S., & Kapoor, N. (2014, September 23). Health Implications of Electromagnetic Fields, Mechanisms of Action, and Research Needs. *Advances in Biology*, *2014*, 1–24. https://doi.org/10.1155/2014/198609

Jensen, M., & Rahmat-Samii, Y. (n.d.). The electromagnetic interaction between biological tissue and antennas on a transceiver handset. *Proceedings of IEEE Antennas and Propagation Society International Symposium and URSI National Radio Science Meeting*. https://doi.org/10.1109/aps.1994.407736

Pasik, M. F., Seidel, D. B., & Lemke, R. W. (1999, January). A Modified Perfectly Matched Layer Implementation for Use in Electromagnetic PIC Codes. *Journal of Computational Physics*, *148*(1), 125–132. https://doi.org/10.1006/jcph.1998.6107

Tchikaya, E. B., Khalil, F., Tahir, F. A., & Aubert, H. (2011). MULTI-SCALE APPROACH FOR THE ELECTROMAGNETIC SIMULATION OF FINITE SIZE AND THICK FREQUENCY SELECTIVE SURFACES. *Progress in Electromagnetics Research M*, *17*, 43–57. https://doi.org/10.2528/pierm11011401

Aijaz, M., & Dar, J. G. (2017, January 1). Mathematical Analysis of Bioheat Equation for the Study of Thermal Stress on Human Brain. *Applied Mathematics & Information Sciences Letters*, *5*(1), 33–39. https://doi.org/10.18576/amisl/050106