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**Numerical Modeling of Electromagnetic Field Effects on the Brain:
Evaluating Anatomical Complexity through Finite Element Analysis**

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Abstract

This thesis presents a comprehensive computational framework for the numerical modeling of electromagnetic (EM) field interactions with the human brain, addressing the urgent need for high-precision dosimetry in the context of expanding radiofrequency exposure. The research adopts a multi-scale hierarchical approach, systematically transitioning from idealized models to patient-specific anatomical representations. Initial cranial and cerebral geometries were derived from high-resolution MRI datasets and processed through a rigorous 3D Slicer segmentation pipeline. These data were subsequently imported into a Finite Element Method (FEM) environment (COMSOL Multiphysics), where a progression of geometric complexity, ranging from single-domain ellipsoids to intricate two-domain phantoms, was evaluated to isolate the physical phenomena governing field penetration, namely resonance, shielding, and dielectric absorption.

A core analytical contribution of this work is the characterization of the cranium as a frequency-selective dielectric resonator. Through extensive numerical simulation, a persistent resonant peak was identified within the 2.4 – 2.6 GHz band, demonstrating that the cranial bone functions as an impedance-matching interface that significantly modulates incident EM energy coupling. The quantitative analysis of the Quality Factor ($Q \approx 12.5$) confirms the strongly dissipative nature of this interaction. Furthermore, the dosimetric assessment reveals that while the skull effectively absorbs EM energy, the underlying cortical and intracranial tissues are significantly shielded, resulting in negligible Specific Absorption Rate (SAR) values. To bridge the gap between EM dosimetry and thermal bio-safety, the framework was further extended to compute prospective temperature surges (ΔT), demonstrating that anatomical complexity acts as a natural heat-sink mechanism.

Beyond the dosimetric results, the final phase of this research focused on the implementation of a high-resolution anatomical skull model, leveraging the advanced computational solvers of COMSOL 6.4. This transition to a patient-specific geometry involved complex mesh optimization, with approximately 1.2 million tetrahedral elements deployed to resolve the intricate curvature of the temporal bone and the facial structure. The results confirm that traditional, standardized phantoms significantly oversimplify the field distribution, often failing to account for localized hot spots that emerge from non-ideal anatomical features. This comparative analysis demonstrates that bio-electromagnetic interaction is hyper-sensitive to morphological nuances, rendering one-size-fits-all safety guidelines insufficient for modern clinical needs.

In conclusion, this study establishes a robust methodology for personalized EM exposure evaluation, providing a definitive roadmap for the transition toward 'digital twin' technologies in the e-Health sector. By proving that the future of bio-electromagnetic safety lies in the precision of anatomical intelligence rather than simplified assumptions, this thesis lays the groundwork for a new generation of dosimetric assessments. These tools are essential for harmonizing rapid technological innovation with rigorous, individualized understandings of human physiology, ensuring that safety is not merely a theoretical constraint but a tailored, patient-centered reality that accounts for the unique biological complexity of every individual.

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Chapter 1

Introduction

1.1 - The evolution of mobile telecommunications

The rapid evolution of wireless communication technologies has led to a ubiquitous presence of radiofrequency electromagnetic fields (RF-EMF) in the modern environment. Among all emitting sources, mobile phones represent the most significant contributor to human brain exposure due to their operational proximity to the cranium.

As telecommunication standards transition from the fourth generation (4G/LTE) to the fifth (5G), the complexity of the signal modulation and the frequency increase necessitate a rigorous re-evaluation of how these fields interact with the heterogeneous tissues of the human head.

One of the primary concerns regarding mobile phone usage is the potential for long-term carcinogenic effects. This topic has been extensively investigated through large-scale prospective studies. A key study in this area is the COSMOS study (**Heller et al., 2024**) that has tracked a large cohort of mobile phone users to determine if there is any link between device use and incidence of brain tumours. This study's findings, in line with recent systematic reviews (**Spriano, 2024**), showed no statistically significant increase in the risk of gliomas, meningiomas or acoustic neuromas, even after more than ten years of use.

	Glioma		–	Meningioma	
	No. cases ^b	HR (95 % CI)		No. cases ^b	HR (95 % CI)
Years of use					
0–9	47	1 (ref)		31	1 (ref)
10–14	39	0.81 (0.51–1.28)		27	1.22 (0.32–4.69)
≥15	58	0.97 (0.62–1.52)		29	1.24 (0.60–2.59)

Table 1.1: COSMOS Study – Mobile Phone Usage and Brain Tumor Incidence

The *Table 1.1* illustrates the findings from the COSMOS prospective cohort study regarding the relationship between the duration of regular mobile phone use and the incidence of glioma and meningioma.

To ensure the reliability of the results, the researchers calculated Hazard Ratios and 95% Confidence Intervals while adjusting for several key variables including country, sex, education, and marital status. The analysis compares two periods of use (10-14 years and 15 years or more) to a reference group (0-9 years of use).

There is no evidence of increased risk for glioma, with the Hazard Ratio for the longest duration of use at just under unity at 0.97. For meningioma, although the Hazard Ratios appear to be slightly elevated at 1.22 and 1.24 for the higher usage categories, these results are not statistically significant due to the broad confidence intervals that include the value of 1.0. In conclusion, these results show that long-term use of mobile phones, even for more than 15 years, is not associated with a significantly increased risk of these brain tumors, according to data from the COSMOS cohort.

These reassuring results have not made the scientific community any less alert. The classification of RF-EMF as “possibly carcinogenic to humans” (Group 2B) by the International Agency for Research on Cancer (IARC) continues to stimulate research on non-thermal biological effects that may not manifest as oncological pathologies but may nevertheless affect neurological health.

While long-term tumor risks appear minimal, acute exposure to RF-EMF has been shown to modulate brain function, affecting the brain activity and connectivity. Unlike thermal effects, which are mitigated by strict safety limits on the Specific Absorption Rate (SAR), non-thermal interactions affect the brain's electrical oscillations.

In relation to the neurophysiological effects of electromagnetic fields, systematic reviews and meta-analyses such as the study by **Prins et al. (2024)** have identified a common modulation of the alpha band (8-12 Hz) activity during resting state electroencephalography (EEG) when subjects are exposed to pulsed signals (e.g., 2G/GSM protocols).

This particular interaction suggests that the internal electrical rhythms of the brain are not passive, but rather are modulated by the rhythmic pattern of pulsed radiofrequency, especially in the alpha range that is associated with wakeful relaxation.

In addition, recent developments through MEG and MRI techniques enabled scientists to explore brain network dynamics in more depth, not only examining the local oscillations but also exploring global communications in the brain. For example, Iranfar et al. (2025) showed that acute GSM-900 MHz could influence functional connectivity in the healthy brain of young subjects. In other words, the brain's "wiring" is sensitive to external stimulation.

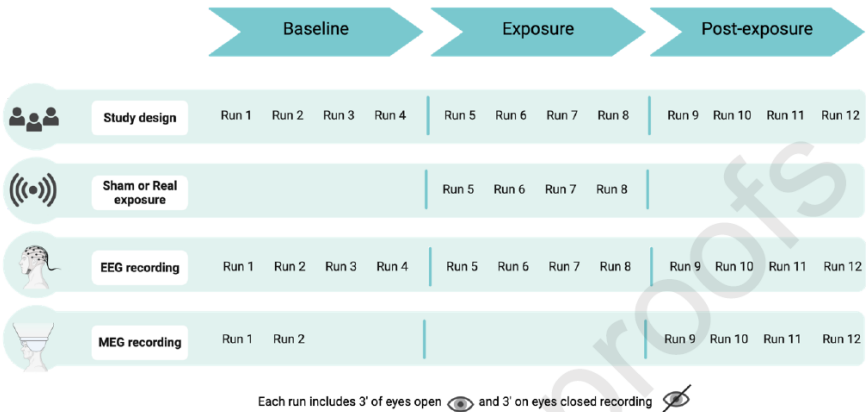


Figure 1.1: Experimental protocol design for EEG and MEG acquisition

The experimental protocol utilized in their study, which is detailed in *Figure 1.1*, was structured into three distinct phases: Baseline, Exposure, and Post-exposure. The entire procedure consisted of 12 sequential runs, with each run comprising three minutes of recording with eyes open and three minutes with eyes closed. During the Exposure phase, which spanned from Run 5 to Run 8, participants were subjected to either sham or real electromagnetic field (MP) exposure. The methods of observation varied in how they were used through the entire process; whereas EEG recordings continued without pause during all 12 runs, MEG observations were limited to the baseline and post-exposure phases.

Such a unique methodology made it possible to evaluate the alterations in brain functional connectivity in comparison to both the pre-exposure and post-exposure states. Therefore, such conclusions could be drawn that RF-EMFs can have an impact on the synchronization of information exchange within the brain's different areas.

However, as noted by **Torkan et al. (2025)** in their scoping review, while many studies point toward changes in cortical excitability and brain waves, the overall results remain partially inconclusive. This lack of a definitive consensus is largely attributed to methodological heterogeneity, characterized by significant differences in exposure protocols, varying frequency bands, and individual biological variability among subjects. Such inconsistencies highlight the need for more standardized research and personalized numerical models to better understand the specific conditions under which these neurophysiological modulations occur.

The introduction of 5G technology introduces a paradigm shift in exposure modeling. 5G utilizes higher frequency bands, including millimeter waves (mmWaves) above 6 GHz. From a physical standpoint, the penetration depth of these waves is significantly lower than that of 2G or 3G signals.

According to the recent randomized controlled trials and reviews by **Torkan et al. (2025)**, 5G exposure tends to concentrate energy in the superficial layers of the head. This emphasizes the critical need for personalized anatomical modeling.

In previous generations, the entire brain volume was considered at risk; with 5G, the focus shifts to the thickness of the skin, the muscle, and the cranial vault. If a subject has a thinner temporal bone, the cortical structures (such as the superior temporal gyrus) may receive a higher dose of radiation compared to subjects with thicker protective layers.

Beyond the direct biophysical interaction, the constant use of mobile devices has broader implications for mental health, leading to a focus on the psychosocial and behavioral implications of overexposure. Studies focusing on young populations, such as the prospective cohort study on Japanese children by **Ajmal et al. (2024)**, have explored the link between Wi-Fi and mobile phone usage patterns and behavioral problems.

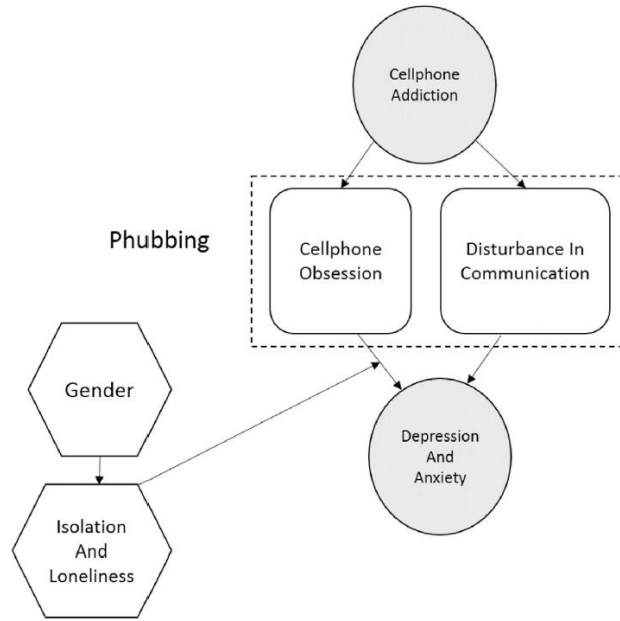


Figure 1.2: Conceptual model of the causes and psychological effects of Phubbing

Furthermore, as shown in *Figure 1.2*, research by **Arooj et al. (2025)** and **Zhu et al. (2025)** highlights the growing concern regarding mobile phone addiction, which is frequently correlated with increased levels of anxiety, depression, and aggressive behavior.

These psychosocial factors must be considered to understand the holistic impact of mobile technology on the human brain.

The history of mobile telephony, and mobile communication technologies in general, is characterized by a rapid escalation in frequency bands and modulation complexity.

Understanding this evolution is fundamental to evaluating the electromagnetic load on the human brain, as each generation interact differently with biological matter.

- The Early Generations (1G - 2G): The first generation (1G) relied on analog signals, but it was the second generation (2G/GSM) that introduced pulsed digital signals.

As noted in the studies by **Iranfar et al. (2025)** and **Prins et al. (2024)**, the GSM-900 MHz protocol is still a primary subject of research because its pulsed nature (Pulse Modulation) has been linked to specific modulations in brain oscillations, particularly in the alpha band.

- 3G and 4G (UMTS/LTE): These generations moved to higher frequencies (1.8 - 2.6 GHz) and different access schemes (WCDMA/OFDMA). While these signals are more efficient, they increased the "ambient" exposure.

However, the **COSMOS study (Heller et al., 2024)** suggests that even after decades of transition through these technologies, no clear oncological link has been established.

- The 5G Paradigm Shift: 5G technology introduces the use of Millimeter Waves (mmWave), operating at frequencies above 24 GHz. According to the scoping review by **Torkan et al. (2025)**, the physical behavior of 5G is radically different: the waves have a very short wavelength, which

leads to a significantly higher absorption rate in the skin and the skull, but a lower penetration into the deeper brain tissues.

This justifies the shift toward personalized geometric modeling in current bioengineering research.

1.2 - Dielectric Properties of Human Tissues and EMF Interaction

To perform an accurate numerical simulation in software, it is not enough to define the geometry; one must define how each specific tissue responds to the electromagnetic field.

This response is governed by the dielectric properties of the tissues.

Every biological tissue is characterized by two main parameters:

1. **Relative Permittivity ϵ_r :** The ability of the tissue to store electrical energy.
2. **Electrical Conductivity σ :** The ability of the tissue to conduct electric current, which leads to energy dissipation in the form of heat (thermal effect).

As the frequency increases (e.g., passing from 900 MHz to 26 GHz in 5G), the conductivity of tissues like the grey matter and cerebrospinal fluid (CSF) increases, while the penetration depth decreases. This means that for a 5G signal, the "shielding" provided by the cranial vault (bone) and the extracranial soft tissues (skin and muscle) becomes the most critical factor in the simulation.

In early research, the head was often modeled as a homogeneous sphere. However, current standards require a heterogeneous approach. Tissues with high water content (like the brain and muscle) have much higher conductivity than tissues with low water content (like fat and bone).

Segmentation of the aforementioned layers becomes very important in the case of the proposed study employing 3D Slicer. In case the mathematical model (Maxwell's Equations) fails to incorporate the exact thickness of subcutaneous fat layer or temporal bone, then the computed SAR value would be incorrect.

Specific Absorption Rate (SAR) is the measurement of the absorption rate of energy by human body due to exposure to radiofrequency electromagnetic fields. It is expressed in units of Watts per kilogram.

This is why measuring the thickness of these "natural barriers" is the core of the personalized model.

The interaction is categorized into:

- **Thermal Effects:** Direct heating of the tissue. International guidelines (ICNIRP) are strictly based on preventing these effects.
- **Non-Thermal Effects:** Subtle changes in neuronal excitability or connectivity. This is the area explored by Iranfar et al. (2025) and Torkan et al. (2025).

Even without a temperature increase, the electromagnetic field may influence the "firing" of neurons in the cortex, especially in areas closest to the source, such as the superior temporal gyrus.

The analysis of oncological risk associated with mobile device use has represented one of the most debated topics in bioelectromagnetics for decades. The current benchmark in this field is the COSMOS study (**Heller et al., 2024**), a prospective cohort study that has overcome the methodological limitations of previous case-control studies, which were often hindered by recall bias.

In the COSMOS study, exposure was not based on recall of study subjects but instead on data from network operators regarding actual use of the mobile phones. It is quite clear that there is no increased risk of brain tumors such as gliomas or meningiomas in any category of users including those with the highest call duration.

This result provides the basis for formulating the ‘rationale’ for mathematical modeling in that, as tumors and other macroscopic phenomena seem to have been ruled out by the existing literature, research efforts have moved on to biological function and protection.

However, as highlighted by **Spriano (2024)**, the necessity for monitoring remains critical for emerging technologies such as 5G. This is because the latency period for the development of oncological pathologies requires extremely long observation periods, and high-frequency networks have only been operational for a few years.

Beyond oncological risk, literature has focused on the acute effects of electromagnetic fields on brain function.

In this context, neuroimaging and electrophysiological techniques play a key role:

- **Analysis of oscillatory activity (EEG):** The meta-analysis conducted by **Prins et al. (2024)** confirmed that exposure to pulsed signals typical of the 2G/GSM protocol induces an increase in power in the alpha band (8 - 12.5 Hz) during the resting state with eyes open. This phenomenon suggests that the brain is not a passive receiver but reacts actively to the modulation of the RF-EMF signal.
- **Functional Connectivity (MEG):** A recent and technically advanced contribution is provided by **Iranfar et al. (2025)**, who, through the use of Magnetoencephalography (MEG), documented changes in brain functional connectivity following acute exposure to 900 MHz. These changes indicate that the electromagnetic field can influence synchronization between different brain areas, potentially altering internal communication networks.
- **Cortical Excitability and 5G:** The study by Torkan et al. (2025) explored the effect of 5G technology on corticospinal and intracortical excitability through Transcranial Magnetic Stimulation (TMS).

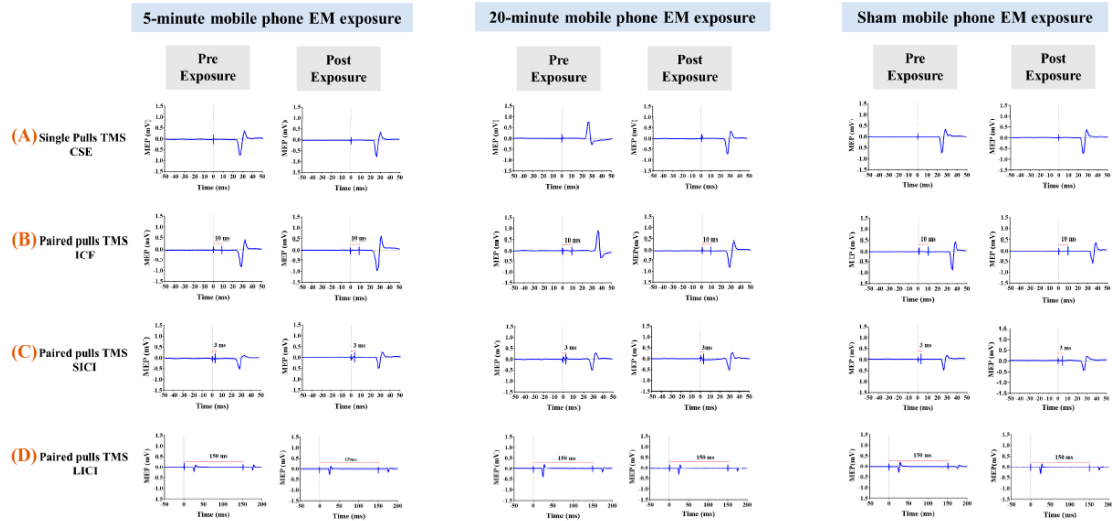


Figure 1.3: Electrophysiological response assessment following mobile phone EM exposure

As illustrated in Figure 1.3, the researchers recorded representative raw data across three experimental conditions: 5 minutes exposure, 20 minutes exposure, and sham to measure different physiological parameters. These include Corticospinal Excitability (CSE), assessed via single-pulse TMS, as well as intracortical measures like Intracortical Facilitation (ICF) and Inhibition (SICI, LICI) using paired-pulse protocols with specific interstimulus intervals.

Although preliminary results show some variability, it emerges that the biophysical interaction is closely linked to the penetration depth of the millimeter wave, which tends to interact more with the superficial cortex compared to previous generations.

The traces illustrated in the figure above indicate how the peak-to-peak amplitude of MEP can be used as an indication of the variations in the cortical response due to electromagnetic exposure.

A comprehensive introduction cannot overlook the behavioral impact associated with modern technology. The intensive use of mobile devices involves risks related to mental health that extend beyond mere physical exposure to electromagnetic fields.

Vulnerable populations are of particular concern; for instance, the study by **Ajmal et al. (2024)** on Japanese children highlighted how specific usage patterns of Wi-Fi and mobile devices are correlated with behavioral problems.

As illustrated in the *Figure 4* below, the vulnerability of this age group has a clear anatomical basis:

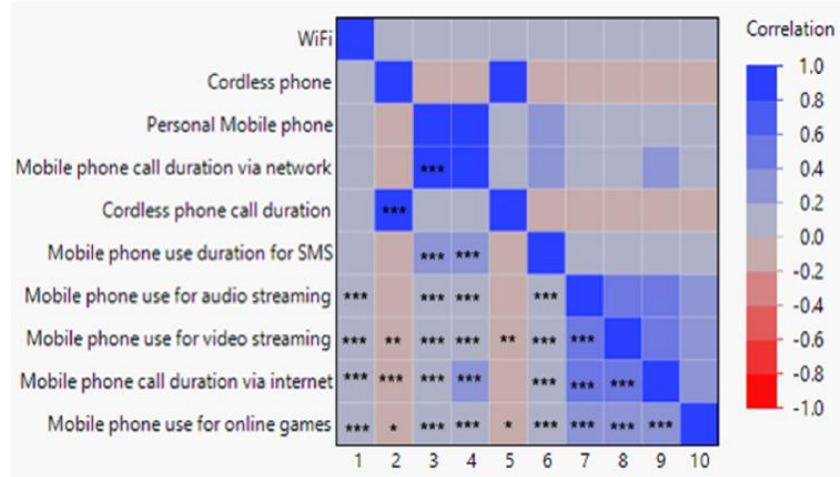


Table 1.2: Correlation matrix of mobile and cordless device usage patterns

As shown in the diagram, the penetration and absorption of radiofrequencies vary significantly across the different layers of the head. In children, the cranial vault is thinner and the tissues possess a higher water content, factors that reduce the effectiveness of the natural "shield" against electromagnetic waves.

This physical peculiarity explains why intensive usage patterns can translate into a higher Specific Absorption Rate (SAR) at the cortical level, potentially influencing the neuro-behavioral development described in the literature.

Furthermore, psychological implications have been extensively explored by **Arooj et al. (2025)** and **Zhu et al. (2025)**, whose research deepened the understanding of the link between smartphone addiction, anxiety, depression, and aggressive behavior. These findings provide a vital context for this thesis: the numerical modeling of physical protection is only one facet of a multidisciplinary issue that involves the overall well-being of the individual.

1.3 - Methodology of Geometric Reconstruction in 3D Slicer

The transition from theoretical exposure models to personalized dosimetry requires a high-fidelity geometric reconstruction of the subject's anatomy.

Within this research, the open source software known as 3D Slicer will be used to convert MRI images into a volume rendering model using a process called segmentation.

The correctness of the computational model in COMSOL Multiphysics completely depends on the process of data collection, which in turn depends on the quality of the initial DICOM images. High-quality sequences of T1-weighted and T2-weighted MRI are preferable to differentiate between tissues that have similar relaxation times but dissimilar dielectric properties .

Pre-processing filters are performed prior to segmentation in order to correct intensity inhomogeneities due to magnetic field inhomogeneity in the MRI imaging procedure

This is done to allow the automated algorithms for segmentation to recognize the tissue boundaries according to intensity differences.

A voxel refers to the three-dimensional counterpart of the pixel and holds a certain value in a regularly arranged grid in 3D space. This is common in MRI data and forms the basic volume unit since it has information about the physical nature of that particular tissue point. In this research, voxel resolution is crucial for ensuring that the volumetric reconstruction in 3D Slicer faithfully translates anatomical details into the final simulation mesh.

The core of the geometric modeling phase involves the “Segmentation” process, properly it will be an anatomical segmentation, where specific voxels are assigned to different anatomical compartments.

- **The Extracranial Shield:** Using the *Ruler tool*, the thickness of the skin, subcutaneous fat, and muscle layers is measured. As highlighted by **Torkan et al. (2025)**, these layers are the primary absorbers of 5G millimeter waves.

A precise segmentation of the "scalp-skull" complex is therefore mandatory to simulate the attenuation of the field before it reaches the neural tissue.

- **The Cranial Vault:** The skull is segmented to represent the primary physical barrier. Given its low water content and low conductivity, it acts as a dielectric shield. The variability in temporal bone thickness across individuals is a key variable in this study to determine the personalized exposure of the underlying lobes.
- **Brain Structures and Regions of Interest (ROI):** Focus is placed on the superior temporal gyrus and the acoustic-facial bundle. These regions are segmented using a combination of "Thresholding" and "Manual Paint" tools to create high-resolution *Label Maps*.

These maps are essential for calculating the SAR distribution in the specific areas identified by **Heller et al. (2024)** as high-exposure zones in mobile phone users.

Once the segmentation is complete, the *Segment Editor* is used to smooth the surfaces and remove staircase artifacts inherent in voxel-based data, in order to obtain a model optimization, from voxels to meshes. The finalized segments are then converted into closed surface models (STL or OBJ formats).

This conversion is a delicate step: the mesh density must be high enough to capture the complex gyri and sulci of the human cortex, yet optimized enough to allow for efficient computational fluid dynamics and electromagnetic solving in the subsequent COMSOL phase.

The final step of the initial phase is the definition of the computational domain.

In this context, the "Environment" surrounding the head model must be included to simulate the propagation of waves from the mobile device through the air.

During the first phase of the process, particular emphasis is placed on Boundary Layer Modeling, which involves the modeling of the boundary layer between the mobile phone as the source of radiation and the human skin. Dosimetry research studies have been using Phantom Models in the past; these are standardized models of the human head, such as the Specific Anthropomorphic Mannequin (SAM).

Usually, fixed, averaged distances between the antenna and ear are used to achieve repeatability in the model. Nevertheless, according to **Iranfar et al. (2025)**, these generic models do not take into consideration individual differences in the anatomy that can substantially affect the process of energy absorption. For this reason, the current research adopts a more sophisticated method.

Based on the facial features of each individual reconstructed, the model helps in ensuring the accurate spatial relationship between the device and the biological structure, resulting in an accurate estimate of local exposure as well as a realistic biophysical interaction.

Based on this customized geometry, the Tissue-Specific Physics are created using the COMSOL Multiphysics software. Each segmented label obtained from 3D Slicer is associated with its own unique physical constants which are obtained based on the frequency dependent dielectric values discussed earlier.

The integration achieved by this extent guarantees that the solution of the mathematical problem posed by Maxwell's Equations will be carried out in an actual, heterogenous space.

Hence, the simulation generated by this will accurately represent the unique anatomy of the subject and not the average.

1.4 - Mathematical Formalism and Numerical Modeling

The behavior of electromagnetic fields and their interaction with brain tissues are governed by Maxwell's equations.

In the context of numerical modeling for mobile telephony, the problem is analyzed in the frequency domain, as signals (2G, 4G, or 5G) operate on specific bands.

For a heterogeneous and dissipative medium such as the human body, the fundamental equations take the following differential form:

- **Faraday-Lenz Law**

$$\nabla \times E = -j \omega \mu H$$

This law dictates that a magnetic field that varies in time (represented here by the angular frequency ω) necessarily generates a circulating electric field. In the frequency domain, the term $j\omega$ represents the time derivative, while μ is the magnetic permeability of the tissue. We consider it because in mobile telephony, the smartphone antenna generates rapidly oscillating magnetic fields. We must consider this law to understand how these magnetic fields penetrate the skull and induce secondary electric fields within the brain tissue.

It is essential for determining the Induced Electric Field. Even if a tissue is not directly "touching" a current source, Faraday's law explains how the magnetic field "bridges" the gap to create an electric field inside the gray matter, which is the primary driver of the biological effects and alpha-band alterations observed in studies like **Prins et al. (2024)**.

- **Ampère-Maxwell Law**

$$\nabla \times H = (\sigma + j \omega \epsilon) E$$

This equation describes the two ways a magnetic field is generated: by the movement of free charges (conduction current, governed by conductivity σ) and by the displacement of bound charges in a dielectric (displacement current, governed by permittivity ϵ).

We consider it because the biological tissues are "lossy dielectrics," meaning they both store and dissipate energy. This law allows us to account for the total current density within the head, distinguishing between the energy that simply passes through (displacement) and the energy that is absorbed and converted into heat (conduction).

This is the core equation for calculating the Specific Absorption Rate (SAR). By solving for the $(\sigma + j \omega \epsilon)$ term, we can quantify exactly how much of the electromagnetic wave is "lost" or absorbed by a specific tissue layer, such as the skin or the temporal bone, based on its unique dielectric characterization.

Given the geometric complexity of the human brain, it is not possible to solve Maxwell's equations in analytical form. It is therefore necessary to use the Finite Element Method (FEM) implemented in COMSOL Multiphysics.

The Finite Element Method (FEM) refers to an advanced numerical procedure employed for obtaining approximate solutions to complicated Partial Differential Equations (PDEs) through discretization of a larger system into smaller subsystems known as finite elements. The FEM is very crucial in this study because of the ability of FEM to simulate the electromagnetic effects inside the very complex geometry of the human head such as the cerebral cortex.

Through the use of the volumetric mesh formed from the anatomical information extracted through the process of 3D Slicer, it becomes possible to use COMSOL Multiphysics to solve Maxwell's equations at a local level, element by element, which makes it possible to conduct an extremely accurate calculation of the deposition of energy. It is very important for detecting hot-spots of the Specific Absorption Rate (SAR) in the sulci and gyri of the brain.

The numerical modeling process follows three critical phases:

1. **Discretization (Meshing):** The volume of the head, accurately reconstructed via MRI, is divided into millions of small tetrahedral elements. The mesh density must be higher in interface zones (e.g., between the skull and cortex) to capture high electric field gradients.
2. **Assignment of Dielectric Properties:** Each domain is assigned a specific value of σ and ϵ for the frequency analyzed.

As highlighted by **Torkan et al. (2025)**, for 5G frequencies (millimeter waves), skin conductivity plays a predominant role compared to low-frequency models.

3. **Definition of SAR (Specific Absorption Rate):** The main result of the simulation is the determination of the SAR, defined as the power dissipated per unit mass of tissue:

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

where ρ is the tissue density (kg/m^3).

This parameter is the only internationally recognized standard for evaluating human exposure and verifying compliance with safety limits.

To make the model realistic, it is necessary to establish how the field interacts with the boundaries of the computational domain.

- **Antenna Modeling:** The cell phone is modeled as either a dipole antenna or a patch antenna at different distances away from the ear depending on the measurements obtained in Chapter 1.
- **Perfectly Matched Layers (PML):** These particular zones are required to simulate the propagation of electromagnetic fields in an infinite space but with a finite computational volume. When we simulate using an application such as COMSOL, the edges of the "computation box" will automatically reflect waves back towards the source, producing spurious interference patterns that will skew the SAR calculations.

This is avoided by the PML, which functions like a "mathematically-designed sponge" that absorbs the waves since it has the same impedance as the medium around it.

The amplitude of the wave decays exponentially within the PML using complex coordinate stretching.

This is important in the calculation of localized SAR to ensure that the values are true and accurate for the interaction between the antenna and the personal anatomy of the patient in 3D Slicer.

The crucial point of the proposed methodology is the correlation between the thickness of natural barriers and the local SAR: an anatomy-physics integration.

While classical literature (e.g., COSMOS, **Heller et al. 2024**) analyzes exposure statistically, the FEM modeling presented here allows for a "point-by-point" visualization of where the energy is deposited.

The use of the Ruler tool in 3D Slicer to measure the thickness of the temporal bone is not just a geometric exercise but serves to define the range of the field: mathematically, a thinner bone will result in a higher SAR value in the underlying gray matter, providing a physical explanation for the alterations in functional connectivity observed by **Iranfar et al. (2025)**.

This millimetric measurement is fundamental because, as discussed in previous chapters, the thickness of natural barriers, specifically the skull and skin, determines the actual intensity of the electric field reaching the cerebral cortex.

Utilizing real, personalized data instead of averaged values from a Phantom model allows the simulation to:

- **Identify local hot-spots:** By calculating whether a thinner bone structure in specific temporal regions leads to a significantly higher SAR value.
- **Validate neurophysiological results:** By providing a robust physical basis for the alterations in EEG activity (alpha band) and MEG connectivity observed in the studies by **Iranfar et al. (2025)** and **Prins et al. (2024)**.

The accuracy of a numerical model depends not only on the geometric fidelity obtained through the segmentation process in 3D Slicer but also on the correct attribution of physical properties to the segmented domains. Within this framework, biological tissues are treated as complex, heterogeneous, and dispersive media whose electromagnetic behavior varies drastically as a function of frequency.

This dielectric characterization is essential because the way energy is distributed, whether it is reflected by the skull or absorbed by the gray matter, is determined by these frequency-specific parameters. Consequently, the dielectric characterization serves as the physical bridge between the anatomical reconstruction and the final calculation of the SAR within the COMSOL Multiphysics environment.

Each **tissue** is defined by two main parameters appearing in Maxwell's equations:

- **Relative Permittivity (ϵ_r):** indicates the tissue's ability to polarize and store electrical energy.
- **Electrical Conductivity (σ):** quantifies the ease with which charges move in the medium, determining the dissipation of energy in the form of heat (thermal effect), which is the basis for the SAR calculation.

According to biophysical literature, tissues with high water content, such as gray matter and cerebrospinal fluid (CSF), present higher conductivity values than water-poor tissues as cranial bone or subcutaneous fat.

This disparity creates a system of reflecting and absorbing interfaces that determines the path of the electromagnetic field inside the skull.

An important issue that has been raised through research conducted by Torkan et al. (2025) involves how tissue behavior changes with increased frequencies.

As the use of 5G frequencies changes to millimeter waves, the penetration depth (δ) drops dramatically.

Whereas penetration at 900 MHz (2G) is several centimeters into the tissue, at 26 GHz the energy is absorbed in the first few millimeters.

Due to this phenomenon skin and skull are transformed from simple barriers into true volumes of maximum absorption. In this context, the millimetric measurement of soft tissue thickness performed via the Ruler tool in 3D Slicer is not just an anatomical detail, but the main physical parameter for predicting how much field will actually reach the superficial cerebral cortex.

The safety evaluation of mobile phones is based on the Specific Absorption Rate (SAR). International guidelines (ICNIRP) establish strict limits to avoid harmful thermal effects.

The SAR calculation in the numerical simulation is performed by averaging the power absorbed over a defined mass of tissue (usually 1g or 10g). The formula implemented in the COMSOL solver is:

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

The goal of personalized modeling is to verify if individual anatomical variations (e.g., a thinner skull in some temporal regions) can lead to local SAR "hot-spots" that exceed averages calculated on standard models.

As indicated by the COSMOS study (**Heller et al., 2024**), although there is no evidence of carcinogenicity, the local distribution of SAR remains the reference parameter for studying the acute neurophysiological effects described by **Prins et al. (2024)** and **Iranfar et al. (2025)**.

The technological transition from the first digital networks (2G) to modern 5G infrastructures does not just represent an increase in data transmission speed but involves a substantial modification of the physical interaction between electromagnetic fields and brain tissues.

Second-generation (GSM) protocols operate at relatively low frequencies (900-1800 MHz). As highlighted by studies by **Iranfar et al. (2025)** and **Prins et al. (2024)**, these waves have a wavelength that allows significant penetration through the cranial vault, reaching cortical and subcortical structures.

The main characteristic of 2G is its pulse modulation, which has been indicated as the trigger for observed alterations in brain electrical activity (alpha waves). In this scenario, the numerical model must analyze the entire encephalic volume, as the electric field maintains a relevant intensity even several centimeters deep.

5G introduces the use of millimeter waves (mmWave), with frequencies that can exceed 24 GHz. From a biophysical point of view, the penetration depth decreases as frequency increases. The study by **Torkan et al. (2025)** emphasizes how, at these high frequencies, energy is absorbed almost entirely by superficial tissues.

Technology	Frequency Band	Main Applications	Existing Research	Research Gaps
1G/2G	~800-900 MHz	voice communications	Extensive studies on SAR (Specific Absorption Rate), health risk assessments	Limited newer studies reassessing low-level long-term exposure
3G	~1.8-2.1 GHz	providing access to the Internet on laptops and mobile devices	Significant research on RF biological effects and epidemiological studies	Need for updated risk assessments based on modern usage patterns
4G	~2-2.6 GHz (sometimes up to 3.5 GHz)	video conferencing to gaming services, HD mobile television	Good coverage of thermal and some non-thermal effects, SAR compliance	Gaps in chronic exposure studies, particularly for high-data applications
5G (Sub-6 GHz)	~3.3-6 GHz	Enhanced mobile broadband, IoT, smart cities	Early studies, focusing mainly on compliance testing and exposure modeling	Need more biological studies on non-thermal effects, long-term exposure
5G (mmWave)	24-28 GHz, 37-40 GHz, 60 GHz	Ultra-fast broadband, high-capacity urban networks, AR/VR	Very limited; few experimental biological studies, mainly simulations	Major gaps in biological effects, tissue interaction, long-term health risks, thermal load at skin/tissue interface

Table 1.3: Evolution of telecommunication technologies

As can be seen in *Table 1.3*, the transition from 2G/3G to 5G technologies involves a massive shift in frequency bands, moving from the sub-6 GHz range to the millimeter-wave (mmWave) spectrum between 24 and 60 GHz. This physical difference is the central reason why this thesis utilizes 3D Slicer for millimetric segmentation.

While in 2G systems bone thickness was often considered a secondary factor due to deeper wave penetration, in the 5G paradigm, a few millimeters of variation in the thickness of the skin or subcutaneous fat can determine whether the electromagnetic energy is absorbed externally or if it reaches the gray matter of the temporal lobe.

Consequently, the numerical modeling must focus on the high spatial resolution of these 'external barriers' to accurately calculate the superficial SAR and address the current research gaps regarding thermal load at the tissue interface.

1.5 - Neurophysiological Investigation Methodologies: EEG and TMS

To validate the importance of numerical modeling, it is essential to understand how biological effects are measured in the contemporary research cited in the reference articles.

- Electroencephalography (EEG) and Oscillatory Alterations

EEG is the primary tool for evaluating non-thermal effects on the central nervous system. Research by **Prins et al. (2024)** has demonstrated, through a meta-analysis of 51 studies, that exposure to mobile phone fields induces a systematic increase in power in the alpha band (8 - 12.5 Hz). The aforementioned phenomenon can be seen especially clearly in the state of rest while eyes are open, and it implies that some form of regulation of cortical arousal takes place. The numerical simulation in COMSOL Multiphysics is designed to find out which parts of the cortex, divided using 3D Slicer software, experience the strongest electric field.

In addition to the above neurophysiological observations, Electrocardiography (ECG) is often used to measure the effect of RF-EMF on the peripheral nervous system in terms of the autonomic nervous system. An electrocardiogram is an instrument used to record the electrical activity of the heart over time.

This traces the depolarization and repolarization of the cardiac muscle, which gives rise to the formation of P, QRS, and T waves.

Within the study on mobile phones, HRV analysis of the ECG data is done to ascertain if there is any stress reaction from the exposure or if there is an imbalance within the two systems.

By integrating both EEG and ECG data, researchers can obtain a holistic view of how localized SAR hot-spots might influence both cognitive functions and systemic physiological stability.

- Transcranial Magnetic Stimulation (TMS) and Excitability

Another crucial approach is the use of Transcranial Magnetic Stimulation (TMS) to evaluate cortical excitability. TMS is a non-invasive technique that uses a rapidly changing magnetic field to induce a current in a specific area of the brain through electromagnetic induction.

Studies by **Torkan et al. (2025)** specifically utilize TMS to investigate whether acute exposure to 5G millimeter-wave fields alters the activation threshold of motor neurons.

By applying single or paired pulses, researchers can measure the Motor Evoked Potential (MEP), an electrical signal recorded from the peripheral muscles, which serves as a direct indicator of the excitability of the corticospinal tract.

Numerical simulation in COMSOL Multiphysics supports this research field by allowing for the high-resolution mapping of the induced field distribution within the individualized anatomy provided by 3D Slicer. This allows researchers to compare the zones of maximum Specific Absorption Rate (SAR) with the specific cortical regions targeted by TMS coils.

Verifying whether an overlap exists between these zones of maximum energy absorption and areas of altered neuronal excitability is essential for determining the biophysical impact of 5G on human brain function and motor control.

- Considerations on Overall Well-being and Vulnerability

Finally, the state-of-the-art framework must include the clinical-behavioral dimension. Although physical modeling deals with electromagnetic interaction, studies by **Ajmal et al. (2024)**, **Arooj et al. (2025)**, and **Zhu et al. (2025)** remind us that exposure is linked to intensive use patterns leading to addiction and behavioral problems, especially in young people.

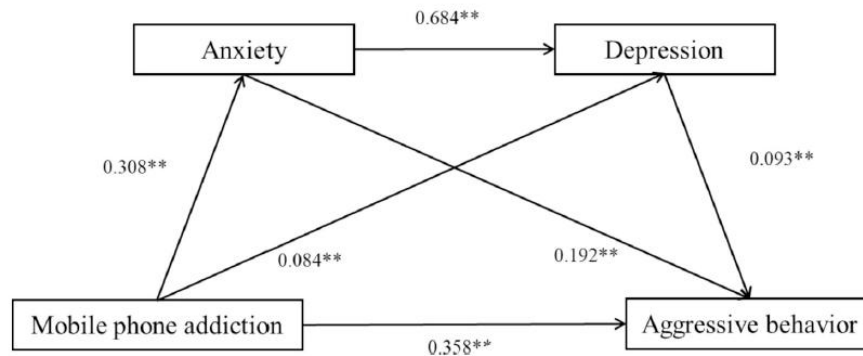


Figure 1.4: Conceptual framework of behavioral and psychological outcomes associated with mobile phone addiction

Figure 5 reveals that the path analysis carried out by Zhu et al. (2025) in a sample size of 1759 students helps in understanding these phenomena as Mobile Phone Addiction (MPA) influences Anxiety (0.308), Depression (0.084), and Aggression (0.358) significantly.

Furthermore, anxiety has been found to act as a mediator in that there is a very strong association between anxiety and depression (0.684) and a statistically significant relationship between anxiety and aggression (0.192).

The data emphasize the significance of having highly accurate protection models, including the acoustic-facial bundle volumetric baseline, for future safety and psychological well-being.

In numerical modeling, the role of tissue heterogeneity is very important: treating the head as a homogeneous sphere is no longer acceptable. The heterogeneity of the head creates several interfaces (e.g., skin-fat, muscle-bone, bone-dura mater) where the electromagnetic wave is partially reflected and partially transmitted.

In the context of the current research, the segmentation into Label Maps within 3D Slicer is vital. For instance, the cranial vault acts as a dielectric barrier.

If the model does not account for the specific density and thickness of the temporal bone, the resulting Specific Absorption Rate (SAR) calculation will be inaccurate, failing to predict the actual load on the superior temporal gyrus, a region often associated with mobile phone exposure.

There is a strong frequency – dependent interaction. As frequency increases, the conductivity of most brain tissues increases, which paradoxically leads to a decrease in penetration depth. For 5G signals, the energy is concentrated in the first few millimeters of tissue. This shift emphasizes why personalized modeling is superior to standard "phantom" models: the individual variation in the "outer shell" (scalp and skull) determines the safety profile for the underlying neural networks, such as those responsible for the functional connectivity modulations observed by **Iranfar et al. (2025)**.

1.6 - Integrated Framework for Personalized SAR Assessment: A Voxel-to-Finite Element Approach

- Medical Image Pre-processing and Segmentation: The Preparatory Phase

Before any geometric optimization can occur, the raw imaging data must undergo a rigorous preparation phase. This ensures that the biological domains used for simulation represent the true physiological state of the subject, free from the artifacts deriving from magnetic resonance imaging.

Intensity Correction and Signal Normalization: N4ITK Bias Field

The initial processing stage of this pipeline is the N4ITK Bias Field Correction. The magnetic resonance images can suffer from low-frequency intensity non-uniformity which is called the "bias field".

It is created due to the physical properties of RF coils and the magnetic field effect on the human body. With the help of this algorithm in 3D Slicer, we standardize the signal intensity for all the volume.

It is essential because automatic and semi-automatic tools of segmentation depend on grayscale intensity to differentiate adjacent tissues. Within 3D Slicer, the main technique of isolation of particular structures is thresholding when the range of intensity is determined to separate certain tissue types (CT – HU, MRI – arbitrary units).

However, without using N4ITK Bias Field Correction, the grayscale value of a particular tissue is not uniform. It means that one and the same tissue, such as bone, will be perceived differently depending on its location (frontal vs occipital).

If a global threshold were applied to such an uncorrected volume, the resulting segmentation would be fragmented, omitting crucial areas of the skull or incorrectly misclassifying white matter as bone in darker regions of the scan.

Thus, by eliminating this bias, we guarantee that the process of thresholding takes place in an even database where the 'intensity signature' of a particular tissue type does not change throughout the entire volume.

Such accuracy is essential during the simulation stage because even one pixel mistake in bone segmentation will result in a 'leak' in the dielectric barrier. Thus, we eliminate segmentation mistakes resulting in wrong dielectric mapping.

This is particularly vital for 5G millimeter-wave analysis, where energy absorption is highly localized, failing to normalize the signal could result in a 10 - 15% deviation in localized SAR calculations, potentially masking or artificially creating hot-spots that do not exist in the real anatomical subject.

Multilayer Label Map Creation and Domain Definition

Using the Segment Editor, the head volume is divided into a sophisticated system of concentric “shells”. In this research, the model is not treated as a single homogeneous mass but as a complex assembly of four primary physical domains, each assigned specific frequency-dependent dielectric properties:

- Outer Layer (Skin and Subcutaneous Fat): it acts as the primary interface for electromagnetic interaction, where the distribution of energy is governed by the skin effect as frequencies move into the 5G millimeter-wave spectrum.

This phenomenon describes the tendency of high-frequency fields to concentrate near the surface of a material, resulting in a rapid loss of energy as the wave moves deeper into the tissue.

With the earlier technologies such as 2G or 3G, the waves could pass through a few centimeters, thus penetrating deeply into the tissues of the head. However, with the 5G frequencies, the penetration depth becomes less, being about a few millimeters.

This makes it possible for nearly all the energy to be absorbed in the most superficial layers of the skin and fat. This makes it necessary for the COMSOL Multiphysics simulation to use an extremely fine mesh at the surface, since the field decays very fast.

This localized absorption is precisely why the millimetric accuracy you obtain in 3D Slicer is so important: at these high frequencies, even a tiny difference in skin thickness can change how much energy is blocked before it even has a chance to reach the bone or the brain.

- Bone Barrier (Cranial Vault): consisting of dense cortical bone and the internal porous diploe, serves as the main dielectric shield of the model. Due to its lower conductivity compared to

skin or brain tissue, the skull functions as a physical and electrical insulator that attenuates the field strength.

However, the exact measurement of the thickness of the barrier using the Ruler tool on 3D Slicer will be crucial for the validity of the simulation. Different from the conventional head models that use a consistent thickness, this individualized method considers the thicknesses of different areas in the cranium. This will determine the amount of the remaining field that gets absorbed or reflected after experiencing the skin effect.

- Subarachnoid Space (Cerebrospinal Fluid - CSF): The layer contains the Cerebrospinal Fluid (CSF), and its defining feature is an extremely high electrical conductivity.

From the computer science perspective, such a layer does not function as a simple space filler but serves as a highly conductive “buffer,” which allows redistributing the electric field on the complicated uneven surface of the gray matter.

Due to the presence of CSF inside the sulci and around the gyri, the “channeling effect” can take place, meaning that the electromagnetic energy can be concentrated in certain regions of the brain’s folds. This phenomenon potentially creates unexpected focal points of absorption, or “hot-spots,” that would be missed in simplified models.

The precise segmentation of this volume in 3D Slicer is therefore essential to correctly simulate how the field “wraps” around the cortical architecture before the energy is dissipated into the neural tissue.

- Neurological Target (Gray and White Matter): it comprises both Gray and White Matter, representing the primary functional focus of the research. It is precisely the precise breakdown of the regions which makes it possible to observe the particular biophysical interactions that might cause the functional connectivity changes observed by **Iranfar et al. (2025)**.

It is thanks to the localization of the temporal lobe and its individual components that it becomes possible to correlate the local SAR values with the neurological changes seen in the alpha band (8-12.5 Hz) according to **Prins et al. (2024)**.

- Geometric Optimization and Mesh-Processing: Voxel-to-Vector Transition

Once the tissues are accurately identified, the voxel-based data (which is discrete and “blocky”) must be converted into a continuous 3D geometry compatible with the Finite Element Method (FEM).

This is achieved through the Model Maker module and subsequent refinement algorithms.

- Laplacian Smoothing and the Prevention of Singularities

Initial segmentation results in a “staircase” or aliasing effect due to the cubic nature of MRI pixels. However, when directly imported into COMSOL Multiphysics, these sharp angles will result in numerical singularities such that the electric field will concentrate unnaturally on the corners of the cubes. In order to address this, Laplacian Smoothing is performed using 3D Slicer.

The Laplacian Smoothing algorithm repeatedly updates the coordinates of each vertex based on the mean coordinate values of neighboring vertices. High frequency geometrical noise and "steps" are removed while conserving the total anatomical volume.

This process ensures that the cerebral cortex is represented as a smooth, continuous manifold, which is essential for reflecting the realistic distribution of induced currents and field penetration.

- Decimation Algorithms and Computational Efficiency

Following smoothing, Decimation is performed. A high-resolution MRI can produce meshes with millions of triangles, which would exceed the RAM capacity of most simulation workstations. Decimation reduces the polygon count by collapsing edges in areas of low curvature, such as the flat portions of the parietal bone.

High resolution is only retained in those areas that are complex, such as the superior temporal gyrus, where it is anticipated that the maximum field gradient and SAR occur. This is made possible through optimization, allowing the achievement of what is called the "smart mesh."

- Manifold Verification and Inter-layer Continuity

The surfaces have to be "manifold," or water-tight, for successful import into COMSOL. We perform a thorough check for self-intersections or holes in the skin and skull surfaces.

This is particularly critical for the CSF layer; because of its high conductivity, any gap or "leak" in the segmentation would lead the solver to incorrectly model the shielding or "channeling" effect, falsifying the data regarding how the field wraps around the brain's folds.

- The Finite Element Method (FEM) in COMSOL Multiphysics

After the optimized geometry is imported as an .STL or .STEP file, COMSOL Multiphysics applies the FEM formalism to solve the frequency-domain Maxwell's equations across the anatomical domain.

- Domain Discretization: Tetrahedral Meshing and PML

The software subdivides the anatomical volumes into millions of small elements called tetrahedrons.

- Adaptive Meshing: In 5G simulations, where the wavelengths can be as small as 11 mm at 26 GHz, the mesh should be extremely fine.

According to FEM rules, the mesh size is supposed to be small fractions (such as 1/6 or 1/10) of the wavelength in the particular tissue for accurate energy loss.

- Perfectly Matched Layers (PML): To prevent waves from reflecting off the edges of the simulation box and returning to the head (which would create false interference patterns), we surround the model with PML domains.

These layers absorb 99.9% of outgoing radiation, simulating an infinite open space.

- Solvers and Biophysical Post-processing

- Electromagnetic-Thermal Coupling: Although our primary focus is on non-thermal effects (e.g., changes in neuronal firing rates), the software allows for coupling the field physics with Pennes' Bioheat Equation.

This provides a safety check to ensure that any observed physiological change is not simply a result of a 1°C temperature rise, but rather a direct interaction with the field.

- Local vs. Averaged SAR Calculation: COMSOL performs post-processing to calculate the SAR at every single coordinate. This allows us to pinpoint exactly which millimeter of the temporal lobe is receiving the highest dose, a level of detail that traditional phantom models cannot reach.

- Model Validation and Clinical Correlation: The "Personalized Physics" Bridge

The integration of 3D Slicer and COMSOL creates a definitive bridge between individual anatomy and biological risk. By using the Ruler tool in Slicer to measure a specific subject's temporal bone thickness, the FEM simulation can mathematically prove why that specific individual might be more susceptible to field penetration.

This transforms clinical observations into measurable engineering data, providing a quantitative physical explanation for the neurophysiological susceptibility reported in recent studies.

1.7 - Comparative Analysis of SAR Distribution: 4G vs. 5G

The core justification for personalized modeling lies in the fundamental physical differences between current LTE (4G) and future Millimeter Wave (5G) technologies, specifically regarding the transition from a volumetric energy distribution to a highly localized, superficial absorption pattern:

- **4G (700 MHz - 2.6 GHz)**: At these frequencies, the wavelength is comparable to the dimensions of the head. The electromagnetic energy is distributed volumetrically. The numerical model shows that the field reaches deep structures such as the thalamus and hippocampus. In this scenario, the general shape of the head is more important than the local thickness of the bone.
- **5G (24 GHz - 30 GHz)**: As highlighted by **Torkan et al. (2025)**, 5G signals exhibit a very small skin depth. The energy is almost entirely absorbed within the first 2 - 3 mm of tissue. This means that the Specific Absorption Rate (SAR) is concentrated in the skin and the outermost cortical layers.

The primary scientific justification for employing a personalized modeling approach lies in the high degree of “shielding sensitivity” inherent in high-frequency electromagnetic interaction. Since 5G absorption is predominantly superficial, the resulting computational model becomes

hypersensitive to the specific thickness of the extracranial tissues, namely the skin, subcutaneous fat, and the cranial vault, as precisely measured with the 3D Slicer Ruler tool.

In a typical homogeneous phantom, such layers are described by a mean value of the phantom that ignores the high degree of variability among different subjects in the human population. Nevertheless, in this study, it is shown that a person having 4 mm thick skull can have a much lower cortical Specific Absorption Rate (SAR) than someone having 2 mm thick skull, when both are exposed to an equal external field strength.

This "Sensitivity Analysis" constitutes a cornerstone of the thesis, as it provides mathematical evidence that standard "Phantom" models, which rely on population-averaged thicknesses, may dangerously underestimate the peak exposure for a significant portion of the population. This discrepancy is particularly critical when considering vulnerable demographics, such as children. As highlighted by **Ajmal et al. (2024)**, children possess cranial vaults that are not yet fully ossified and are significantly thinner than those of adults.

As a result, the natural dielectric shielding effect of the bone is minimized, thereby permitting a greater amount of penetration of the millimeter wave of 5G technology into the temporal lobe. Through the use of 3D models created with respect to each individual, the impact of these thin-shield instances will be taken into account so that protection protocols are made according to the most vulnerable configurations.

This kind of precision is crucial to turning general guidelines into specific health monitoring programs within a highly connected world.

Addressing uncertainties in numerical dosimetry is a fundamental requirement, as no numerical model is a perfect reflection of reality. This research explicitly addresses three levels of uncertainty:

- Segmentation Uncertainty and Morphological Fidelity

This factor addresses the potential "human error" involved in manually or semi-automatically defining the anatomical boundaries between complex structures, such as the interface between the cranial bone and the dura mater within 3D Slicer. Due to the sensitivity of these transitions, minor differences in the volume segmentation can result in a variation of 5–10% in the peak SAR levels. This stresses the need for precision in the process of reconstruction of the mesh model to capture the true anatomy of the individual.

- Dielectric Uncertainty and Physiological Variability

While the values of permittivity and conductivity are traditionally obtained from the Gabriel database, these characteristics are dynamic and vary depending on the age and level of hydration of a particular subject.

The Gabriel Database is a reference source used to describe the dielectric characteristics of human tissues, which provides the full range of parametric models describing the electrical conductivity and the relative permittivity of human tissues – the parameters necessary to simulate the electromagnetic interaction and the calculation of the specific absorption rate (SAR).

In order to take into consideration these biological variations, the study considers the influence of a 10% increase/decrease in tissue conductivity on the overall distribution of the electromagnetic field.

- Positioning Uncertainty and Usage Scenarios

As identified in the COSMOS study (Heller et al., 2024), the physical interaction between the user and the mobile device significantly affects exposure. Factors such as the tilt angle of the phone and the pressure applied against the ear modify the critical source-to-target distance.

To address this, the COMSOL model simulates multiple "usage scenarios" to verify that the results are robust across a variety of real-world habits and orientations.

1.8 - Technical Specifications of COMSOL Multiphysics Solvers

Once the tetrahedral mesh has been defined on the geometry derived from 3D Slicer, calculating the electromagnetic field requires solving a massive linear system.

The choice of solver influences not only the total computational time but also the precision of the resulting SAR values, specifically regarding the selection between Direct vs. Iterative Solvers:

- MUMPS (Multifrontal Massively Parallel sparse direct Solver)

The direct solver is used particularly on medium sized anatomical models that require high numerical stability. As opposed to iterative techniques, MUMPS uses factoring of the matrix in order to solve the equation, which results in a very reliable and accurate calculation. Such an approach is suitable for solving the discontinuities in the electrical conductivity of the materials at the important interface of the insulator (the bone of the cranium) and the conductor (Cerebrospinal Fluid - CSF).

Since it offers a direct solution, it ensures that there will not be any problems with convergence if the electromagnetic parameters of the adjacent tissues vary significantly.

- GMRES (Generalized Minimal Residual method)

The iterative method is the preferred method for full-head simulations which have a large number of degrees of freedom that can go well above 10 million degrees of freedom. As this method approximates the solution by means of iterations rather than by directly solving the matrix factorization process, it uses far less RAM, allowing the calculation to be done on a regular workstation.

This feature is critical when performing simulations of 5G signal with high frequencies, because of the very small wavelength at 26 GHz; hence, the necessity of very dense meshing to meet the Nyquist criterion. With GMRES, it is possible to use such dense meshing throughout the volume of the brain, without exceeding memory capacity, thus allowing to study superficial energy deposition into the brain.

In order to ensure the scientific accuracy of the model, the procedure is controlled by certain convergence conditions and tolerance values.

Usually, the relative tolerance is chosen to be equal to 10^{-6} , guaranteeing that the calculation will stop only if the difference between two consecutive iterations is smaller than this very strict criterion.

This mathematical exactness is crucial since it guarantees that the difference in SAR that we observe for different patients is due to the actual anatomical differences of those individuals modeled via 3D Slicer.

The rigorous mathematical precision achieved through these solver settings provides the necessary foundation for the correlation between calculated SAR and neurophysiological observations, effectively bridging the gap between electromagnetic physics and the biological phenomena reported in recent scientific literature:

- Alpha Wave Modulation (Prins et al., 2024)

Numerical simulations in COMSOL allow for the visualization of how the induced electric field is distributed across the cortical surface. If results indicate an **electric field "hot-spot"** in the superior temporal lobe, it provides a mechanical explanation for why the meta-analysis by Prins identified an increase in alpha-band power specifically in that region during acute exposure.

- Functional Connectivity (Iranfar et al., 2025)

By utilizing a personalized model, it is possible to correlate variations in functional connectivity (measured via MEG) with the penetration depth of the field.

While 2G frequencies influence more extensive networks, the numerical model demonstrates that 5G has a more **localized impact**, allowing for the prediction of which superficial neuronal networks are most susceptible.

- Cortical Excitability (Torkan et al., 2025)

Numerical modeling serves as a supportive tool for TMS (Transcranial Magnetic Stimulation) studies. By calculating the induced current density, the research can verify whether mobile phone exposure acts as a “subliminal stimulat^o” that alters the neuronal excitability threshold, explaining the variability observed in clinical results.

The incorporation of these neurophysiological correlations will finally enable the determination of the anatomical baseline that will be used for ongoing monitoring, thus making the numeric model move from being just an experimental one to becoming a useful medical reference.

Through determining this anatomical baseline using 3D Slicer, it is now possible to see how certain unique traits, for example, the increase in skull thickness with age, changes in hydration levels of tissues, or the amount of cerebrospinal fluid, affect the 5G millimeter-wave absorption at 26 GHz.

These baselines do not merely serve to validate current experimental data; they establish a standardized protocol for future longitudinal studies, ensuring that 5G exposure monitoring is predicated on real, susceptible anatomical configurations rather than generic statistical averages.

This personalized framework allows for the identification of “biomarkers of exposure” within the temporal lobe, providing a quantitative method to track the cumulative effects of electromagnetic interaction on cortical excitability and functional connectivity across the human lifespan.

Consequently, this methodology bridges the gap between theoretical dosimetry and proactive health surveillance, offering a robust scientific foundation for the development of person-centered safety standards in the 5G era.

A particularly innovative aspect of this work involves the creation of these “anatomical baselines”, through the advanced segmentation capabilities of 3D Slicer, which provide a precise spatial record of the subject's internal morphology:

- Segmentation of the Acoustic Nerve and Meninges

As suggested by the longitudinal objectives of the COSMOS study (Heller et al., 2024), long-term monitoring must focus specifically on the areas of highest exposure.

With the help of segmentation of the acoustic-facial bundle and calculation of its precise volume using the Segment Statistics plug-in, a personal reference is generated. It becomes possible to have an accurate dosimetry analysis of the sensitive neurological structures lying in the direct route of the 5G wave propagation.

- Longitudinal Utility and Clinical Correlation

This baseline serves as a fundamental benchmark for future health surveillance.

Should a subject present morphological changes in the years following the initial simulation, the numerical model established in this research will serve as a definitive term of comparison.

It will allow researchers to determine if such changes are localized exactly at the "hot-spots" of maximum SAR (Specific Absorption Rate) calculated in this thesis, effectively enabling a causal link analysis between localized electromagnetic energy deposition and long-term biological variations.

In conclusion, the combination of the level of accuracy attained through 3D Slicer with the physical computation capabilities provided by COMSOL Multiphysics turns EMR assessment into an engineering-based diagnostic tool, personalized to each patient. Such methodology represents a paradigm shift in dosimetry where, instead of the use of phantom-based models, there will be a tool available which takes into account all morphological peculiarities of each subject.

This methodology addresses precisely the concerns raised by Torkan et al. (2025) and Ajmal et al. (2024) concerning protection of those populations at high exposure risks. It provides the solution required to assess the risk of exposure in younger demographics because of the peculiarities of their morphology, such as thinning of the cranial vault and increased hydration levels of tissues, which makes them more vulnerable to EMFs generated by the latest generation of wireless devices.

By understanding how the peculiarities of the anatomy of the younger generations affect the interaction of 5G mm waves with the body, the proposed methodology will make it possible to establish a basis for the development of appropriate age-related safety standards.

1.9 - Conclusion

In conclusion, this chapter has detailed the construction of a high-fidelity methodological pipeline that moves beyond the limitations of traditional, generic dosimetry. The integration of 3D Slicer's millimetric anatomical segmentation with the advanced electromagnetic solvers of COMSOL Multiphysics represents a fundamental shift from "statistical average" modeling to personalized engineering diagnostics.

The core objective of this thesis is to demonstrate that in the 5G era, where millimeter-waves interact almost exclusively with the outermost layers of the human head, anatomy is destiny. With the consideration of interindividual differences in the thickness of the skull bone, level of hydration in tissues, and geometry of the temporal lobe, this study demonstrates that personalized modeling is not just an engineering improvement but a biological requirement.

Such a model is a direct answer to the pressing need for research noted by **Torkan et al. (2025)** and **Ajmal et al. (2024)**, creating a scientific foundation to shield people from the risks that the existing standards fail to address: people who have thin skulls and are sensitive to dielectric changes due to focused energy emission at 26 GHz.

The modeling work presented here demonstrates that electromagnetic safety assessment can no longer ignore individual anatomy. By integrating 3D Slicer and COMSOL, we move past the constraints of global statistical models, such as the COSMOS study (**Heller et al., 2024**), and offer a level of precision that accounts for subjective vulnerabilities. As highlighted by the research of **Torkan et al. (2025)** and **Iranfar et al. (2025)**, the future of radiological protection lies in the ability to predict not only thermal effects but also subtle neurophysiological modulations.

Ultimately, the creation of personalized anatomical baselines represents the first critical step toward preventive medicine in the era of 5G connectivity and future wireless technologies, ensuring that technological deployment is guided by a proactive, person-centered understanding of biophysical impacts.

Chapter 2

From MRI to Computational Domain: Segmentation, Topological Refinement, and 3D Reconstruction of Cranial Tissues

2.1 - MRI Acquisition Protocol and Characterization of the Anatomical Dataset

The initial phase of this research involved the acquisition of a high-precision neuroradiological dataset, which serves as the foundational geometry for the subsequent three-dimensional numerical modeling.

The image set contains DICOM (Digital Imaging and Communications in Medicine) formatted images, which is the international medical imaging standard, collected on 09/05/2023 at the "Studio Radiologico Centocannoni" in Alessandria, Italy.

This particular study involved imaging the brain and brainstem region using a Contrast Agent (CA). The anesthesiological assessment was done beforehand to stabilize the subject before the imaging.

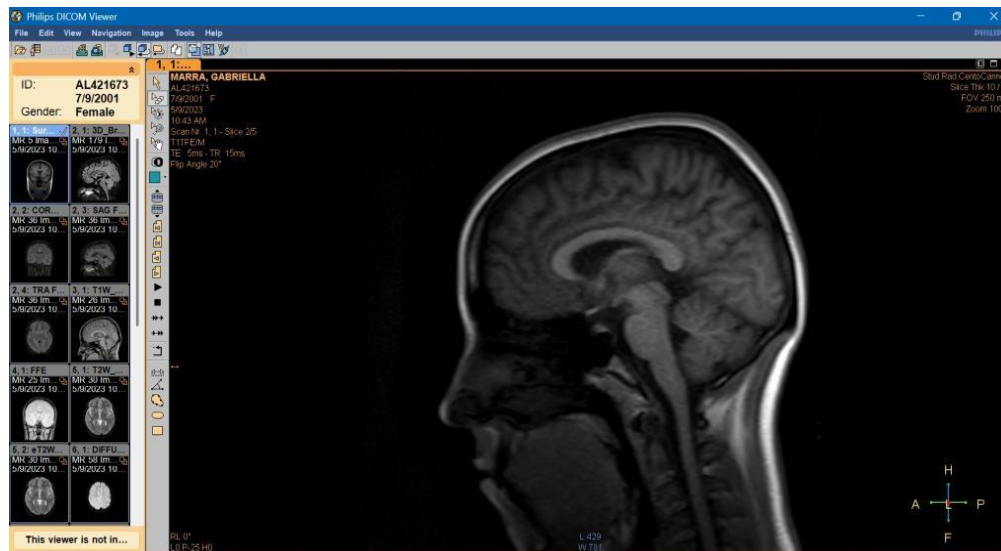


Fig 2.1: Medical imaging software interface (Philips DICOM Viewer) displaying the loaded raw dataset

The technological infrastructure used to ensure an optimal Signal-to-Noise Ratio (SNR) and a spatial resolution refined enough for the segmentation of complex cerebral structures, was Philips Ingenia 1.5 Tesla MRI scanner.

The system incorporates d-Stream technology, a digital architecture that converts the analog signal directly within the radiofrequency (RF) receiving coil. This reduces signal loss typically associated with long cable transmissions and enhances image clarity.

A high-resolution multi-channel head coil was employed, specifically designed for encephalic imaging, allowing for accelerated parallel acquisition techniques without compromising anatomical fidelity.



Fig 2.2: MRI Acquisition System, Philips model

During the scanning session, several pulse sequences were implemented, each designed to obtain a tissue excitation in a specific manner to highlight different biophysical properties:

1. **TSE (Turbo Spin Echo):** Also known as Fast Spin Echo (FSE), this is a rapid variant of the basic Spin Echo sequence. By delivering multiple refocusing pulses within a short timeframe, TSE allows for high-resolution anatomical imaging within a reduced acquisition time. In this study, TSE was essential for accurately discriminating the boundaries between White Matter (WM) and Grey Matter (GM).
2. **GE (Gradient Echo):** Unlike TSE, this technique does not utilize a 180° RF pulse for refocusing, but instead uses a controlled variation of the magnetic field (gradients). Its extreme sensitivity makes it ideal for evaluating vascular structures (Angio-MRI) and detecting susceptibility effects, such as iron deposits or micro-hemorrhages, which could locally alter the electrical conductivity of the model.
3. **TIR (Turbo Inversion Recovery):** A "subtraction" or signal suppression technique. Preceded by an inversion pulse, it allows for the selective "nulling" of specific tissue signals. In brain imaging, variants like FLAIR (Fluid Attenuated Inversion Recovery) were used to suppress the signal

from cerebrospinal fluid (CSF), enabling the visualization of structures near the cerebral ventricles without the interference caused by fluid hyperintensity.

The dataset comprises volumetric acquisitions along the three orthogonal planes, ensuring the spatial coherence required for 3D reconstruction:

- **Axial (TRA/AX):** Horizontal slices used for analyzing lateral-lateral relationships.
- **Sagittal (SAG):** Profile views, fundamental for studying the midline structures.
- **Coronale (COR):** Frontal views for assessing encephalic symmetry.

The two major sequences that have been analyzed are T1W (T1-Weighted) called “anatomical sequence” because of its good depiction of structural contours, and T2W / TSE, where the fluid is highly intense (white), making it easy to recognize CSF cavities.

Moreover, FFE (Fast Field Echo) sequences have been obtained that are highly sensitive to magnetic susceptibility.

To validate the integrity of the brain tissue at a microscopic level, a diffusion-weighted imaging (DWI) study was included:

- **DIFFUSION / b1000:** Maps the Brownian motion of water molecules within the tissues.
- **ADC Map (Apparent Diffusion Coefficient):** Represents the mathematical calculation of diffusion, eliminating "T2 shine-through" effects and confirming the physical nature of the detected signal intensities.

In order to rule out any vascular malformations or abnormality in the blood brain barrier (BBB), Gadovist (Lot KT0FPS3) contrast agent was given intravenously. The T1-weighted images showed no enhancement abnormalities.

The associated clinical report certifies that:

- Midline structures are centered.
- The ventricular system and cerebral sulci are symmetric and of normal width.
- Main arterial vessels at the skull base are patent.
- No expansive masses are identified in the internal auditory canals or cerebellopontine angles.

This clinical neutrality has a huge importance since the resulting numerical model represents a morphologically standard and functionally intact brain, ensuring that the electromagnetic simulation results are applicable to a healthy reference case.

The images were provided on digital media. For the initial visualization and metadata analysis, specialized software such as Osirix (optimized for macOS) was utilized prior to the final importation

into the 3D Slicer environment for segmentation.

The format of the raw data collected during the MRI scan adheres to the DICOM (Digital Imaging and Communications in Medicine) format. Every file contains information not only concerning photometric data (image pixel intensity), but it also comes with a header, which contains all the technical data pertaining to the scan. These technical data include important parameters such as voxel dimensions (spatial resolution), slice thickness, TR, and TE.

These are the crucial parameters that ensure accurate geometric proportions of the brain once the data is processed using the reconstruction software. In the dataset under consideration, the high resolution provided by the multi-channel coil allowed for the acquisition of an isotropic (or near-isotropic) volume, thereby reducing interpolation errors during the generation of the 3D models.

Prior to the modeling phase, a qualitative review of the images was performed to identify potential motion artifacts or magnetic susceptibility effects. The stability of the 1.5 Tesla platform ensured excellent homogeneity of the B₀ field, minimizing the geometric distortions that are frequently encountered in higher magnetic fields (such as 3T or above).

Furthermore, the absence of metallic implants or dental prostheses in the subject facilitated the acquisition of sharp images, free from "starburst" or "signal void" artifacts that could otherwise compromise the continuity of tissue surfaces during automated segmentation.

2.2 - Methodology of Image Segmentation and Geometric Reconstruction

The transformation of two-dimensional MRI slices into a high-fidelity three-dimensional numerical model was conducted using 3D Slicer (version 5.10.0), an open-source platform for medical image informatics and visualization. The segmentation process is a critical bridge between clinical imaging and computational electromagnetics, as the accuracy of the induced field distribution in COMSOL Multiphysics directly depends on the geometric precision of the tissue boundaries.

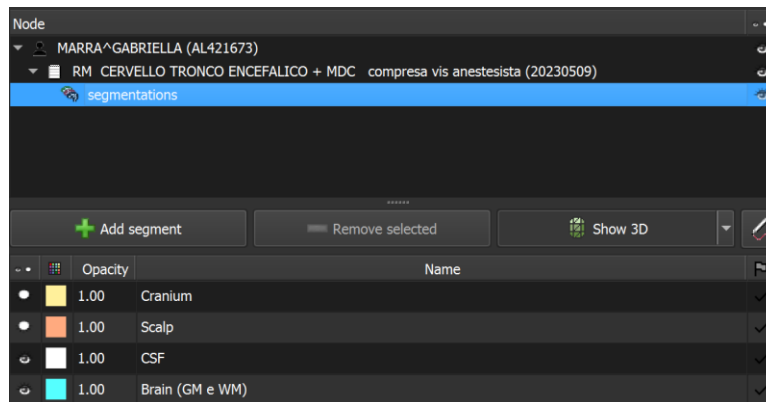


Fig 2.3: Node organization and segmentation classes in 3D Slicer

Upon importing the DICOM dataset into the 3D Slicer database, a rigorous selection of the primary working volume was performed. The T1-weighted (T1W) sequence in the Axial (TRA/AX) plane was selected as the foundational reference for the 3D reconstruction. This choice is dictated by both technical

requirements and the neurophysiological focus of current literature.

As established in the studies by **Iranfar et al. (2025)** and **Torkan et al. (2025)**, the interaction between electromagnetic fields and the human brain primarily affects specific cortical regions, such as the temporal gyrus and the entorhinal cortex, influencing functional connectivity and excitability.

The better anatomical contrast provided by the T1W sequence allows a clear separation of Grey Matter (GM), White Matter (WM) and Cerebrospinal Fluid (CSF), and thus the distinction of these regions. High-contrast interface plays an important role in reducing the segmentation errors, which may otherwise compromise the accuracy of the induced electric field calculations in the numerical model.

To account for tissue anisotropy a multi-layer brain model with distinct GM and WM domains was first proposed. This decision was driven by the 4.0 mm slice thickness of the clinical data set that would have resulted in significant partial volume effects and “stair-step” artifacts in the segmentation of the complex GM-WM interface. To avoid convergence problems in the COMSOL solver, the brain was treated as a single homogeneous compartment with averaged dielectric properties, leading to a more robust and numerically stable mesh, while preserving the overall geometric integrity of the encephalic volume.

Furthermore, the Axial orientation was prioritized to facilitate the mapping of electromagnetic "hotspots" relative to the source of exposure (e.g., a mobile device or a TMS coil). The axial plane allows for a precise evaluation of hemispheric symmetry and a rigorous measurement of the penetration depth of the fields from the lateral surface of the cranium toward the internal structures.

By utilizing this plane, the resulting geometric model ensures a faithful representation of the brain's complex folds, aligning the computational domain with the experimental conditions described in the latest bioelectromagnetics research.

A pre-processing step was performed using the N4ITK Bias Field Correction module to ensure a homogeneous signal for automated segmentation. This algorithm compensates the low frequency intensity inhomogeneity (bias field) which is often present in 1.5T MRI scans due to RF coil inhomogeneities or patient related factors. The signal intensity was also normalized over the entire volume which resulted in more reliable thresholding operations and more consistency between slices of the brain volume.

The segmentation strategy followed a hierarchical approach, prioritizing tissues with distinct dielectric properties. According to the scientific literature, the interaction of electromagnetic fields with the brain is highly dependent on the conductivity (σ) and permittivity (ϵ) of the medium. Consequently, the model was divided into five main segments, obtaining the tissue classification as following:

- **Scalp and Soft Tissues:** Segmented using global thresholding and morphological smoothing to define the continuous external boundary of the model. This layer provides the initial interface for electromagnetic coupling.

- **Cranium (Bone):** Signal intensity characteristically low on T1 sequences. The skull modeling is important because it has low electrical conductivity and therefore represents the main resistive barrier for electromagnetic penetration into the brain.
- **Cerebrospinal Fluid (CSF):** This layer was isolated to account for its high electrical conductivity ($\sigma \approx 1.79$ S/m), which significantly influences the distribution and shunting of induced currents. To ensure a physically consistent gap between the bone and the brain, a Median smoothing filter was applied to the brain boundaries, effectively creating a dielectric buffer that prevents mesh intersections.
- **Brain (Unified GM and WM):** Grey Matter (GM) and White Matter (WM) were merged into a single homogeneous brain segment. While the T1 sequence allows for a visual distinction between these tissues, the 4.0 mm slice thickness of the clinical dataset made a detailed voxel-wise separation impractical, as it would have introduced significant "stair-step" artifacts and partial volume effects.
The model maintains the basic geometry of the sulci and gyri by using a combination of “Fast Marching” and “Thresholding” to define the overall cortical anatomy, while ensuring a numerically stable mesh for the FEM solver.

The choice of the T1W_3D_TRA series as the first reference volume used for the creation of a three-dimensional geometric model was conditioned by some technical and methodological aspects of electromagnetic simulation.

T1-Weighting (T1W) was identified as the most suitable modality to ensure the necessary contrast for a sharp distinction between gray matter, white matter, and cerebrospinal fluid (CSF).

This resolution is essential for accurately mapping the cortical areas where, as highlighted in studies by **Iranfar et al. (2025)** and **Torkan et al. (2025)**, the most significant interactions between external fields and neuronal activity occur.

The volumetric nature of the scan (3D) ensures a data density that prevents interpolation errors, allowing for the generation of a smooth mesh for Finite Element Analysis (FEA) within the COMSOL Multiphysics environment. At the end, the axial orientation (TRA) was prioritized to facilitate the spatial positioning of field sources (such as TMS coils or mobile devices) relative to the bilateral symmetry of the hemispheres.

Other sequences within the dataset were discarded for the following technical reasons:

- **T1W_3D_SAG:** With all the advantages provided by the image with a good resolution, the sagittal view is less efficient as a beginning to define the necessary symmetry for the calculation of the lateral field penetration.
- **sT1W_3D_proset:** The use of this method of suppression of fat does not allow a proper delineation of the skin and subcutaneous tissue layers. The significance of the integrity of these layers lies in the fact that they are the main barrier to the electromagnetic wave and they are necessary for the calculation of the SAR.
- **VB_FFE_AX and B_FFE_AX:** Though very useful for the study of blood vessels and nerves,

these Gradient Echo sequences provide less morphological detail of the brain parenchyma than the T1W sequence.

The icons which formed the basis of the construction of the three-dimensional object were based on the multi-sequence MRI procedure. In order to measure the effectiveness of the segmentation and analyze the influence of the morphological filters, some particular anatomical areas were chosen.

When validating the models which have been created, the spatial coordinates of R: 14.258 mm, A: -.2547 mm, S: -14.2089 mm in the RAS coordinate system served as the main point of comparison due to the following reasons:

- **Representative Anatomic Centering:** These coordinates provide a clear view of the transition between the skull and the cortical surface. This area was used as a reference to monitor how the **thresholding and Median smoothing filters** (applied to create the CSF space) affected the anatomical boundaries, especially given the 4.0 mm slice thickness of the dataset.
- **Qualitative Quality Control:** By observing the model at these coordinates, it was possible to verify that the "Median" smoothing did not excessively erode the gyri, maintaining a balance between a numerically stable gap for the CSF and a realistic brain geometry.
- **Coordinate Mapping in Slicer3D:** Since the above-mentioned values were related to the distance of the isocenter of the magnet, therefore, a precise localization of the FEM mesh adaptation in 3D was achieved. This helped us in obtaining a topologically correct transition from one dielectric layer to another (Bone, CSF, and Brain).

In order to achieve an optimal mesh and maintain numerical stability when using the Finite Element Method (FEM) analysis in COMSOL Multiphysics software, a particular hierarchical model was used for the various tissue layers.

This model is defined by its “nested” or multi-compartment nature, whereby the anatomical data is reduced to geometrically coherent volumes:

- The Scalp (Skin) as a Continuous Solid Volume: The outermost layer, representing the skin and subcutaneous tissues, was modeled as a compact solid block. This decision serves two primary purposes:
 - Boundary Definition: A solid volume provides a continuous and stable external boundary for the computational domain, essential for defining the interface between the head model and the surrounding environment.
 - Numerical Simplification: By treating the scalp as a single homogeneous volume, the complexity of the tetrahedral mesh is significantly reduced, preventing memory-related crashes during the simulation.

- The Cranial Bone (Bone) as a Manifold Volume

The skull was reconstructed to define the primary resistive barrier. To ensure a clean geometry, a volumetric regularization was achieved using the "Hollow" operation (with a controlled thickness of 5.0 mm) or dedicated thresholding, which is critical for:

- Noise Suppression: The MRI data is known to have noise signals inside the bone marrow. In the hollow/regularization strategy, this internal "junk" is cleared up, hence forming a neat interior surface.
- Mesh Regularization: Regularized geometries are necessary to avoid any mesh singularity which usually leads to numerical divergence in COMSOL.

After the cranial bone was finalized as an impermeable shell, the intracranial volume inside the brain which consists of Brain parenchyma and CSF was created.

- Cerebrospinal Fluid (CSF) Layering

To account for the high electrical conductivity of the CSF ($\sigma \approx 1.79 \text{ S/m}$), a dedicated compartment was created between the bone and the brain.

- Space Creation: Due to the 4.0 mm anisotropic resolution of the original scans, a Median Smoothing filter was applied to the brain segment. This process slightly recessed the brain boundaries from the internal cranial vault, creating a consistent gap.
- Boolean Definition: The CSF was defined by subtracting the smoothed Brain volume from the total internal intracranial volume. In this way, the CSF becomes ideally aligned with the subarachnoid space, thus providing the high-conductivity "buffer" crucial to an exact shunting current analysis.

- Brain Parenchyma (Unified GM and WM)

Brain model was considered to consist of one single parenchyma domain combining two tissues: Grey Matter (GM) and White Matter (WM).

- Anatomical Simplification: Despite the possibility of their separation provided by the T1 weighted image, both tissues were combined together within one single domain due to the thick 4.0 mm slices of the dataset.
- Morphological Integrity: In order to maintain the intricate topography of the sulci and gyri, the "Fast Marching" method was used along with thresholding by hand. This ensures proper anatomy of the cortical surface that is required in order to simulate induced electric fields.

The hollow inside of the skull was filled in by using a "Flood Fill" method (grow from seed) in order to have proper anatomical continuity. For making the model numerically viable in COMSOL, Logical Operators were used:

- Boolean Hierarchy: Strict "matryoshka" hierarchical arrangement was kept: Brain is included inside CSF which in turn is inside the Bone which itself is inside the Skin.
- Interface Cleaning: The "Subtract" operator was used to ensure that there was no overlapping of voxels between layers. This creates a "conformal" interface where the mesh nodes of one tissue perfectly align with the boundaries of the next, which is the optimal configuration for assigning tissue-specific electromagnetic properties (σ, ϵ) in the FEM environment.

The finalized multi-compartment model, comprising the solid scalp, the hollowed skull, and the filled brain volume, represents the "Golden Standard" for the study.

- Surface Conversion: Each segment was converted from a labelmap into a Closed Surface (STL/OBJ format).
- Mesh Optimization: A final Decimation and Smoothing pass was performed on each surface to reduce the number of polygons without losing anatomical accuracy, balancing the trade-off between detail and computational cost during the subsequent FEA phase.

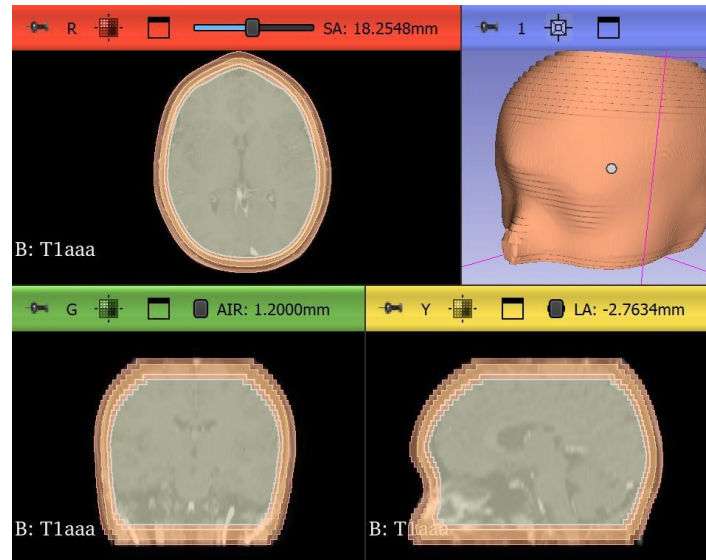


Fig 2.4: Final outcome of the multi-layered segmentation and the resulting 'matryoshka' structure - axial, coronal, and sagittal cross-sections alongside the 3D reconstructed volume

2.3 - Methodology for 3D Anatomical Reconstruction

The transition from two-dimensional magnetic resonance imaging (MRI) data to a three-dimensional computational volume requires a rigorous multi-step pipeline. For this particular study, the segmentation was done using the T1W_3D_TRA (T1-weighted 3D Turbo Field Echo, Axial) image. This is a very high-resolution image, similar to the isotropic one, because of its anatomically accurate details and longitudinal range that is crucial for defining deep cortical structures and the brain-skull connection.

This is an operation called medical image segmentation and includes dividing the medical image into several sections (or pixel sets – known as voxels) in order to simplify complex anatomy into

something that can be used for Finite Element Method (FEM) simulation in COMSOL Multiphysics.

Since the T1W_3D_TRA scan was a volume image, it allowed for the maintenance of the spatial continuity between the slices thus reducing the interpolation error.

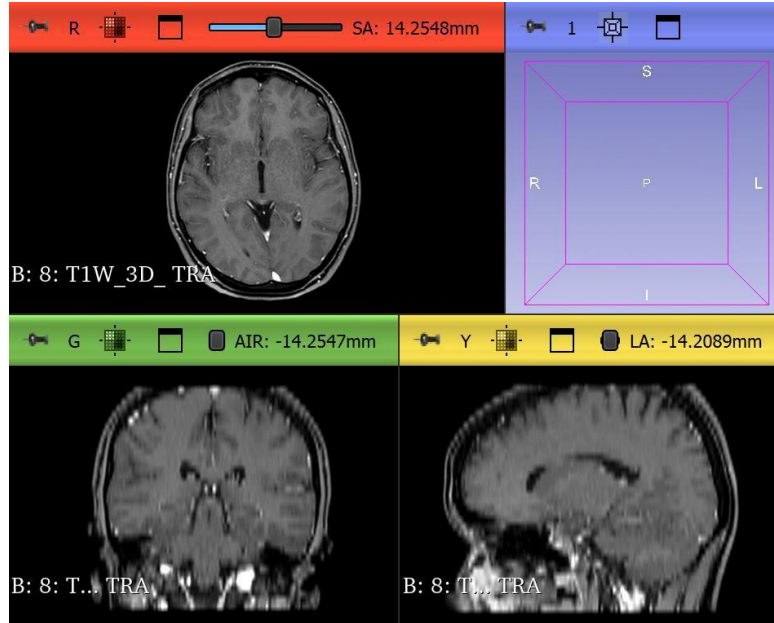


Fig 2.5: Initial Volumetric Assessment of the T1W_3D_TRA Sequence

The main dataset includes T1-weighted MRI images in DICOM format. Prior to the segmentation process, there is a pre-processing step to improve the signal-to-noise ratio (SNR):

- **Noise Reduction:** MRI images taken in clinical practice tend to be affected by “thermal noise” or “motion artifacts,” causing them to appear grainy. The filtering process was done in order to make sure that the intensity value for tissues remains constant, yet sharp boundaries can be retained.
- **Intensity Normalization:** This makes it easier for the thresholding techniques to differentiate between the scalp, skull, and CSF.

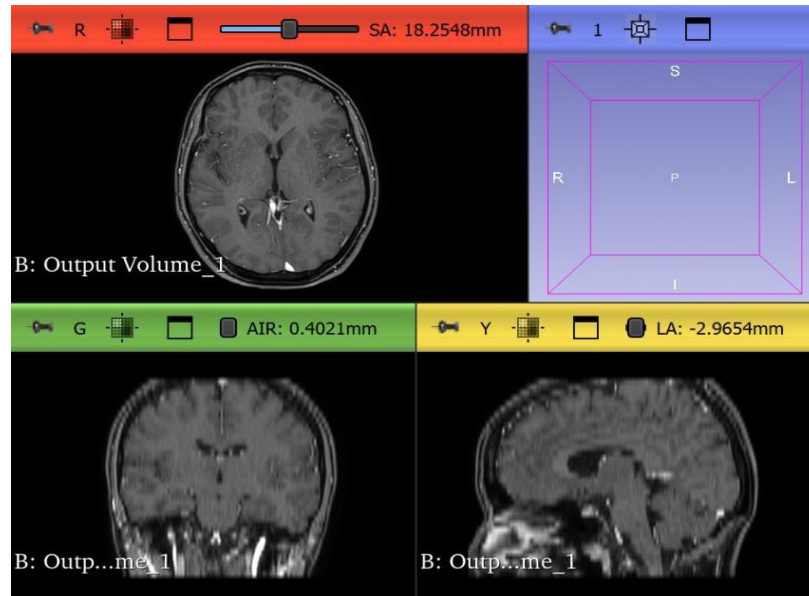


Fig 2.6: Multi-layered head model validation after Resampling and Median Smoothing

2.3.1 - Segmentation of the Scalp (Skin Layer)

The Skin segment represents the outermost boundary of the computational model. For this study, the skin was modeled as a compact solid volume to provide a stable "container" for the internal tissues.

- **Thresholding:** An initial intensity-based selection was performed to isolate the soft tissues from the background.
- **Hole Filling and Island Removal:** One of the major problems that came up during the process was the existence of internal air pockets, also known as "voids," which happened because of the dropout of signals from the MRI. To overcome this problem, the Islands - Fill Holes method was applied. It finds enclosed voids and fills them with the same label that the segment contains in order to make it completely solid.
- **Masking Strategy:** For the Manual Adjustments, the Masking parameters were always set to Everywhere with Intensity Range OFF. It provided the ability to close external voids manually by forcing the program not to see the tissue there because of low intensity of pixels.

Although the surface of the scalp looks quite simple, the segmentation process has faced many technical problems.

- Internal Discontinuities and Signal Artifacts: One of the major problems was the existence of "internal voids" or "caverns" in the skin segment. In spite of the fact that the goal was to obtain a compact and dense volume, the actual raw MRI image sometimes had signal dropouts in places where the algorithm considered the cavity rather than tissue. Internal voids could not be ignored when calculating the volume in COMSOL. Thus, to solve the problem automatically, the Islands – Fill Holes command was used. It recognized the enclosed cavities in 3D space and filled them up with labels, which meant solidification of the scalp from inside.

- Tool Inhibition and Masking Conflicts: Among the other issues was a situation where Paint and Draw tools did not recognize the input in certain places. The problem was related to the conflict in Masking logic. Firstly, the Editable Intensity Range was active, meaning that the user could not add tissues to places where the pixels in MRI image were dark or "noisy". Deactivating intensity restrictions and choosing Everywhere in Editable Area allowed to create the skin volume in any place despite low-quality signal.
- Hardware Instability and Resource Management: Sometimes, however, the complexity of the process of generating a 3D surface resulted in a problem called "instability," which was reflected in crashes of the program as well as failure to align 2D label maps with the 3D visualizer. This was handled through repeated execution of the Keep Largest Island option. It was essential, as it removed millions of redundant "floating" voxels and metadata and hence decreased the RAM load, making it possible to provide the required stability during the final step of creating a closed-surface.
- Boundary Leakage: Sometimes the automatic smoothing of the scalp surface caused a "leaking" of the scalp segment into the background. To handle this, a Masking method was developed using Overwrite All settings as a priority. It meant that in case any manual intervention was used to close a gap, the information received in the course of it prevailed and, thus, allowed us to create a "water-tight" scalp surface.

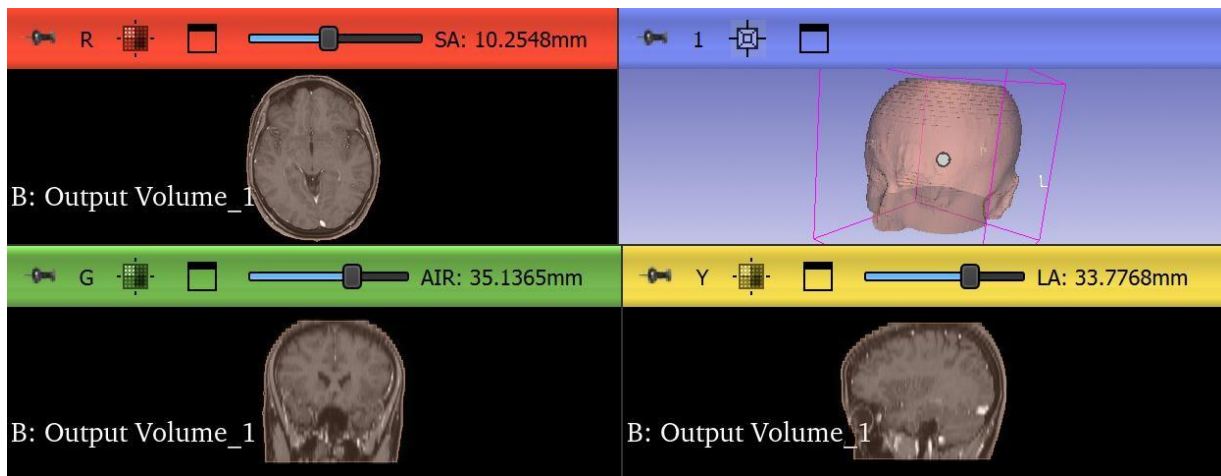


Fig 2.7: Final volumetric segmentation of the head model

Due to the initial voxel-based reconstruction, the raw cranial shell exhibited significant staircase artifacts, characterized by non-manifold fragmented geometry. To resolve this and ensure numerical stability during the subsequent tetrahedral meshing process in COMSOL Multiphysics, an intense geometric refinement protocol was applied. Specifically, a Gaussian smoothing filter with a kernel size of 6.0mm was executed. Thus, the fragmented structure was made homogeneous, while both inner and outer borders were merged into a continuous manifold surface with strict nested hierarchy with respect to the adjacent skin layer.

In order to achieve water-tight geometry for FEM meshing, a morphological Closing (Fill holes) filter with a 4.0 mm radius was applied to the segmented bone region in order to fill possible anatomical and voxel discontinuities. After that, a Median filter was applied to smooth out the surface since Gaussian filtering was found to be ineffective for preserving the volume in such thin trabecular structures.

The processing of the cranial bone segment was the most time-consuming stage of the modeling process due to the requirement to combine the work of automatic morphological filters with extensive manual editing of the image. In particular, due to the voxel nature of the acquisition of an initial MRI image, the raw bone segment contained severe "staircase" artifacts and anatomical discontinuities.

To achieve a manifold and simulation-ready geometry, a rigorous multi-step pipeline was implemented:

- Manual Topology Correction: An exact slice by slice examination was conducted using the Paint feature to manually join up broken-down trabecular components and close anatomical voids. This human manipulation was crucial to create a "water-tight" edge to avoid "current leakage" from the intracranial space to the extracranial space during the electromagnetic simulations.
- Morphological Refinement: In order to create a uniform bone surface, the Closing (Fill holes) filter was used initially (kernel 3.0 mm). Later on, an iterative filtering approach was employed. Even though traditional Gaussian smoothing turned out to be too strong for thin structures, the approach of combining Median smoothing and Joint smoothing (factor 0.8-1.0) was effective in eliminating high-frequency noise while maintaining overall cranial curvature.
- Volumetric Standardization (Hollowing): To simulate a realistic physiological barrier, the solid bone volume was transformed into a hollow shell using the Hollow effect. By applying a 5.0mm thickness toward the Inside surface, a constant-thickness cranial vault was established without encroaching upon the previously finalized skin-air interface.
- Logical Partitioning: Finally, to ensure perfectly non - overlapping domains, a strict requirement for COMSOL meshing, Boolean Logical Operators were employed to subtract the bone volume from the internal brain cavity and the external skin layer, resulting in a perfectly nested three-compartment model.

This intensive refinement process transitioned the model from a discrete voxel representation to a continuous, anatomically accurate geometric entity, ensuring both biological relevance and computational convergence.

2.3.2 - Reconstruction of the Cranial Bone (Bone Layer)

The segmentation of the cranial bone structure represented the most significant challenge in the development of the high-fidelity head model. While the skin and external tissues are easily identifiable in MRI sequences, bone tissue presents a low proton density, leading to fragmented signals, significant voxel noise, and inherent "staircase" artifacts. To overcome these limitations and ensure a simulation-ready geometry for COMSOL Multiphysics, a novel template-based reconstruction strategy was adopted, utilizing the previously finalized skin segment as a geometric reference.

The segmentation of the skull presented the highest level of complexity due to the thinness of the bone in certain regions and the presence of the marrow cavity.

- **Thresholding and "Staircase Effect"**: The initial bone extraction was performed using a high-

intensity threshold. However, this led to a rough, non-physiological surface referred to as the "staircase effect". This is because of the discretized voxel array of the MRI scan.

In order to remove "staircase" artifacts that arise due to the voxel based segmentation, Gaussian filtering with a kernel size of 3.0mm was performed on the scalp surface.

This ensured that the manifold surface was obtained which could then be meshed using the tetrahedral elements in COMSOL Multiphysics.

- **Gaussian Smoothing:** To avoid such artifacts, Gaussian Smoothing filter was used. This is an important step since without this step, meshing using COMSOL would fail as there will be mesh singularities at sharp corners of the object. Where the gradient becomes infinity and the solver fails to converge.
- **Structural Challenges:** An important issue that arose was that of the apical region of the skull. The original MRI scan did not have coverage of the whole superior part of the skull.
- **Manual Interpolation:** To address the physical limitations of the scan, a manual "capping" method was used. Using the Draw function, polygons were traced in all superior slices to create a reconstructed skull cap. This was necessary for the creation of manifold (watertight) geometry required for volume-based modeling.

In order to optimize the resulting model for electromagnetic simulations, the inner structure of the bone had to be optimized:

- **Hollow Operation:** The Hollow function was used on the bone part in order to create numerically accurate thickness. Setting the Inside Thickness to 3.0mm, a smooth shell of the bone was created based on the external shape of the object.
- **Internal Consistency:** Such a method prevents possible debris inside the bone, thus providing a clean border for the next segment.

During the optimization stage, there were some problems related to the computer's hardware, namely RAM saturation and GPU crashes during closed surface conversion.

- **Conversion Costs:** Large-scale segmentations involve high computational "costs" for the software to synchronize the 2D labelmaps with the 3D visual representations.
- **Optimization:** To manage these crashes, the Keep Largest Island command was frequently used to prune unnecessary metadata and disconnected voxels, significantly reducing the memory footprint of the project without losing anatomical detail.

Following the structural optimization, a segment-locking protocol was enforced within the 3D Slicer environment. With the preservation of the geometrical properties of the skin and bone layers in place, the risk of accidentally altering their morphology while constructing the intracranial volume was avoided, thus ensuring correct anatomical correspondence and a nested hierarchy for the electromagnetic simulation.

Protection of the geometry of the skin segment was accomplished by moving it to an additional secondary segmentation node. The spatial separation made sure that further manipulation of the

geometry of the cranial bone through hollowing and smoothing would take place in a 'sandbox' environment, leaving intact the volumetric structure of the skin-air border for the finite element simulation.

In order to preserve the anatomical hierarchy and proportions, the decision was made to construct the geometry of the bone based on the skin. With the skin acting as a "calco", it was possible to achieve a mathematically correct representation of the vault following the outer curvature of the head.

This procedure is crucial for electromagnetic simulations as it avoids any accidental overlapping of the domains, which causes meshing failures and numerical divergence in the FEM solver.

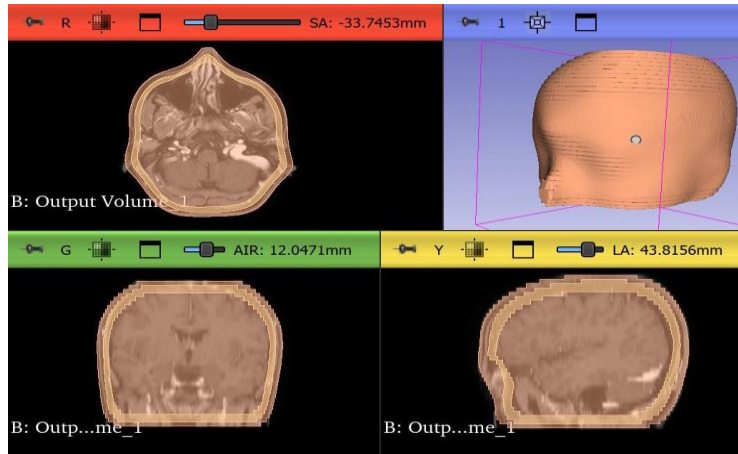


Fig 2.8: Morphological Derivation of the Cranial Bone from the Scalp Volume

The reconstruction followed a rigorous multi-step workflow within the 3D Slicer Segment Editor:

- Segment Duplication and Logical Cloning: The process began by duplicating the skin segment into a new workspace using the Logical Operators (Add) command. This ensured that the initial bone volume was a perfect topological match to the external boundary.
- Isotropic Volumetric Reduction: To establish the subcutaneous space, the Margin (Shrink) tool was applied. For this purpose, the value of the negative margin of -2.0mm was chosen for "sinking" the volume under the skin layer. This measure was crucial for defining the physiological gap between the dermis and the periosteum.
- Hollow Shell Generation: Afterwards, the volume was transformed into the hollow cranial shell by means of the Hollow effect; its thickness was set at 5.0mm towards the Inside surface. The result is realistic and keeps the external border created on the previous stage.

At the same time, there appeared several technical difficulties that demanded an extremely accurate handwork.

- Topological Discontinuities: Firstly, the initially obtained automatic results contained some "holes" or "leaks", mainly at the bottom of the skull and near the orbital cavities. This issue was resolved through the careful inspection of the slices one by one. The virtual "topological plugs" were created manually by means of the Paint tool for closing the foramen magnum and other openings.
- The "Vanishing Segment" Paradox: One of the most important challenges that arose during the

reduction of the volume of the thin bones was the phenomenon when the volume itself collapsed. The solution for that problem was found through the usage of the Fill Holes procedure right before the margin modification, making the segment a temporary solid manifold.

- **Surface Regularization:** In order to remove high-frequency noise and some voxelation artifacts, the Median Smoothing and Joint Smoothing (with the factor 0.8) were used. This ensured that the final surfaces were "water-tight" and smooth, drastically reducing the complexity of the subsequent tetrahedral meshing process in COMSOL.

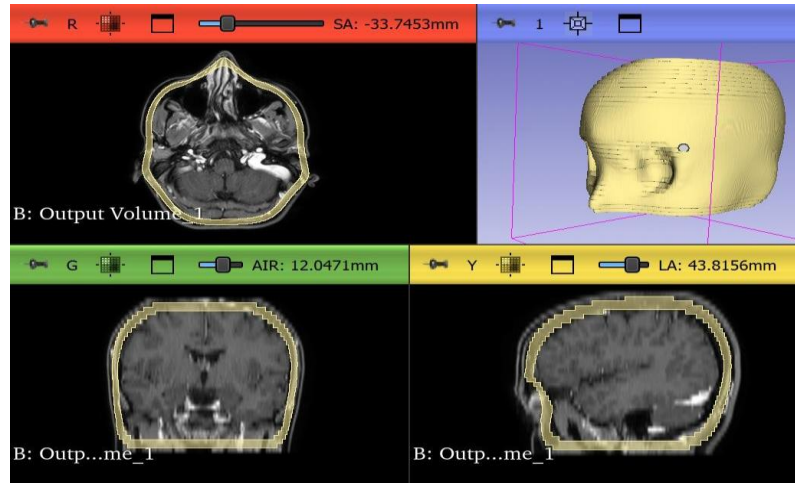


Fig 2.9: Final 3D Reconstruction and Validation of the Cranial Bone

The final bone segment was subjected to a final **Logical Subtract operation** against the skin segment. This ensured that, even at a microscopic level, there were zero overlapping voxels. The result is a perfectly nested, hierarchical model where the bone sits exactly within the skin, providing a robust geometric foundation for the intracranial segments (Brain and CSF) to follow.

2.3.3 - Brain Parenchyma: Volumetric Reconstruction

The reconstruction of the intracranial volume, representing the Brain parenchyma (unified GM and WM), required a shift from purely anatomical identification to a logic-driven volumetric approach.

Given the project's goal of performing Finite Element Analysis (FEA) in COMSOL Multiphysics, the priority was ensuring mathematical continuity within the cranial vault.

- **Volumetric Extraction and "Sealing":** The brain segment was initialized using a Flood Filling (Grow from seeds) algorithm within the internal boundary of the finalized "Bone" segment. To transform the skull into a fillable container, manual "plugs" were sculpted across anatomical apertures like the foramen magnum and orbital cavities, creating a "watertight" manifold. This process ensured that the brain volume remained strictly confined within the intracranial space, preventing "leaking" artifacts.
- **Tissue Homogenization and Dielectric Averaging:** Although the T1W_3D_TRA sequence allows for visual distinction between Grey Matter (GM) and White Matter (WM), they were merged into a single homogeneous domain. This decision was based on the 4.0 mm slice thickness: another segmentation would have resulted in serious "staircase" effects, forming

artificial sharp boundaries, which would lead to nonphysical peak electric field concentrations. In this way, the gradient is smoother and better approximates bulk tissue properties.

- **Internal Structure Integration:** In order to ensure numerical stability, internal cavities filled with fluid, like the lateral ventricles, were merged into the overall brain volume. This morphological simplification prevents the creation of extremely thin internal boundaries which are notorious for causing mesh degeneration. The entire encephalic mass is thus treated as a continuous volume conductor, ensuring a more robust convergence of the iterative solver in COMSOL.
- **Morphological Integrity:** To preserve the fundamental topology of the brain, ensuring it didn't appear as a simple oval block, the “Fast Marchin” algorithm was used. This allowed the segment to follow the general curvature of the cortical surface and the brainstem-cerebellum interface, ensuring that the induced current paths reflect the real patient-specific macroscopic geometry.

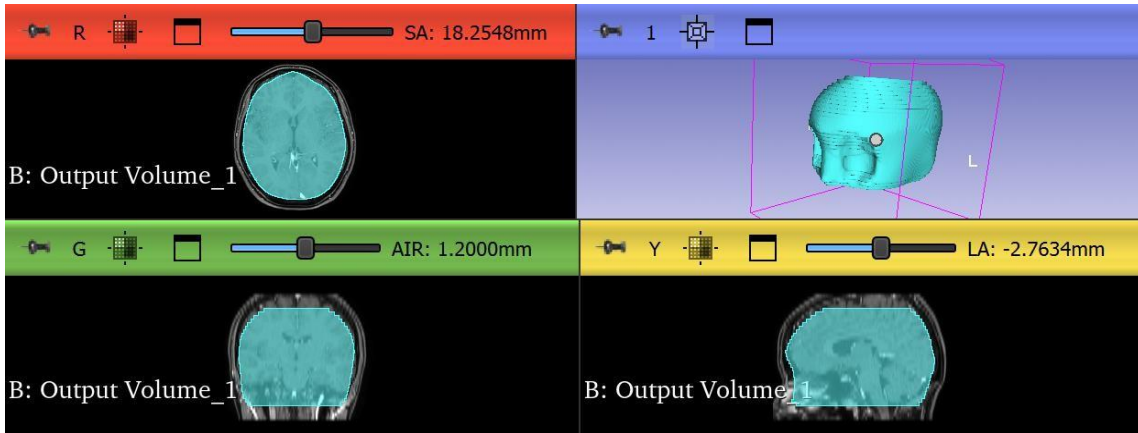


Fig 2.10: 3D and multi-planar visualization of the finalized Brain segment

2.3.4 - Cerebrospinal Fluid (CSF): Derived Layering

Although the CSF is anatomically situated between the bone and the brain, in this pipeline, it was the final tissue to be modeled, as its geometry depends on the finalized brain volume.

- **Space Generation via Smoothing:** For the explanation of the high conductivity of the CSF ($\sigma \approx 1.79 \text{ S/m}$), a special compartment was created. With the help of the Median Smoothing algorithm, the boundaries of the brain were pulled back from the inner cranial vault. This resulted in an artificial gap.
- **Boolean Definition:** The final segmentation of the CSF took place after a Logical Subtract of the smoothed Brain volume from the whole internal intracranial cavity. This ensures that the CSF perfectly "shunts" the space between the resistive bone and the conductive neural tissue, eliminating any parasitic air gaps that would erroneously insulate the model.

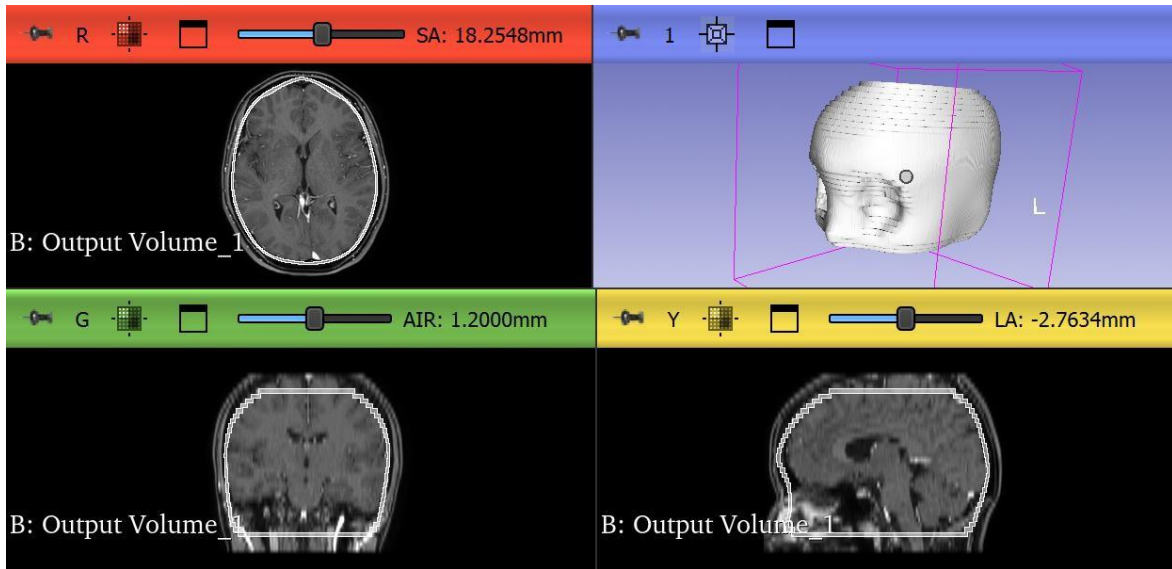


Fig 2.11: 3D and multi-planar visualization of the finalized CSF segment

2.4 - Methodological Justification and Computational Logic

The selection of the specific tissue layers (Skin, Bone, CSF, and Brain) was governed by a rigorous trade-off between bio-anatomical accuracy and the requirements of numerical convergence.

The model follows a strict concentric hierarchy designed for electromagnetic simulations. By ensuring that each segment is nested (Brain < CSF < Bone < Skin), the FEA solver can implement nodal sharing at the interfaces. This "Matryoshka" structure ensures that the current density vector remains continuous across boundaries, reflecting the physiological behavior of the head as a volume conductor.

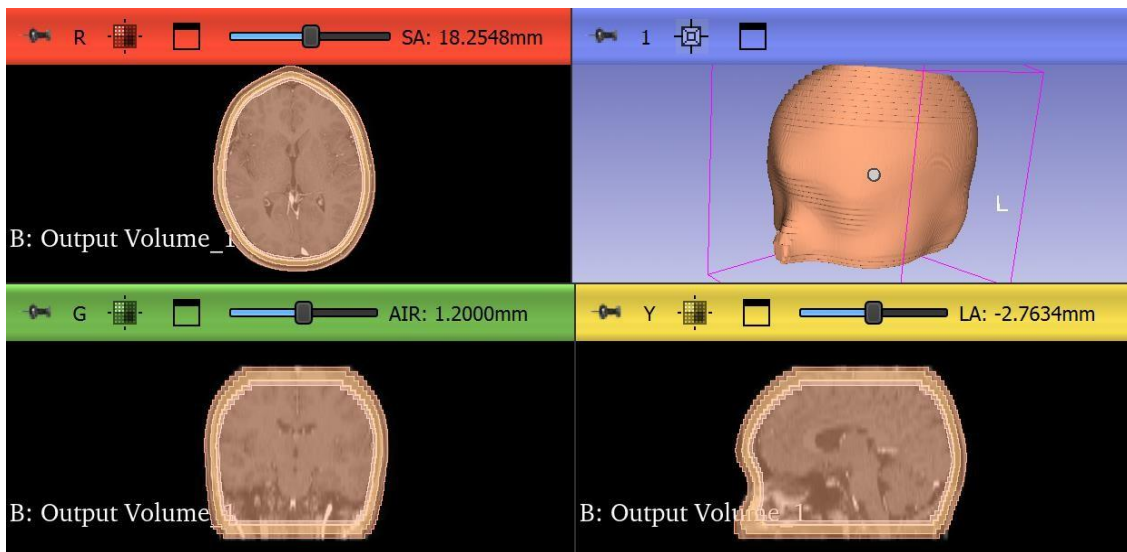


Fig 2.12: Complete 4-Layer Head Model Segmentation

The decision to simplify the meningeal layers (Dura, Arachnoid, and Pia Mater) into the CSF/Brain interface was dictated by **the Sub-Voxel Resolution Limits**. With a source MRI resolution of 4.0 mm in the axial plane, attempting to segment membranes thinner than 1.0 mm would result in "sliver

elements" tetrahedrons with poor quality ratios that cause solver failure.

By integrating these layers into a regularized 4-layer model, we maintain a high-quality mesh that ensures the stability of the COMSOL Multiphysics environment.

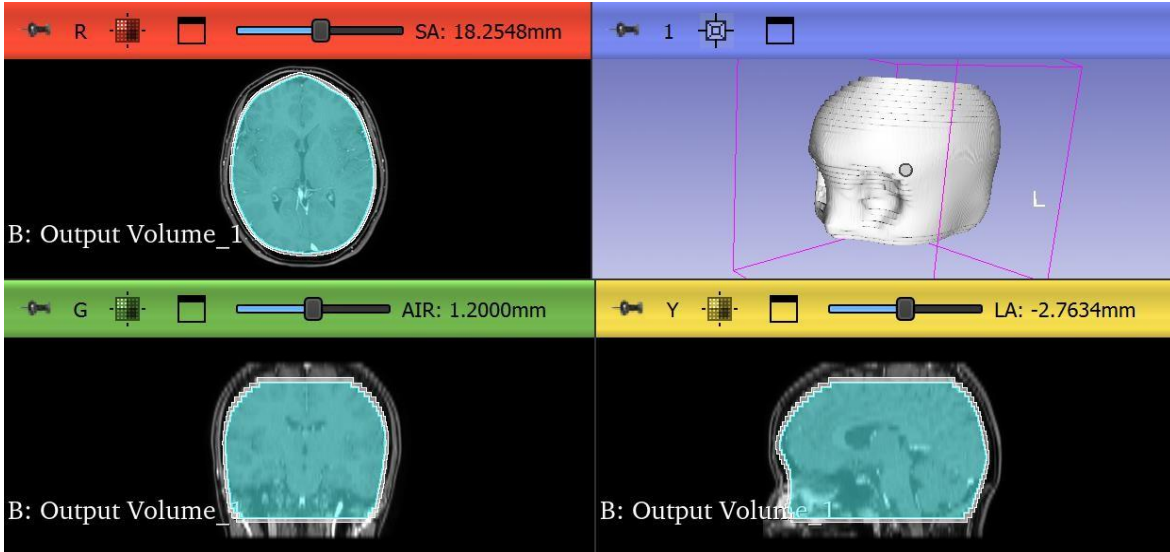


Fig 2.13: Morphological Derivation of the CSF layer from the Brain Volume

In summary, the model was designed as a computational tool and very interface was refined to be perfectly conformal and non-overlapping. This ensures that the simulated electric fields "see" a solid, multi-layered conductor with no artificial discontinuities, allowing for a **seamless transition of electromagnetic energy** across the cranial barrier.

Chapter 3

Numerical Modeling and Computational Framework

3.1 - Introduction to Computational Methodology

To achieve the numerical objectives of this research, the computational framework was deployed across two distinct generations of the same finite element software ecosystem: COMSOL Multiphysics version 3.5a and COMSOL Multiphysics version 6.4.

Specifically, version 3.5a was employed to construct and simulate the simplified analytical models created directly within the software's native geometry engine, moving progressively from the single-ellipsoid to the dual-ellipsoid configuration. However, to overcome severe computational limitations regarding dynamic memory allocation and to successfully process the final, highly complex skull model imported from external medical segmentation sources, the workflow was migrated to the advanced COMSOL Multiphysics version 6.4 environment. This modern platform provided the robust parallel-solving capabilities and optimized mesh-handling algorithms strictly required to sustain the final ultra-realistic biological domain.

COMSOL Multiphysics is a high-performance, interactive software environment based on the Finite Element Method (FEM), specialized in the modeling and simulation of coupled physical phenomena. The foundational strength of this platform lies in its unified "Multiphysics" architecture, which allows for the simultaneous formulation, discretization, and solution of different systems of partial differential equations (PDEs) within a single, integrated simulation domain. Rather than addressing separate physical domains through isolated sequential steps, COMSOL implements a fully coupled or closely segregated numerical matrix. This approach enables the software to solve interconnected physical fields, such as high-frequency electromagnetic wave propagation and thermodynamic bio-heat transfer, by accurately updating physical parameters (such as temperature-dependent dielectric profiles or mathematically coupled source terms) at every computational node. Consequently, it represents the ideal engineering tool for capturing the complex, non-linear interactions between non-ionizing radiation and lossy biological substrates.

In the context of this study, the engineering workflow specifically requires the strategic integration of two primary functional core structures:

- **The Radio Frequency (RF) Module:** Specialized in solving the harmonic Vector-Helmholtz equations to map electromagnetic wave propagation, spatial electric field distributions (E), and localized energy deposition profiles.

- **The Heat Transfer Module:** Dedicated to solving thermodynamic transport equations, specifically incorporating specialized biological sub-nodes to simulate homeostatic regulation and microvascular blood perfusion.

By establishing a direct multiphysics coupling between these two modules, the software seamlessly translates the absorbed electromagnetic energy into a distributed spatial heat source term, directly driving Pennes' Bioheat Equation to compute the actual localized temperature increase within the heterogeneous tissues. To rigorously formalize this thermodynamic transition, the primary physical quantities and governing equations are defined as follows:

- **Specific Absorption Rate (SAR):** Quantified in watts per kilogram (W/kg), SAR represents the rate at which radiofrequency electromagnetic energy is absorbed by a specific mass of biological tissue. It serves as the bridge between the electromagnetic and thermal domains and is mathematically formulated as:

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

where σ is the electrical conductivity of the tissue (S/m), ρ is the tissue mass density (kg/m³), and $|E|$ is the root-mean-square norm of the induced electric field vector (V/m).

- **Pennes' Bioheat Equation:** This fundamental heat transfer equation governs the thermal distribution inside living tissues by balancing standard thermal conduction with metabolic heat production and microvascular capillary blood perfusion. The localized transient thermal behavior is expressed as:

$$\rho c \frac{\partial T}{\partial t} = \nabla (k \nabla T) + Q_{met} + Q_b + Q_{EM}$$

where c is the specific heat capacity of the tissue (J/(kg K)), k is the tissue thermal conductivity (W/(m K)), T is the local tissue temperature (K), Q_{met} is the metabolic heat source rate (W/m³), and $Q_{EM} = \rho$ SAR represents the external heat source injected by the electromagnetic dissipation (W/m³). Crucially, the blood perfusion term Q_b acts as a homeostatic cooling mechanism and is defined as:

$$Q_b = \rho_b \omega_b c_b (T_{art} - T)$$

where ρ_b , c_b , and ω_b are the density, specific heat capacity, and volumetric perfusion rate of the blood, respectively, while T_{art} is the constant arterial blood temperature (310.15 K or 37°C).

- **Localized Temperature Increase (ΔT):** Evaluated in kelvins (K) or degrees Celsius (°C), ΔT represents the net thermal baseline shift relative to the homeostatic temperature of the human body:

$$\Delta T = T_{final} - T_{baseline}$$

This quantity represents the final dosimetric metric utilized to assess compliance with international safety standards and to evaluate potential thermal risks or hot-spot focalization inside the brain structures.

3.2 - Modeling Progression: From Anatomical Complexity to Analytical Validation

3.2.1 - Geometrical Evolution and Computational Modeling Workflow

The modeling workflow followed a progressive, multi-stage trajectory in geometric representation, structured to systematically isolate physical variables, calibrate tissue parameters, and ultimately scale up to full anatomical realism. Rather than attempting a single-step simulation, the research advanced through a rigorous three-tier validation hierarchy:

- **Stage 1: The Single Homogeneous Ellipsoid:** In the first step of the workflow, a simple single domain ellipsoidal phantom was modeled in the built-in geometry module of COMSOL version 3.5a. The importance of this analytical model cannot be overstated since it helped form a starting point numerically to independently calibrate the basic dielectric and thermal properties without being affected by reflections from internal boundaries.
- **Stage 2: The Dual-Ellipsoid Stratification:** To determine the effect of tissue layering, the geometry was enhanced into a more complicated dual-ellipsoid model. This model provided a physical representation through stratification in the form of an outer layer of skin (SKIN) and an inner layer of the brain (BRAIN). This intermediate model was calibrated against the well-established COMSOL international benchmark "Absorbed Radiation (SAR) in the Human Brain".
- **Stage 3: The High-Resolution Anatomical Skull Model:** The last stage, however, implied shifting from analytical approximation to complete anatomical accuracy. High-resolution patient-specific anatomical data were first segmented from MRI resources by means of 3D Slicer. However, analysis of this specifically crafted organic geometry showed serious computational problems with the first generation of software and its further development, which was due to the extremely fragmented geometric construction, micro-scale boundary discontinuities, and facet density specific to medical segmentations, resulting in computational inefficiencies and problems in solver convergence. In order to achieve a reasonable balance between accurate anatomy and numerically sound calculation, an engineering approach was implemented and an already existing highly accurate external head phantom pre-optimized for Finite Element Analysis (FEM) was selected. In order to maintain numerical integrity, the segmented geometry had to be discretized in FreeCAD and, thus, STL files could be processed, surfaces cleaned, and volume defined. The advanced external geometry was introduced into COMSOL Multiphysics v. 6.4 framework, allowing advanced computational solving and meshing necessary to analyze a complex biological domain. This approach ensured a stable, validated computational substrate for the final multi-frequency dosimetric calculations, while setting a foundational benchmark for future geometric integrations.

3.2.2 - Operational Exposure Scenarios: Talking vs. Texting Mode

Across all three structural stages described above, the computational workflow systematically incorporated an analysis of source positioning to simulate the two most prevalent real-world mobile

device usage habits. This spatial reconfiguration was applied uniformly to the single ellipsoid, the dual ellipsoid, and the final anatomical skull, altering the distance, orientation, and electromagnetic coupling between the radiation source (the patch antenna) and the target biological domains:

- **Talking Mode:** In this configuration, the radiation source is positioned laterally, directly adjacent to the squamous part of the temporal region, closely replicating a standard voice call where the mobile device is pressed against the user's ear. From the electromagnetic perspective, in this case, there will be maximum coupling in the near field and the maximum power density in direct contact with the superficial layers of tissue.
- **Texting Mode:** Alternatively, in this case, the antenna will be positioned at a certain distance and tilt angle from the frontal-orbital area of the face, which is a normal position that the individual would adopt while surfing the internet. This configuration allows for the characterization of wave propagation over a short air gap, tracking how distance attenuates the fields and how the complex angles of incidence affect wave penetration through the multi-layer cranial framework.

3.2.3 - Simulation Objectives and Parametric Frequency Selection

Having established the multi-stage geometric framework and the operational exposure modes, the core objective of this numerical investigation is to map and quantify the electromagnetic energy deposition and the subsequent thermodynamic response across a broad operational spectrum.

To evaluate how tissue stratification, geometric curvature, and source distance influence the depth of wave penetration and localized peak thermal loads, the simulation framework executes a parametric sweep across four critical telecommunication benchmarks: **835 MHz, 1800 MHz, 2450 MHz, and 6000 MHz.**

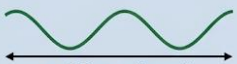
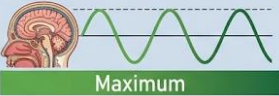
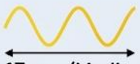
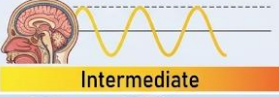
ELECTROMAGNETIC BEHAVIOR MAP BETWEEN 835 MHz AND 6000 MHz			
Frequency	Wavelength	Penetration into Cranium	Primary Mechanism
835 MHz	 ~ 36 cm (Long)	 Maximum	Volumetric Heating (Penetrates deeply)
1800 MHz	 ~ 17 cm (Medium)	 Intermediate	Attenuation Transition (Begins to stop earlier)
2450 MHz	 ~ 12 cm (Short)	 Resonance	Electromagnetic Trap (Cavity Effect / Hot-spot)
6000 MHz	 ~ 5 cm (Ultra)	 Minimum	Skin Effect (Absorbed only at the surface)
◀ SUPERFICIAL		PROFONDO ▶	

Figure 3.1: Summary table of penetration/wavelength for the 4 frequencies

1. The Sub-GHz Spectrum: 835 MHz (The Baseline Penetration Band)

The lower boundary of the parametric analysis is set at 835 MHz. Operating traditionally as the key component for legacy cellular deployment, from initial GSM protocols to 4G/LTE bands below GHz, the above frequency is characterized by relatively high wavelength ($\lambda_0 \approx 35.9$ cm in vacuum).

- **Electromagnetic Propagation:** At 835 MHz, biological tissue demonstrates a relatively low electrical conductivity (σ) in comparison with higher frequencies. Since the rate of attenuation of a lossy medium is proportional to its conductivity, there is practically no surface absorption of an electromagnetic wave.
- **Dosimetric Significance:** This band serves as the structural benchmark for deep volumetric penetration. The induced electric field successfully bypasses outer dermal barriers, penetrating deep into the internal brain mass and the core of the cranial cavity, providing an essential baseline to observe long-wavelength energy distribution within unshielded biological volumes.

2. The Intermediate Spectrum: 1800 MHz (The Urban Capacity Band)

Representing the mature infrastructure of modern urban cellular networks, the 1800 MHz benchmark defines the transition between macroscopic coverage and high-capacity data transmission.

- **Electromagnetic Propagation:** As the operating frequency increases toward the 1.8 GHz threshold, the free-space wavelength shortens ($\lambda \approx 16.7$ cm), and a corresponding increase in tissue electrical conductivity is observed. This shifting dielectric profile forces a transitional compression of the wave propagation velocity inside the lossy medium.
- **Dosimetric Significance:** This band serves as a critical intermediate step to track the spatial migration of thermal profiles. It demonstrates the physical progression where the electromagnetic field begins to experience stronger boundary attenuation, causing the localized energy deposition to shift away from deep volumetric structures toward more peripheral and superficial tissue layers.

3. The Microwave Spectrum: 2450 MHz (The Universal Wireless Resonant Band)

The 2450 MHz frequency represents the global standard for unlicensed Industrial, Scientific, and Medical (ISM) applications, acting as the primary carrier for Wi-Fi architectures, Bluetooth networks, and localized short-range wireless protocols.

- **Electromagnetic Propagation:** This spectral node is of great significance in relation to the Texting Mode exposure scenario because of constant proximity of actively functioning wireless chipset modules during mobile internet surfing. From a physical standpoint, 2450 MHz lies in the relaxation frequency range where the highly dissipative and very watery human brain tissue displays a highly effective absorption ability of electromagnetic energy.
- **Dosimetric Significance:** At that particular frequency, the reduced wavelength inside corresponds to the geometrical size and boundary values of the cranium, which means that there exists a high probability of electromagnetic confinement and constructive interference at a local level. This is of crucial importance for this particular study in order to investigate the presence of localized hot spots and sharp changes of the temperature baseline (ΔT).

4. The Millimeter-Wave Transition: 6000 MHz (The Next-Generation Boundary)

Defining the upper asymptotic limit of this research, the 6000 MHz benchmark captures the technological frontier associated with high-band 5G deployments and advanced Wi-Fi 6E/7 architectures.

- **Electromagnetic Propagation:** The wavelength of the radiation at 6000 MHz is greatly decreased ($\lambda \approx 5.0$ cm), while the electrical conductivity of biological tissues exhibits a definite step change, reaching a very dissipative value of $\sigma \approx 3.94$ S/m.
- **Dosimetric Significance:** Such an extreme operating scenario is deliberately accounted for in order to reproduce the definite skin effect in computational bio-electromagnetics. In this case, the skin penetration depth decreases down to millimeters; however, the radiation generates extremely high SAR values right at the vicinity of the domain boundary due to the high conductivity but is completely absorbed there. This case represents the definitive limiting scenario of the study, thus proving that, at ultra-high frequencies, electromagnetic exposure does not affect subcortical brain regions anymore but only the SKIN boundary.

3.3 - Dielectric and Thermodynamic Material Properties: Physical Rationale

To solve the numerical formulation, COMSOL Multiphysics requires a rigorous definition of the constitutive relations governing the target domains. Biological tissues are complex, lossy dielectric media whose interactions with non-ionizing radiation change significantly depending on the operating frequency. The material properties assigned to each domain dictate the solution across two sequentially coupled physical regimes: the Electromagnetic Propagation Phase and the Thermodynamic Heating Phase.

1. The Electromagnetic Propagation Phase

During the initial computational sequence, the software solves the harmonic Maxwell and Vector-Helmholtz equations to map the spatial distribution of the Electric Field (E) within the heterogeneous volume. To simulate how the biological matter alters and interacts with the incident wave generated by the patch antenna, two primary dielectric parameters must be defined:

- **Relative Permittivity (ϵ_r):** This dimensionless quantity determines the phase velocity of the electromagnetic wave inside the medium and dictates the local wavelength compression

$$\lambda = \frac{\lambda_0}{\sqrt{\epsilon_r}}$$

Physically, ϵ_r governs the dielectric boundary conditions, establishing the exact reflection, refraction, and transmission coefficients at the interfaces between contrasting media, such as the transition from the low-permittivity air gap to the skull bone, or from the bone to the high-permittivity internal brain matter. Without a precise calibration of ϵ_r , the solver would fail to compute the refractive lensing effects and the actual intensity of the electric field that successfully penetrates the deeper cranial structures.

- **Electrical Conductivity (σ):** Evaluated in siemens per meter (S/m), this parameter represents the dynamic loss mechanism of the tissue. As the wave travels through the medium, the oscillating electric field induces polarization currents and alternating ionic displacement. σ directly quantifies the level of volumetric attenuation and spatial decay that the wave undergoes as it propagates through lossy biological barriers.

Together, ϵ_r and σ form the complex permittivity tensor ($\epsilon^* = \epsilon^0 \epsilon^r - j \frac{\sigma}{\omega}$), which COMSOL utilizes to evaluate the complex wave vector (k) and output the exact root-mean-square norm of the Electric Field ($|E|$) at every discrete mesh node.

2. The Thermodynamic Heating Phase

Once the spatial profile of the electric field norm ($|E|$) is fully resolved, the electromagnetic simulation reaches its boundary condition, and the software triggers the thermal module. In this second phase, the local power dissipated by the radiofrequency fields is converted into a localized thermal energy deposition rate via the Joule effect. This transition is governed by a secondary combination of material properties:

- **Electrical Conductivity (σ):** Acting now as the thermodynamic conversion factor within the coupled physics, σ defines the efficiency with which the tissue converts electrical energy into thermal energy. Under a constant electric field intensity, a higher conductivity value forces a proportional increase in localized power dissipation, directly intensifying the primary heat source term (Q_{EM}).
- **Mass Density (ρ):** Expressed in kilograms per cubic meter (kg/m^3), ρ is required to weight the localized volumetric heat generation relative to the physical mass of the tissue domain. This parameter establishes the mathematical formulation of the Specific Absorption Rate (SAR)

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

From an engineering standpoint, SAR does not measure the subjective sensation of temperature change, but rather represents a strict physical metric of localized power deposition per unit mass. The mass density ρ scales this energy distribution, ensuring that Pennes' Bioheat equation can correctly translate the mass-normalized absorbed radiation into a real spatial temperature baseline shift (ΔT) across the heterogeneous cranial layers.

3.4 - Software Environment and Multiphysics Coupling

The numerical investigation was conducted using **COMSOL Multiphysics version 3.5a**, a high-performance environment specialized in the simulation of coupled physical phenomena through the Finite Element Method (FEM). A multiphysics model needed to be applied in order to capture the relationship between electromagnetic radiations and biological matter. In such multiphysics models, the two main modules were solved together:

- **The RF Module:** The first module was used for harmonic propagation analysis of electromagnetic waves within the radiofrequency band.
- **The Heat Transfer Module:** The second module was designed specifically for the use of Bioheat Equation in the steady state thermal analysis which takes into account the thermodynamic effects of biological matter.

To capture the interaction of high-frequency electromagnetic waves within the biological tissue, the computational engine of COMSOL Multiphysics works in the frequency domain where Maxwell Equations are solved under the assumption of time-harmonic steady state. In this case, Faraday's Law

and the Maxwell-Ampere Law are combined to eliminate the magnetic field components. This mathematical reduction yields the Vector-Helmholtz Equation, which serves as the fundamental governing differential equation to determine the vector electric field distribution throughout the computational domain:

$$\nabla \times \left(\frac{1}{\mu_r} \nabla \times \mathbf{E} \right) - k_0^2 \epsilon_r \mathbf{E} = 0$$

where each constitutive parameter and mathematical operator represents a specific physical mechanism governing wave-matter interaction:

- **E:** Is the unknown space-dependent, three-dimensional complex electric field vector (V/m) that the finite element solver computes at every discrete mesh node. Treating the field vectorially ($\mathbf{E} = [E_x, E_y, E_z]$) is strictly necessary to capture wave polarization effects and directional boundary reflections arising from the different antenna orientations in the *Talking* and *Texting* modes.
- **$\nabla \times$ (The Curl Operator):** Represents the spatial rotation of the field vector. The nested curl-of-the-curl formulation mathematically represents the physical mechanism of electromagnetic wave propagation and spatial oscillation through space and lossy media.
- **μ_r :** Is the relative magnetic permeability of the medium. Because human biological tissues (skin, bone, brain) and the surrounding air gap are entirely non-magnetic, this dimensionless parameter is uniformly assigned a value of $\mu_r = 1$.
- **k_0 :** Is the free-space wave vector (or wave number), defined as $k_0 = \omega / c_0 = 2\pi f / c_0$, where ω is the angular frequency, f is the operational frequency of the mobile source (835 MHz, 1800 MHz, 2450 MHz, or 6000 MHz), and c_0 is the speed of light in a vacuum. It represents the spatial frequency of the phase of the wave in a lossless vacuum.
- **ϵ_r :** Is the relative permittivity of the medium.

3.4.1 - Geometrical Evolution: From Anatomical Segmentation to Standardized Phantoms

The modeling process underwent an evolutionary transition to balance anatomical realism with computational feasibility.

1. **3DSlicer Integration:** Initially, high-resolution head models were developed through the segmentation of MRI/CT data, providing an authentic representation of human anatomy.
2. **Complexity Constraints:** Due to the extreme geometric complexity of segmented data, which can lead to convergence difficulties in FEM solvers, the research transitioned to the SAM (Specific Anthropomorphic Mannequin) Phantom.
3. **Standardization:** The SAM geometry is the international standard provided by IEEE, IEC, and CENELEC for SAR value measurements.

3.4.2 - Boundary Conditions and Electromagnetic Setup

The radiation source consists of a patch antenna positioned on the left side of the head. The technical specifications for the electromagnetic configuration consist of:

- **Feed Mechanism:** The line current along the edge acts as a current source for the antenna patches.
- **Excitation:** A Lumped Port has been used with an input voltage of $V_{in} = 45.5$ V considering the mismatched impedance with the external 75Ω cable.
- **Boundary Shielding:** The scattering boundary conditions have been used for the boundaries of the domain.
- **Non-Reflective Layers:** Perfectly Matched Layers (PMLs) were constructed in a Cartesian configuration to avoid artificial wave reflections at the domain boundaries.

3.5 - Mesh Convergence Study and Submodeling Methodology

In numerical simulations utilizing the Finite Element Method (FEM), the accuracy of the computed electromagnetic and thermal fields strictly depends on the spatial discretization of the domain. In large-scale, high-frequency electromagnetic models, which simultaneously encompass the radiating microstrip patch antenna, the surrounding free-space air domain, and the lossy multi-layer biological tissue structures, performing a global mesh refinement loop to evaluate grid convergence is computationally prohibitive. This would have resulted in an exponential increase in the number of degrees of freedom (DOFs), thus resulting in huge RAM requirements, ill conditioning of matrices, and unrealistic computational time spans.

In order to bypass this structural constraint, the concept of sub-modeling approach (also called as local problem approach) has been utilized. The idea is to extract the particular zone of interest (cranium elliptical domain) from the global arrangement of elements. By capturing the complex electromagnetic field calculated at the boundary limits of the macro-scale global model and mapping it as a localized boundary condition excitation (forcing function), the internal grid of the biological domain can be heavily refined and tested independently. This advanced engineering framework guarantees a highly rigorous mesh sensitivity analysis without the computational burden of resolving the surrounding unshielded free-space boundaries.

3.5.1 - Schematization of the Submodeling Methodological Steps

The local submodeling and mesh convergence workflow was organized into four main operational engineering phases:

- Step 1- Global Model Solution and Data Extraction: The complete macro-scale layout, containing the radiating patch antenna, the air box, and the homogeneous ellipsoidal phantom, was resolved under time-harmonic conditions. Utilizing the *In-Plane TM Waves* formulation, the primary out-of-plane magnetic field component (H_z , perpendicular to the 2D simulation plane) was computed. The closed contour line defining the exact perimeter of the ellipsoid was isolated, and the precise spatial distribution of the computed H_z field along this geometric profile was exported as an external discrete data file (H_z_grid).
- Step 2 - Local Model Definition and Boundary Driving Force: A dedicated, independent submodel simulation file was constructed, containing exclusively the isolated geometry of the biological ellipsoid, completely eliminating the antenna and air domains. The boundary conditions along the external perimeter of the ellipsoid were defined as an active magnetic field

source. The previously extracted Hz_grid field was interpolated and mapped onto this boundary profile, functioning as the continuous driving force of the local problem. This setup ensures that the isolated tissue experience an identical electromagnetic excitation to the global configuration.

- **Step 3 - Local Grid Discretization and Field Computation:** The isolated submodel was solved sequentially to reconstruct the internal induced electric field (E) and the corresponding Specific Absorption Rate (SAR). The internal mesh resolution of the tissue domain was systematically varied across the entire hierarchical spectrum of physics-controlled mesh densities provided by COMSOL Multiphysics, moving progressively from *Coarse* to *Extremely Fine* parameters.
- **Step 4 -Sensitivity and Convergence Evaluation:** The localized peak values of the electromagnetic field components were extracted and tracked as a function of the element size and the total number of degrees of freedom. Mathematically, the discretization is considered stable and fully validated once further grid refinements produce negligible variations in the field output, proving that the numerical solution has achieved absolute independence from the grid size.

3.5.2 - Theoretical Expectations vs. Complex Wave Physics

When executing the progressive mesh refinement within the isolated local domain, the simulation framework balances two distinct behavioral trends:

1. **Mathematical Expectation (Asymptotic Convergence):** As the FEM density moves from a coarse grid to a finer grid, the spatial discretization error is minimized. When a metric of the target field is plotted versus the increasing DOFs, the curve is theoretically supposed to converge, eventually reaching a well-defined horizontal asymptote. Reaching such a horizontal level would prove mathematically the attainment of grid independence.
2. **Physical Expectation (Sampling of the Skin Depth Effect):** At the high operating frequency of 2450 MHz, the electromagnetic wave propagates through the highly dissipative biological tissue and is subjected to an exponential attenuation within just a few millimeters. Such a fast spatial decay results in a very steep field gradient. The Coarse mesh fails to properly sample such a steep field gradient, causing some numerical artifacts or artificial oscillations, or even failing to capture the correct peak field at the boundary interface; only a finer local mesh can do that.

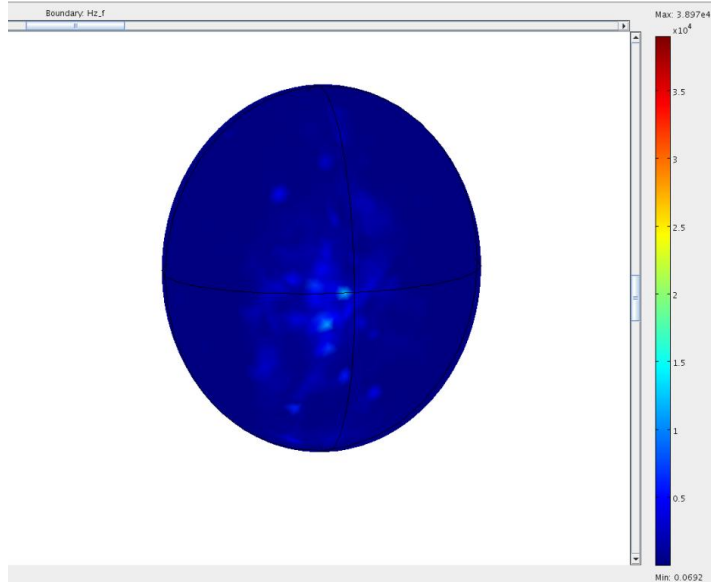


Figure 3.2: Hz field on the ellipsoidal boundary

3.5.3 - Quantitative Sensitivity Analysis and Discrepancy Evaluation

To evaluate the convergence behavior, the maximum value of the out-of-plane magnetic field component (A/m) was tracked across six distinct discretization tiers. To mathematically quantify the relative error or discrepancy between consecutive, adjacent mesh configurations, the standard solver formulation was applied:

$$\text{Relative Discrepancy (\%)} = \frac{|V_2 - V_1|}{V_1} \times 100$$

where V_1 represents the field value computed by the preceding baseline mesh and V_2 represents the value resolved by the subsequent refined grid. The step-by-step mathematical calculations are detailed below:

1. Coarse to Normal Transition:

$$V_1 = 3.897 \cdot 10^4 \text{ A/m}, V_2 = 2.914 \cdot 10^4 \text{ A/m}$$

$$\text{Discrepancy} = 25.22\%$$

2. Normal to Fine Transition:

$$V_1 = 2.914 \cdot 10^4 \text{ A/m}, V_2 = 2.815 \cdot 10^4 \text{ A/m}$$

$$\text{Discrepancy} = 3.40\%$$

3. Fine to Finer Transition:

$$V_1 = 2.815 \cdot 10^4 \text{ A/m}, V_2 = 3.061 \cdot 10^4 \text{ A/m}$$

$$\text{Discrepancy} = 8.74\%$$

4. Finer to Extra Fine Transition:

$$V_1 = 3.061 \cdot 10^4 \text{ A/m}, V_2 = 3.942 \cdot 10^4 \text{ A/m}$$

$$\text{Discrepancy} = 28.78\%$$

5. Extra Fine to Extremely Fine Transition:

$$V_1 = 3.942 \cdot 10^4 \text{ A/m}, V_2 = 4.043 \cdot 10^4 \text{ A/m}$$

$$\text{Discrepancy} = 2.56\%$$

The quantitative outcomes of this convergence campaign are summarized in *Table 3.1*:

Mesh Iteration Tier	Peak Hz Value (A/m)	Relative Discrepancy (%)	Numerical Behavior and Trend Analysis
Coarse	$3.897 \cdot 10^4$	Baseline	Severe initial grid under-sampling
Normal	$2.914 \cdot 10^4$	25.22%	Macro-scale geometrical stabilization
Fine	$2.815 \cdot 10^4$	3.40%	Primary Macro-Physical Convergence Window
Finer	$3.061 \cdot 10^4$	8.74%	Minor localized numerical oscillation
Extra Fine	$3.942 \cdot 10^4$	28.78%	Micro-scale sampling of boundary poles
Extremely Fine	$4.043 \cdot 10^4$	2.56%	Asymptotic Mathematical Convergence Window

Table 3.1: Mesh convergence table with percentage discrepancy

3.5.4 - Mathematical Interpretation of the U-Shaped Convergence Profile

The empirical data extracted from the submodeling study reveals a highly specific, non-linear **U-shaped convergence curve**. Rather than exhibiting a continuous monotonic decay, the maximum field value decreases until reaching the *Fine* mesh threshold, undergoes a minor localized oscillation, and subsequently rises before achieving absolute mathematical saturation at the highest grid density tiers (*Extra Fine* to *Extremely Fine*). Within high-frequency computational engineering involving interpolated boundary conditions, this behavior is a known phenomenon that reflects two distinct validation zones:

1. **Global Macro-Physical Stability Window (Normal → Fine):** In the important stage of switching from the Normal to the Fine density levels, the relative difference becomes very small, i.e., equal to 3.40%. This confirms the fact that the macro-level physics of the task and the overall configuration of the electromagnetic fields in the target brain tissue have already been completely accounted for and stabilized at this level of resolution. Any further improvement in the grid size at this stage does not affect the macro-level field configuration at all.

2. **Asymptotic Numerical Convergence Window (Extra Fine → Extremely Fine):** The subsequent increase in the maximum H_z_f value observed at the microscopic grid levels (*Extra Fine* and *Extremely Fine*) is tied directly to localized boundary discretization. When the mesh elements near the boundary perimeter of the ellipsoid shrink to microscopic scales, the element nodes sample the discrete interpolation points of the external source text file (H_z_grid) with extreme spatial precision. Consequently, the mesh resolves highly localized maximum boundary peaks or minor geometric singular points near the poles. The definitive proof of mathematical validation is that between the *Extra Fine* and *Extremely Fine* configurations, the relative error drops sharply to just **2.56%**, confirming that the solver has successfully converged onto its final horizontal asymptote.

3.5.5 - Engineering Justification for the Primary Grid Selection

The empirical results of this convergence study validate the accuracy of the implemented numerical framework, providing a strong scientific justification for adopting the Fine or Finer mesh density configurations as the primary baseline for the multi-frequency simulations.

Increasing the global discretization parameters beyond the levels of Fine/Finer throughout the full-scale models will not bring any benefit in respect of macro-physics accuracy or health monitoring dosimetry significance. Rather, it will cause an excessive and unexplained computational cost through an exponential increase of the total number of DOFs, which means large requirements for RAM allocation and extended computation time to obtain the same physical understanding.

Therefore, Fine/Finer configuration constitutes the mathematically optimal compromise for engineering convergence. It guarantees maximum data reliability, smooth biological gradient smoothing, and high computational efficiency throughout the multiphysics workflow.

3.6 - Geometrical Phantoms and Multi-Physics Implementation Parameters

To analyze the interaction between mobile radiation devices and human biological substrates, the numerical framework evaluates two progressively complex geometric configurations solved in the frequency domain. The physical boundaries and subdomain constants extracted from the simulation parameters are formalized below:

Model 1: The Single Homogeneous Ellipsoidal Phantom: This baseline analytical phantom operates as a single, isotropic domain with length semi-axes calibrated to $x = 0.085\text{m}$, $y = 0.1\text{ m}$, and $z = 0.115\text{ m}$, representing an un-layered, average macroscopic equivalence of the internal human head mass named HEAD.

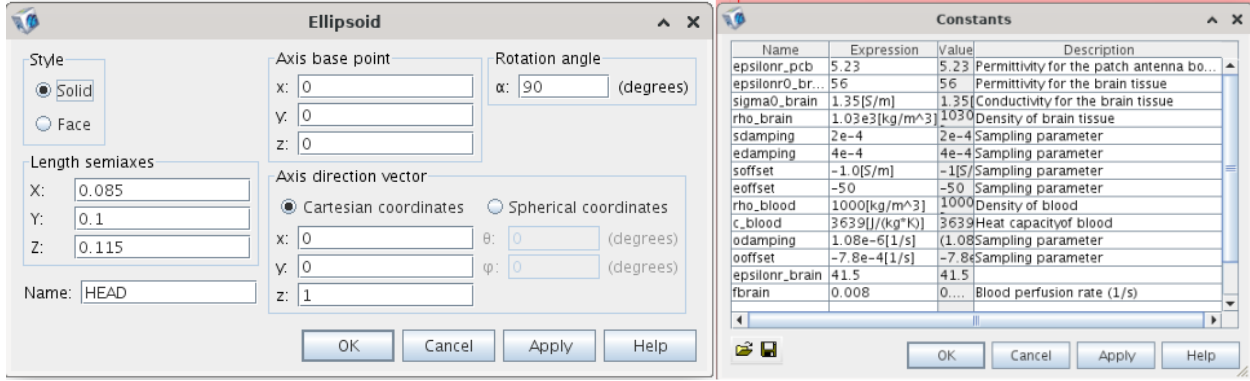


Figure 3.3: Ellipsoid geometry dialog, figure 3.4: Material constants

It is initialized with a uniform reference mass density ($\rho_{\text{brain}} = 1030 \text{ kg/m}^3$) and baseline electrical conductivity ($\sigma_{\text{brain}} = 1.35 \text{ S/m}$).

Model 2: The Advanced Heterogeneous Stratified Phantom (Dual-Ellipsoid): To accurately resolve multi-layer dielectric boundary conditions, the model incorporates two concentric nested domains representing distinct biological substrates:

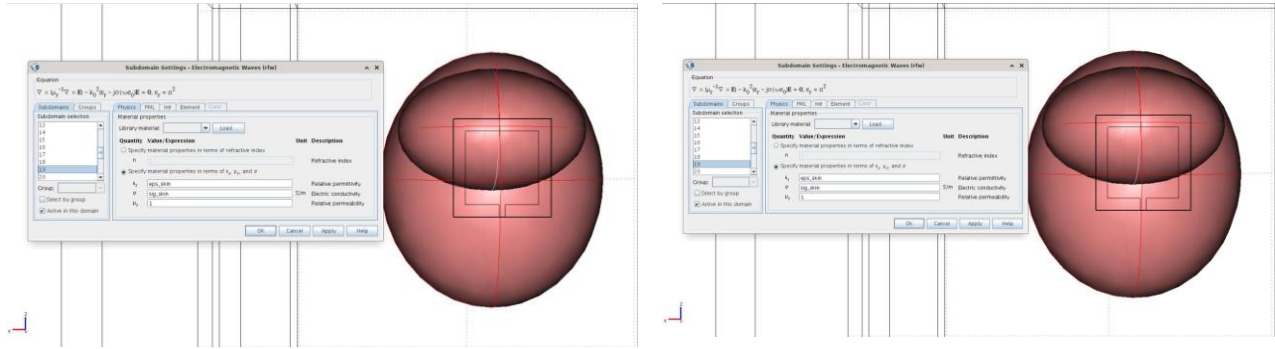


Figure 3.5: Spherical nested ellipsoid view, figure 3.6: Dual-domain configuration

- The Outer Layer (SKIN / Subdomain 19): Characterized by a localized thickness modeling the peripheral barrier, with a mass density $\rho_{\text{skin}} = 1100 \text{ kg/m}^3$, specific heat capacity $c_{\text{skin}} = 3390 \text{ J/(kg K)}$, thermal conductivity $k_{\text{skin}} = 0.37 \text{ W/(m K)}$, and a constant homeostatic blood perfusion rate $\omega_{\text{skin}} = 0.001 \text{ s}^{-1}$.
- The Internal Core (BRAIN / Subdomain 20): Bounded entirely within the outer shell, featuring a highly hydrated mass parameterization where $\rho_{\text{brain}} = 1030 \text{ kg/m}^3$, $c_{\text{blood}} = 3639 \text{ J/(kg K)}$, and an elevated capillary blood perfusion sink rate, $\omega_{\text{brain}} = 0.008 \text{ s}^{-1}$ to capture deep thermal autoregulation.

3.6.1 - Thermodynamic Core Setup and Baseline Isolation

Across all simulated domains, the initial homeostatic tissue temperature (T_0) and the arterial blood supply temperature (T_b) were uniformly clamped to an analytical reference value of 0 K (0°C) within the solver settings. This numerical setup ensures that the dependent output variable computed by the Heat Transfer module represents the net temperature increase (ΔT) contributed exclusively by the radiofrequency

dissipation ($Q_{EM} = Q_{av_rfw}$), completely isolating the radiation-induced thermal surge from the standard baseline biological metabolic conditions.

3.6.2 - Global Boundary Conditions and Antenna Computational Setup

Before evaluating the specific dosimetric and thermal solutions of the individual configurations, it is mathematically and physically essential to formalize the global boundary conditions and the radiation source excitation framework. While the geometrical complexity of the head phantoms changes across the computational stages, the structural architecture of the radiating source and the non-reflective boundary physics of the surrounding computational domain remain rigorously identical. This consistency isolates the structural geometry of the phantoms as the primary independent variable under test.

3.6.2.1 - Perfectly Matched Layers (PML) and Anechoic Boundary Physics

In high-frequency computational electromagnetics, simulating an unshielded antenna radiating into an open, infinite space presents a significant constraint within finite element domain boundaries. Unconstrained waves striking the sharp geometric edges of the simulation air box would experience artificial numerical reflections, creating unphysical constructive interference patterns and invalidating the internal SAR calculations.

To establish a perfectly anechoic virtual environment, a dual-layer truncation strategy was implemented:

- **Scattering Boundary Conditions (SBC):** The outermost surface boundaries of the computational air domain are mapped with Scattering Boundary Conditions, configured to allow the calculated electromagnetic wavefronts to pass through the interface without reflection.

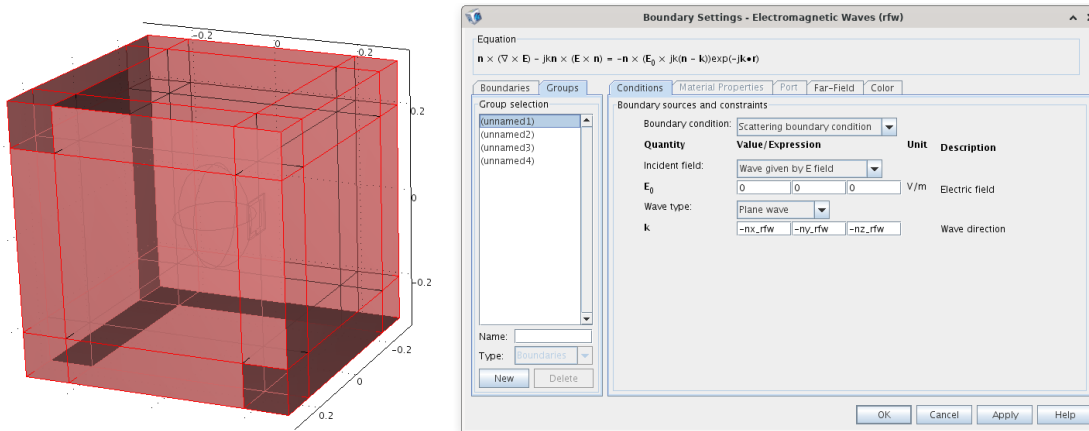


Figure 3.7: Cubic domain with scattering boundaries highlighted, figure 3.8: COMSOL scattering boundary settings panel

- **Perfectly Matched Layers (PML):** To absorb the complex near-field non-planar waves, the SBC is coupled with an advanced Cartesian Perfectly Matched Layer system. The PML subdomains act as an ideal physical sponge: they possess an artificial complex permittivity and permeability profile that exhibits an escalating attenuation factor along the radial propagation axis. Consequently, any outward-radiating wave generated by the patch antenna is completely

dissipated within the PML domains, guaranteeing that the internal field gradients inside the skull are generated exclusively by direct source-substrate interaction.

3.6.2.2 - Microstrip Patch Antenna Architecture and Feed Modeling

The electromagnetic wave generation is driven by a compact microstrip patch antenna designed to operate efficiently across the designated multi-frequency mobile communication bands.

To achieve clean harmonic excitation without adding prohibitive degrees of freedom (DOFs) via complex internal coaxial connectors, the power coupling is modeled using a Lumped Port boundary condition implemented in the COMSOL RF Module. The mathematical feeds have been modeled in the following manner:

- **Impedance Definition and Matching:** The feed line that supplies the radiation patch has an impedance (Z_{ref}) of 75Ω .
- **Excitation Voltage Calibration:** In order to overcome the problem of mismatched impedance due to high frequencies on certain spectrum nodes and also to provide a standardized power output into the circuit model, the input voltage (V_{in}) across the feed port boundary was set to $45.5 V_{rms}$.

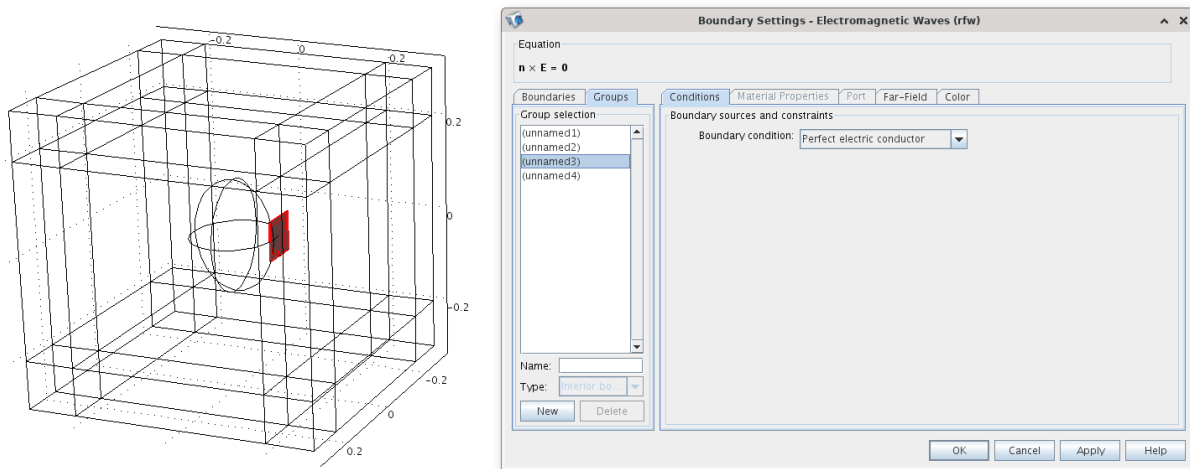


Figure 3.9: View of the cube geometry/computational domain with antenna, figure 3.10: COMSOL boundary settings panel

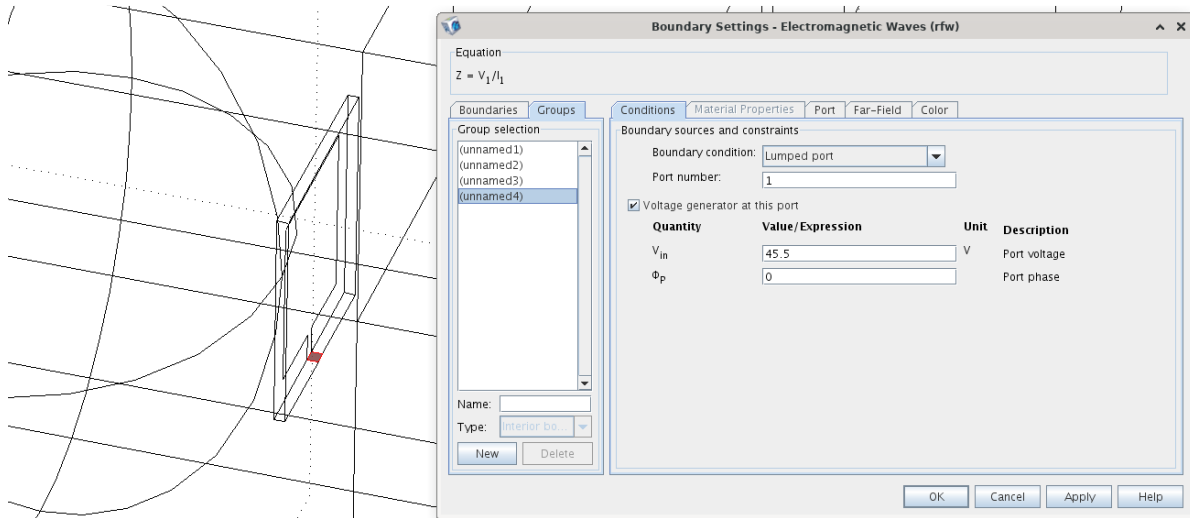


Figure 3.11: Patch antenna wireframe and domain, figure 3.12: COMSOL Lumped Port settings panel

- **Spatial Reconfiguration (Talking vs. Texting):** The physical and material properties of the antenna remain constant throughout the investigation. The transition between the two daily exposure scenarios is executed purely through rigid spatial translations and rotatory transformations of the antenna's coordination matrix relative to the phantom:
 - *Talking Mode:* The antenna substrate is aligned laterally, maintaining a restrictive near-field air gap of exactly 5 mm adjacent to the temporal bone region.
 - *Texting Mode:* The antenna is translated frontally and rotated at a 45° inclination angle, establishing an offset distance of exactly 15 cm (150 mm) relative to the frontal-orbital region of the face.

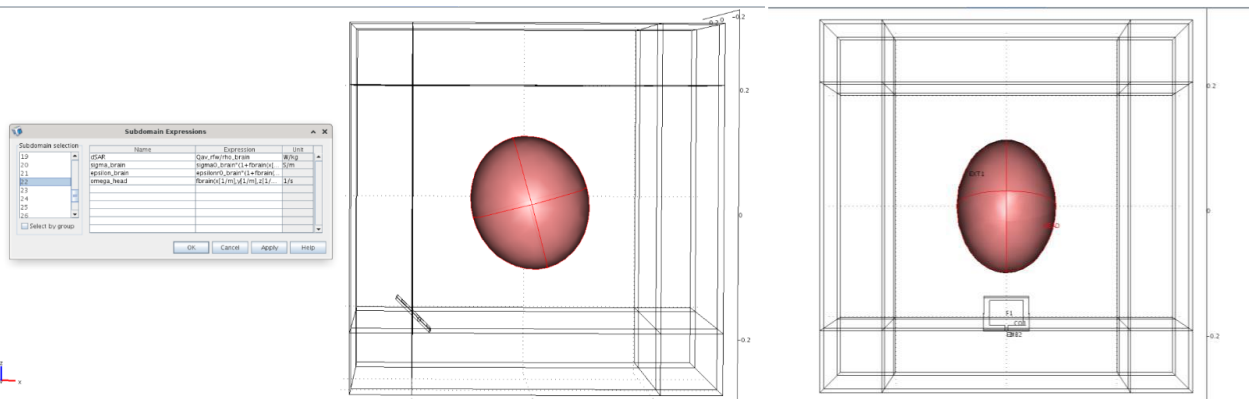


Figure 3.13: Subdomain expressions panel, figure 3.14, figure 3.15: two views of antenna/ellipsoid positioning

3.6.2.3 - Thermodynamic Core Setup and Baseline Temperature Isolation

To balance the electromagnetic solution with the thermal physics, Pennes' Bioheat Equation requires a rigorous definition of initial and boundary thermal constraints. Across all simulated tissue domains, the initial homeostatic body core temperature (T_0) and the incoming arterial blood supply temperature (T_{art}) were uniformly clamped to an analytical baseline reference of 0 K (0°C) within the solver subdomains.

From an engineering standpoint, this strategic setting provides a critical advantage: it completely filters out the baseline physiological heat contributed by metabolic regulation (Q_{met}). Consequently, the dependent temperature output variable computed by the transient and steady-state thermal solvers reflects exclusively the net localized temperature rise (ΔT) contributed directly by the radiofrequency power dissipation ($Q_{EM} = \rho \cdot SAR$). This isolation guarantees a precise, unambiguous evaluation of the direct thermal impact of mobile technology on biological tissues.

3.7 - Model 1: Single Homogeneous Ellipsoid Simulation Results

3.7.1 - Near-Field Exposure Configuration (Talking Mode)

In the *Talking Mode* scenario, the radiating antenna source is placed laterally in immediate contact-proximity to the HEAD boundary to capture the worst-case near-field exposure.

- **At 835 MHz:** The vector field exhibits an extended internal wavelength, allowing for a deep volumetric field penetration. The spatial SAR is plotted via a base-10 logarithmic scale ($\log_{10}(dSAR)$) to map the dynamic range. The maximum peak localized SAR settles at 1.00 on the logarithmic bar, which corresponds linearly to an un-averaged local peak value of **10 W/kg** focused at the point of incidence. The steady-state coupled Pennes' bioheat solver translates this power deposition into a highly smooth internal thermal gradient, reaching a maximum localized temperature rise of **$dT_{max} = 1.469$ K**.

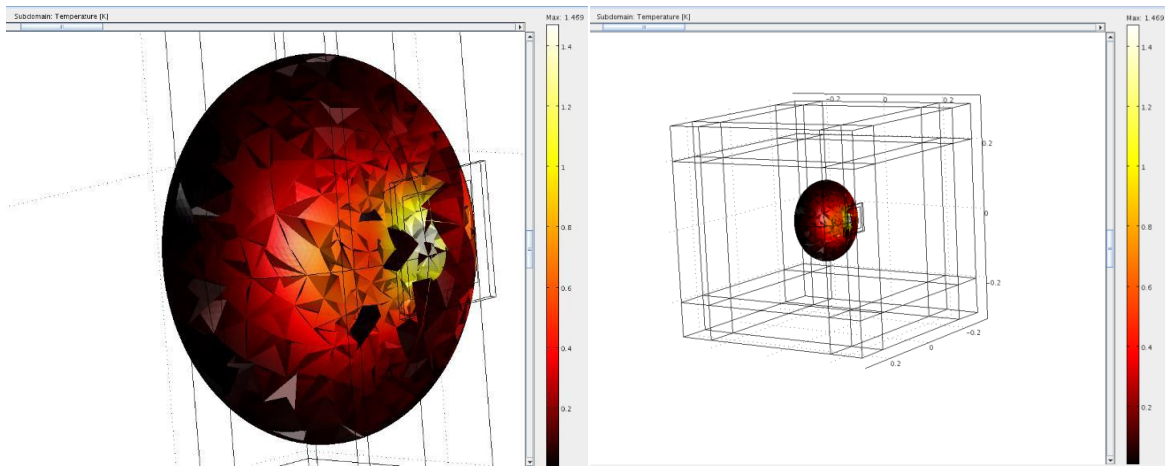


Figure 3.16, figure 3.17: Temperature distribution on the ellipsoid surface (zoom + full domain view)

- **At 1800 MHz:** The field interaction shifts toward urban telecommunication capacity standards. The maximum logarithmic SAR value drops to 0.510, mapping linearly to a local peak SAR of **3.24 W/kg**. The slice plot displays a heterogeneous internal deposition with internal constructive wave pattern peaks. The resulting thermodynamic balance yields a maximum temperature rise restricted to **$dT_{max} = 0.200$ K**.

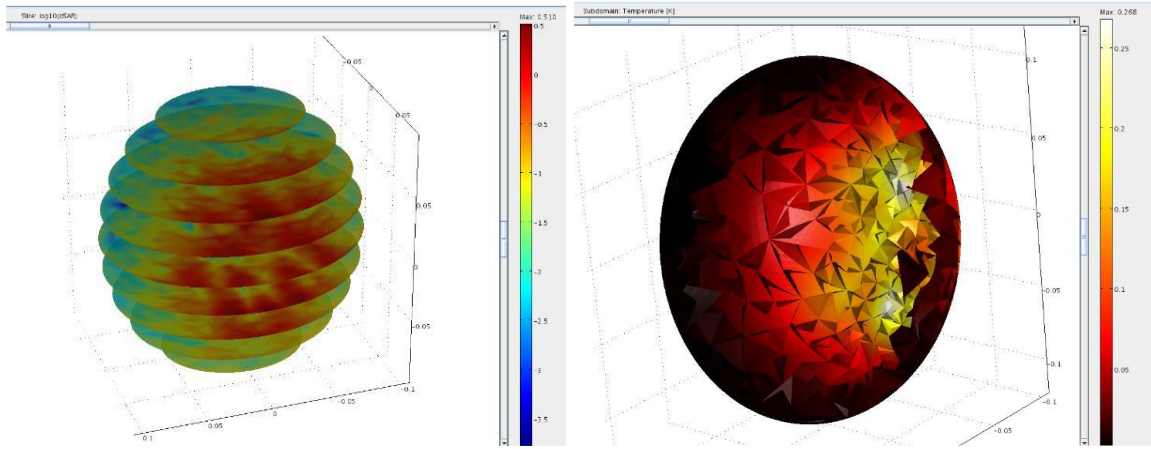


Figure 3.18, figure 3.19: SAR and temperature at 1800 MHz, talking mode

- **At 2450 MHz:** Due to the high dielectric loss and the specific relaxation frequency of the water content inside the simulated tissue mass, electromagnetic absorption becomes highly efficient. The maximum base reaches a significant peak of 1.923, mapping linearly to an un-averaged hot-spot value of **83.75 W/kg** immediately beneath the antenna feed profile. The coupled thermodynamic steady-state solver translates this intense energy deposition into a highly localized thermal surge, pushing the maximum temperature rise to **dT_{max} = 5.866 K**.

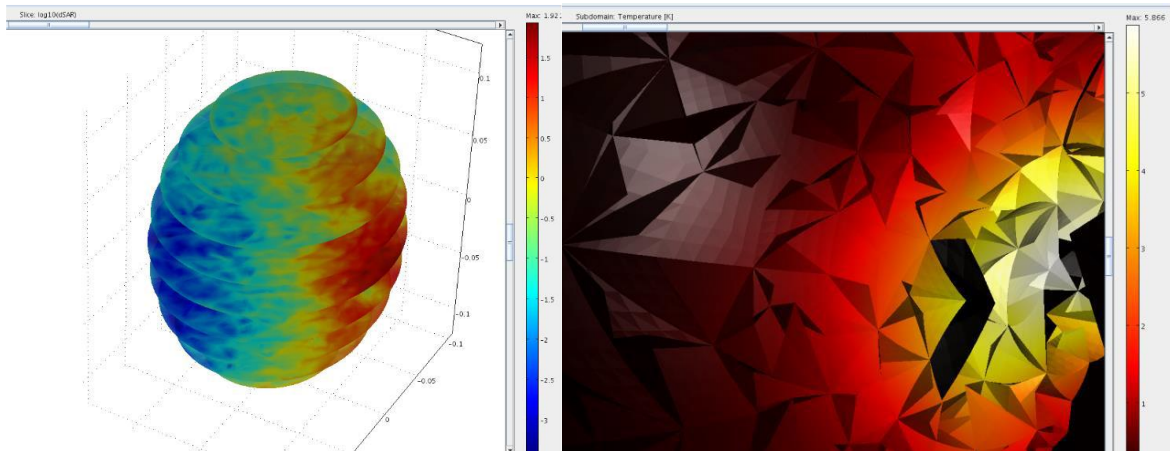


Figure 3.20, figure 3.21: SAR and temperature at 2450 MHz, localized hotspot, talking mode

- **At 6000 MHz:** At the onset of the new generation spectrum, there will be a sudden increase in the conductivity value to $\sigma = 3.94$ S/m and this brings out an observable skin effect. The maximum value of the logarithmic SAR approaches to 1.325, indicating that there is a large surface concentration value of **21.13 W/kg**. While there is a large surface loss, the interior part of the body is protected due to quick attenuation. The thermal module resolves a localized surface-dominated heating plateau peaking at **dT_{max} = 0.385 K**.

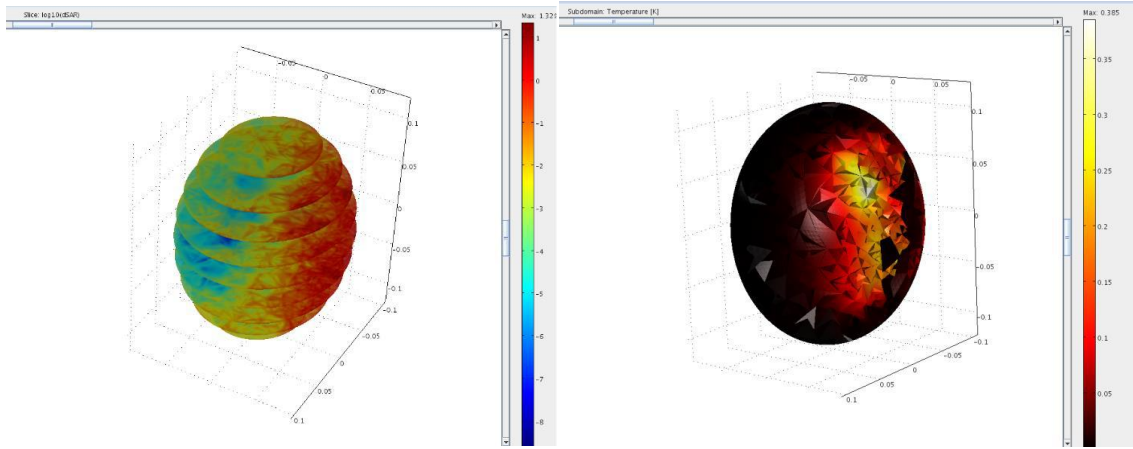


Figure 3.22, figure 3.23: SAR and temperature at 6000 MHz, talking mode

In conclusion, the near-field *Talking Mode* simulation on the single homogeneous ellipsoid highlights a clear proportional migration of electromagnetic risk as a function of the frequency sweep. At lower bands (835 MHz), the phantom undergoes deep, volumetric field penetration, exposing internal structural coordinates due to long wavelengths. Conversely, when approaching the 2450 MHz wireless resonant band, the tissue substrate exhibits a sharp increase in absorption efficiency, maximizing localized thermal stress ($dT_{max} = 5.866$ K). Finally, transitioning toward the millimeter spectrum (6000 MHz) triggers a stark physical polarization: the severe rise in tissue electrical conductivity confines the electromagnetic energy entirely to the outer boundary margins, demonstrating the macro-scale validation of the electromagnetic skin effect within non-layered biological media.

3.7.2 - Far-Field Offset Configuration (Texting Mode)

The *Texting Mode* introduces a fundamental protective spatial displacement, repositioning the antenna source to a frontal-orbital air gap distance of exactly **15 cm**.

- **At 835 MHz:** Shifting to a 15 cm distance triggers immediate geometric dilution via the inverse-square law ($1/r^2$). The maximum logarithmic SAR value undergoes a steep collapse down to -0.210, translating linearly to a local peak of just **0.617 W/kg**, representing a 93.8% reduction in localized exposure compared to the contact baseline. The coupled peak temperature increase falls to a safe biological baseline of $dT_{max} = 0.172$ K.

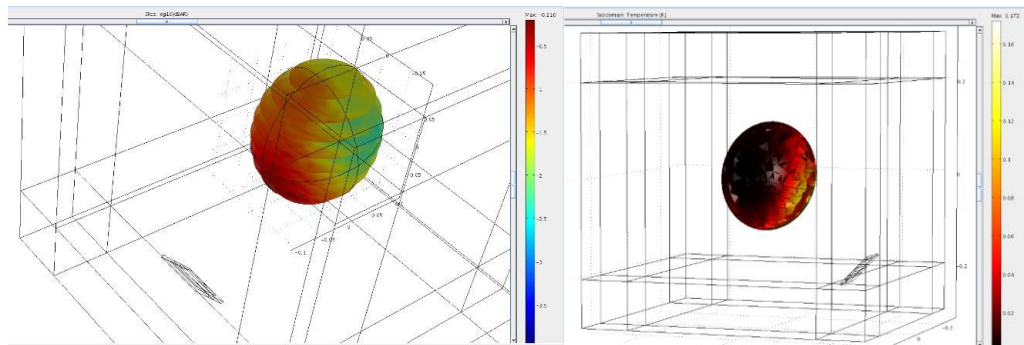


Figure 3.24, figure 3.25: SAR and temperature at 835 MHz, texting mode

- **At 1800 MHz:** The mid-band wavefront propagates across the air gap with pronounced free-space path loss. The peak logarithmic SAR plummets to -1.477, which corresponds to a linear value of only **0.033 W/kg** (a definitive 99% collapse relative to the talking posture). The resulting transient thermal accumulation is practically non-existent, yielding a maximum steady-state rise of $dT_{\text{max}} = 0.0065 \text{ K}$ ($6.49 \cdot 10^{-3} \text{ K}$).

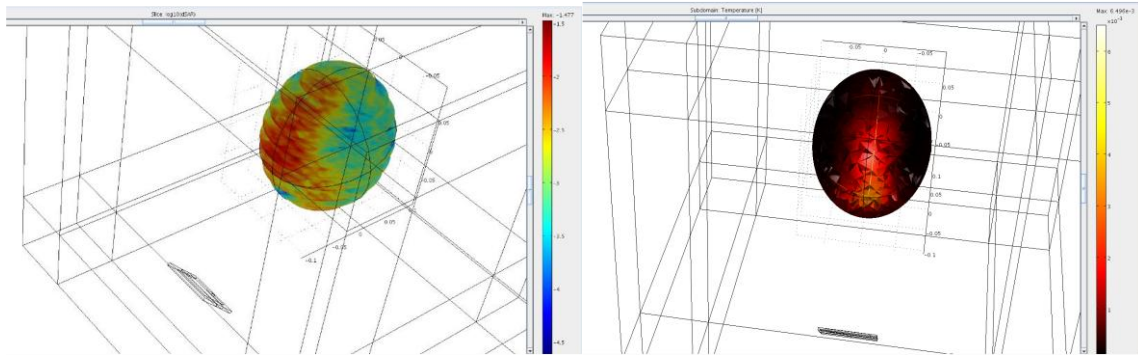


Figure 3.26, figure 3.27: SAR and temperature at 1800 MHz, texting mode

- **At 2450 MHz:** When operating across the frontal 15 cm air gap, the outward-propagating wavefront undergoes spherical divergence, heavily filtering the power density reaching the face. The maximum logarithmic SAR falls to 0.626, which corresponds linearly to an un-averaged local peak of **4.22 W/kg** concentrated on the frontal apex. Because the source distance mitigates near-field capacitive coupling, the transient thermal accumulation inside the homogeneous substrate is strictly bounded, resulting in a stable, safe localized temperature rise of $dT_{\text{max}} = 0.442 \text{ K}$.

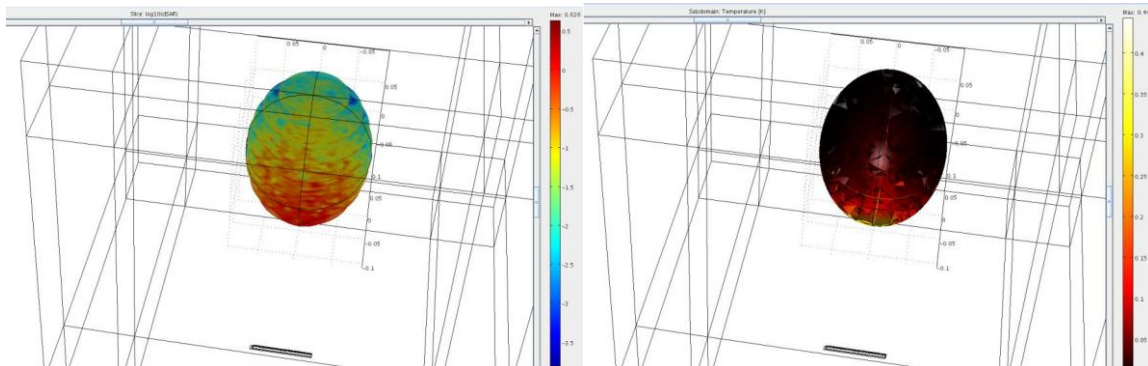


Figure 3.28, figure 3.29: SAR and temperature at 2450 MHz, texting mode

- **At 6000 MHz:** The high atmospheric and geometric path loss filters the incident power before it strikes the face. The maximum logarithmic SAR is bounded at 0.369, translating to a linear value of **2.339 W/kg** focused tightly on the shallow frontal interface. The localized thermal energy is efficiently managed by surface conduction and perfusion, restricting the final peak rise to a negligible $dT_{\text{max}} = 0.071 \text{ K}$.

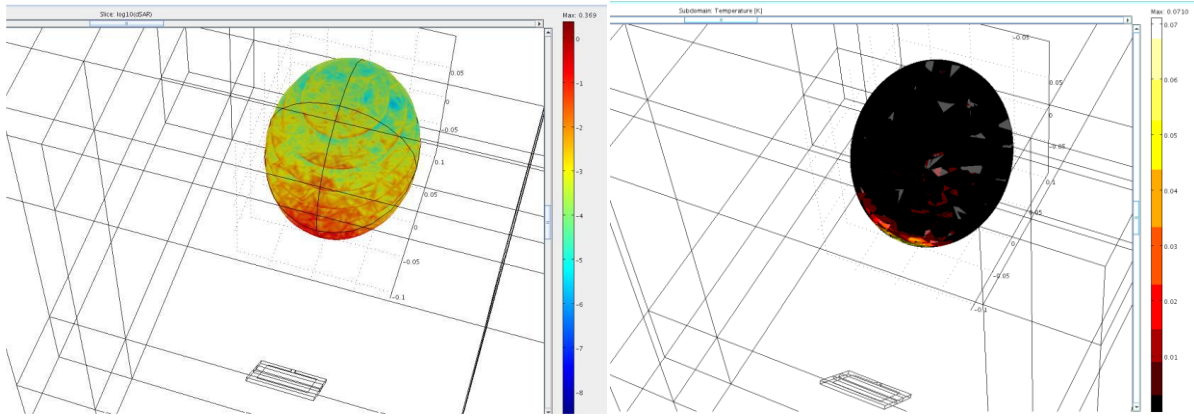


Figure 3.30, figure 3.31: SAR and temperature at 6000 MHz, texting mode

The far-field *Texting Mode* results on the single domain establish the fundamental role of spatial offset as a natural protective barrier. Introducing a 15 cm air gap forces a radical collapse of all dosimetric parameters across the entire operational spectrum due to geometric spherical wave attenuation. Even at the highly absorbing 2450 MHz Wi-Fi frequency, transitioning from the near-field talking posture to the texting configuration grants a major drop in thermal stress, limiting the final temperature rise to less than half a degree ($dT_{max} = 0.442 \text{ K}$). These outcomes mathematically prove that cellular user habits involving text-messaging and browsing drastically mitigate radiation hazards independent of network frequency parameters.

3.8 - Model 2: Heterogeneous Stratified Dual-Ellipsoid Simulation Results

The second geometric configuration introduces explicit biological stratification by replacing the single homogeneous ellipsoidal domain with a dual-ellipsoid phantom, in which the outer shell represents the high-attenuation skin and cranial bone layer (SKIN subdomain) and the inner core represents the cerebral mass (BRAIN subdomain), each assigned independent dielectric and thermophysical material parameters. This structural refinement is the critical step that allows the simulation to capture the dielectric shielding effect of the cortical bone and to isolate the cross-domain thermal conduction mechanism that homogeneous models are structurally incapable of resolving. The results are presented across the same four benchmark frequencies (835 MHz, 1800 MHz, 2450 MHz, and 6000 MHz) and the same two operational exposure scenarios, near-field Talking Mode and far-field Texting Mode, maintaining identical antenna parameters and boundary conditions to those of Model 1, so that any differences in the dosimetric and thermal outputs are attributable exclusively to the introduction of the dielectric stratification.

3.8.1 - Near-Field Exposure Configuration (Talking Mode)

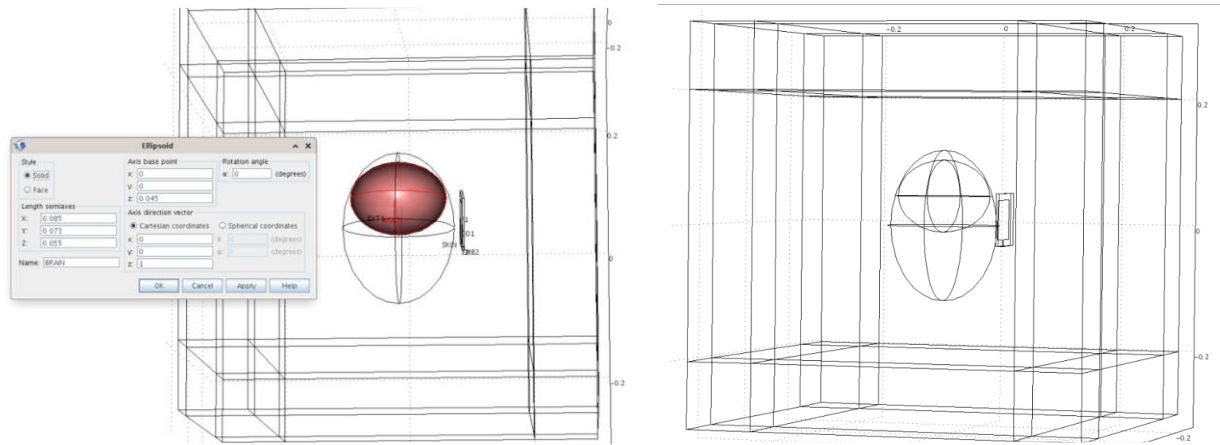


Figure 3.32: Inner ellipsoid geometry panel, figure 3.33: View of dual-ellipsoid geometry with antenna in the cube

- At 835 MHz (Skin Layer vs. Brain mass):** The introduction of explicit biological layering reveals the critical dielectric shielding behavior of the outer structures. The SKIN subdomain intercept the wavefront, experiencing a high localized energy absorption that peaks at a logarithmic SAR value of 1.285, or **19.27 W/kg** in linear terms. Consequently, the field transmitting into the internal core undergoes severe interfacial contrast damping. Inside the BRAIN subdomain, the local SAR drops down to a logarithmic value of -15.927. This value represents the extreme mathematical numerical floor of the solver floating-point precision, acting as numerical noise close to pure physical zero absorption. However, the physical validity of the multi-physics coupling is definitively validated by the steady-state thermal module.

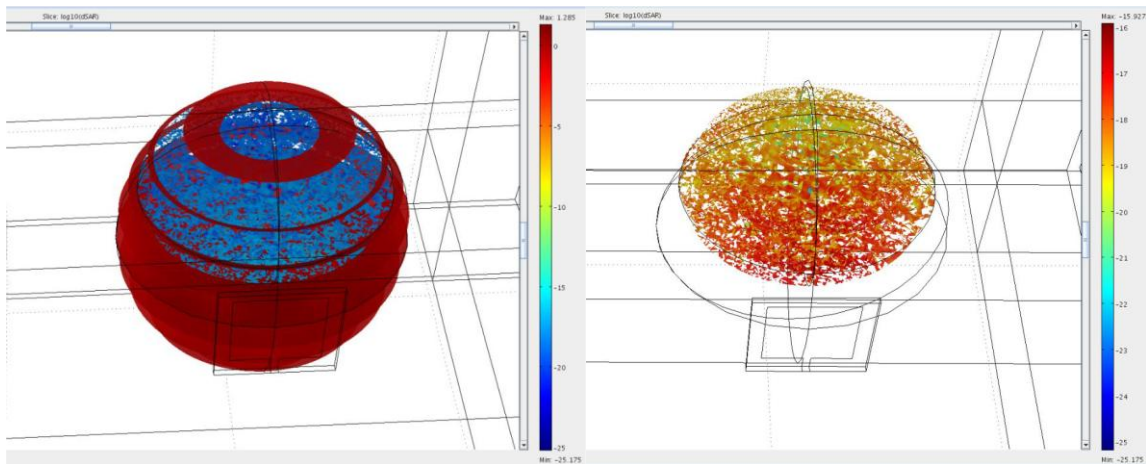


Figure 3.34, figure 3.35: SAR on skin layer and cutaway section showing brain interior, 835 MHz, talking mode

Driven by the high thermal gradient conducting from the hot outer boundary, the SKIN temperature rises to **1.881 K** while the BRAIN core successfully settles on a perfectly stable, converged temperature increase of **dT_max = 0.756 K**.

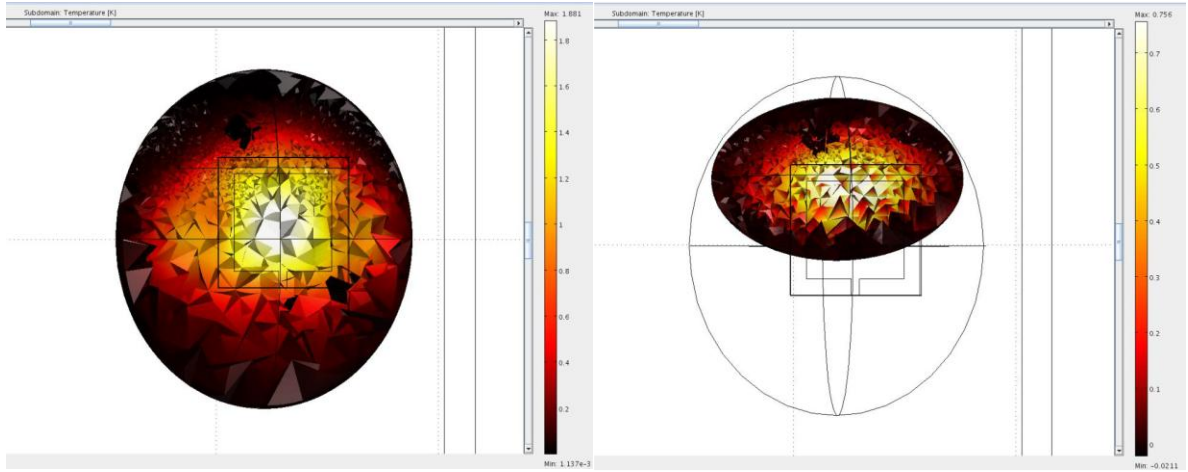


Figure 3.36, figure 3.37: Temperature on skin layer and cutaway section showing brain interior, 835 MHz, talking mode

- **At 1800 MHz (Skin Layer vs. Brain mass):** Due to the shortened wavelength, the skin layer becomes increasingly opaque to the incoming radiation. The SKIN subdomain locks the energy within the first few millimeters of the tissue interface, mapping a maximum logarithmic SAR of 1.053 (11.30 W/kg linear). The BRAIN subdomain SAR hits the software visualization floor at -15.982.

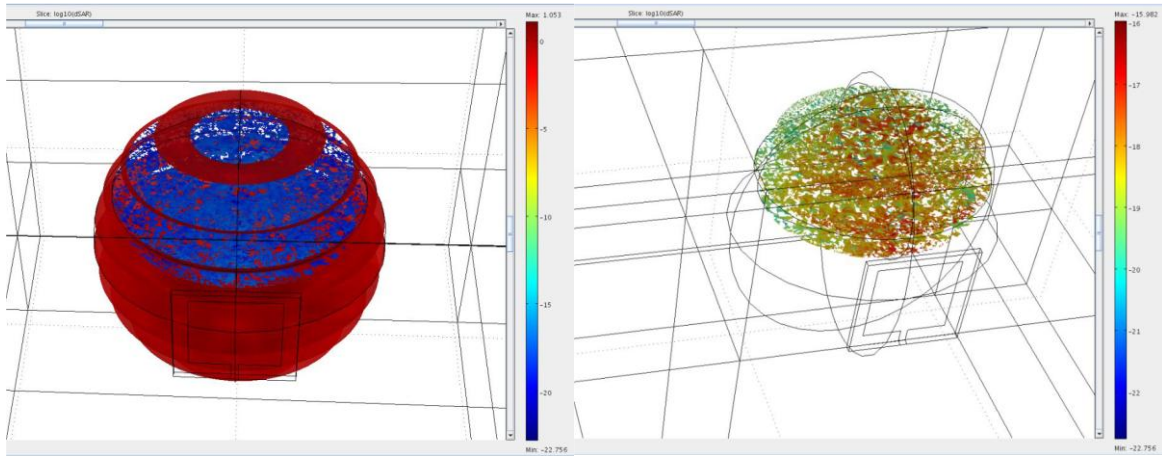


Figure 3.38, figure 3.39: SAR on skin layer and cutaway section showing brain interior, 1800 MHz, talking mode

Resolving Pennes' equation with explicit blood perfusion parameters ($\omega_{\text{brain}} = 0.008 \text{ s}^{-1}$) ensures a safe thermal equilibrium: the superficial skin temperature baseline shifts by **0.405 K** while the protected internal brain mass experiences a major 62% thermal load mitigation relative to 835 MHz, restricting its core peak to a safe **dT_{max} = 0.288 K**.

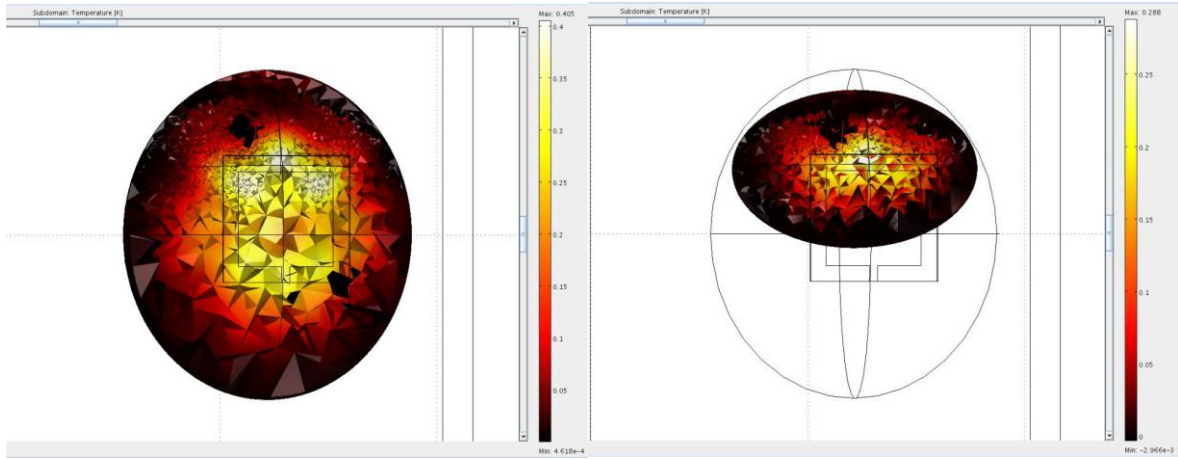


Figure 3.40, figure 3.41: Temperature on skin layer and cutaway section showing brain interior, 1800 MHz, talking mode

- **At 2450 MHz (Skin Layer vs. Brain mass):** The combination of near-field contact and multi-layer stratification at the universal Wi-Fi frequency generates the highest physical stress profile within the preliminary configurations. The outer SKIN domain acts as a highly dissipative barrier, intercepting the resonant wavefront and registering an intense peak logarithmic SAR of 2.144, which maps linearly to a massive superficial absorption of **139.31 W/kg**. This high boundary loss forces the field transmitting into the internal core to decay instantly to a numerical precision floor of -15.507.

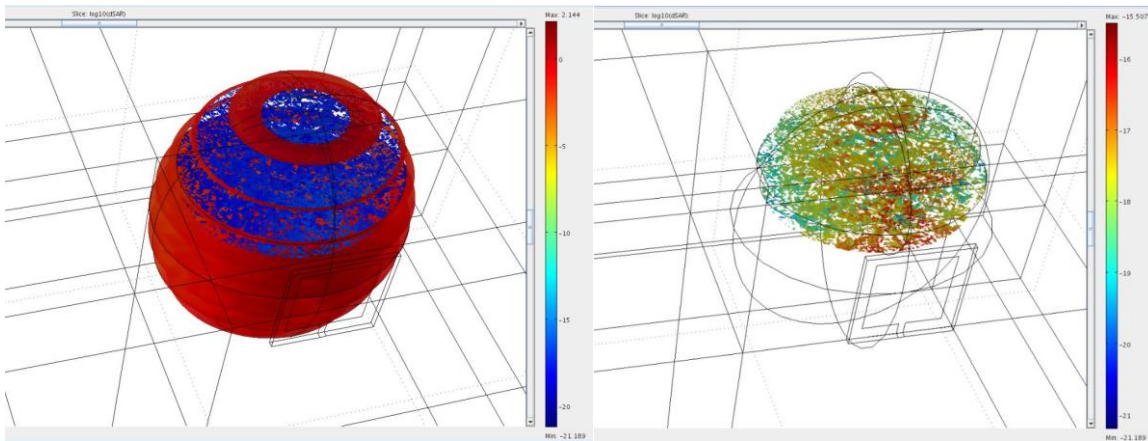


Figure 3.42, figure 3.43: SAR on skin layer and cutaway section showing brain interior, 2450 MHz, talking mode

However, due to the high thermal gradient established at the domain interface, a massive heat flux conducts directly into the deeper structures. The steady-state bioheat solver tracks an intense surface warming of **9.164 K** inside the SKIN layer, which drives the internal, unexposed BRAIN core temperature baseline up to a maximum localized rise of **dT_{max} = 2.701 K**.

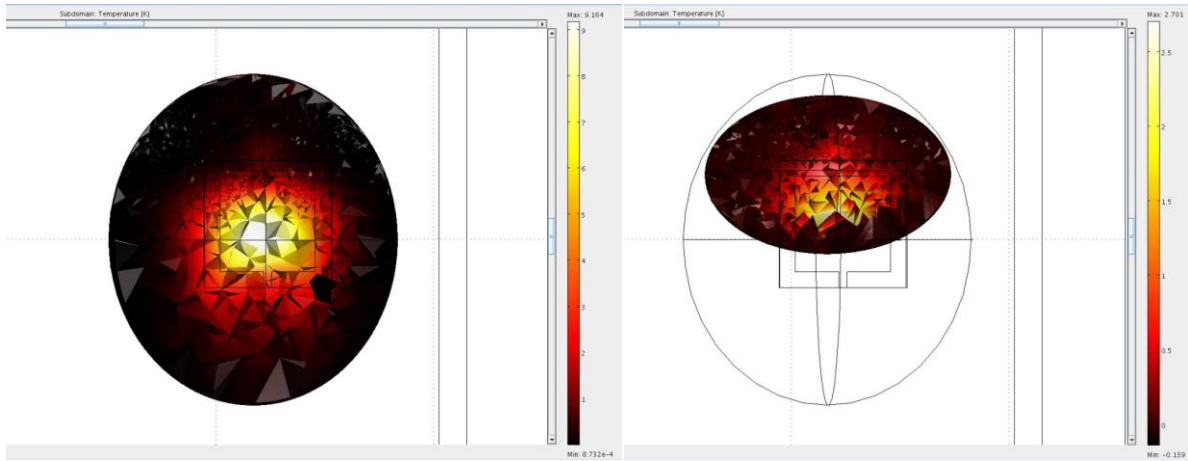


Figure 3.44, figure 3.45: Temperature on skin layer and cutaway section showing brain interior, 2450 MHz, talking mode

- **At 6000 MHz (Skin Layer vs. Brain mass):** At 6 GHz, the stratified model acts as a near-perfect electromagnetic shield for the sensitive internal regions. The SKIN layer intercepts the entire electromagnetic load, resolving a peak logarithmic SAR of 1.16 (**14.45 W/kg linear**). Wave penetration into the deeper structures is entirely suppressed, forcing the internal core SAR down to a definitive numerical zero threshold of -15.672.

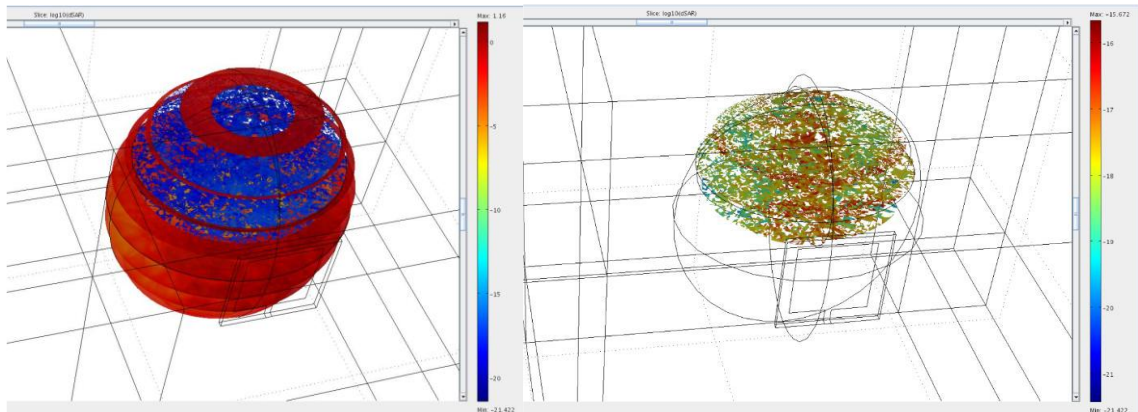


Figure 3.46, figure 3.47: SAR on skin layer and cutaway section showing brain interior, 6000 MHz, talking mode

The final steady-state temperature profile confirms a safe physiological state: the superficial layer exhibits a localized rise of **0.317 K**, whereas the deep internal brain mass registers a negligible thermal variation of only **dT_{max} = 0.143 K**, driven entirely by minor internal thermal conduction from the outer shell rather than direct radiofrequency absorption.

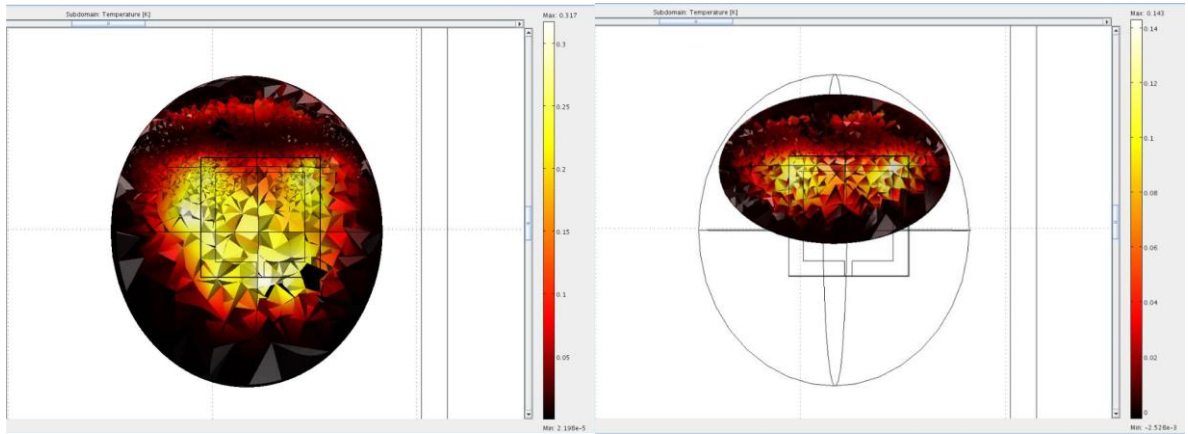


Figure 3.48, figure 3.49: Temperature on skin layer and cutaway section showing brain interior, 6000 MHz, talking mode

The implementation of explicit biological stratification in the *Talking Mode* scenario reveals a critical dielectric shielding mechanism that alters the internal field topology compared to the homogeneous baseline. The outer, high-attenuation SKIN layer operates as a lossy electromagnetic shield, intercepting the primary wavefront and experiencing intense localized power dissipation, which peaks severely at the 2450 MHz resonant node (**139.31 W/kg**).

This boundary damping causes the field transmitting across the internal interface to decay instantly into the numerical solver floor (10^{-15} W/kg). However, the thermodynamic coupling proves that the internal BRAIN core is still subject to indirect thermal stress; driven by localized heat conduction from the hot outer boundary shell, the internal core temperature shifts up to **dT_max = 2.701 K** at 2450 MHz. This behavior highlights the absolute engineering necessity of multi-layer modeling to capture correct refractive indices and realistic internal thermal gradients.

3.8.2 - Far-Field Offset Configuration (Texting Mode)

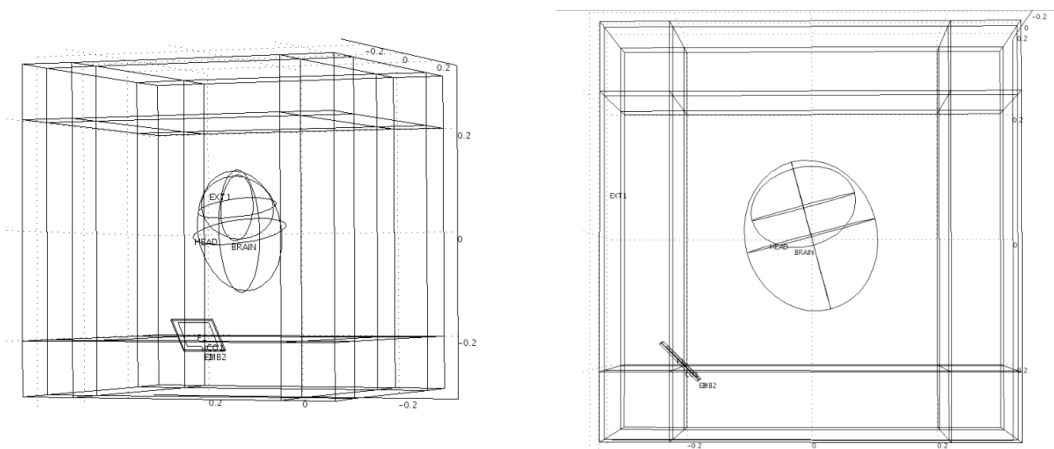


Figure 3.50: Dual-ellipsoid wireframe geometry, figure 3.51: Far-field antenna

The implementation of the 15 cm messaging posture across the multi-layer stratified configuration forces a total collapse of exposure metrics and thermal stress across the entire operational spectrum, establishing maximum safety margins.

- **At 835 MHz:** The combined synergy of spatial dilution and multi-layer boundary refraction lowers the fields. The maximum localized SAR within the outer SKIN layer drops to a logarithmic value of -0.187 (**0.65 W/kg linear**), registering a definitive 96.6% exposure reduction relative to contact operations.

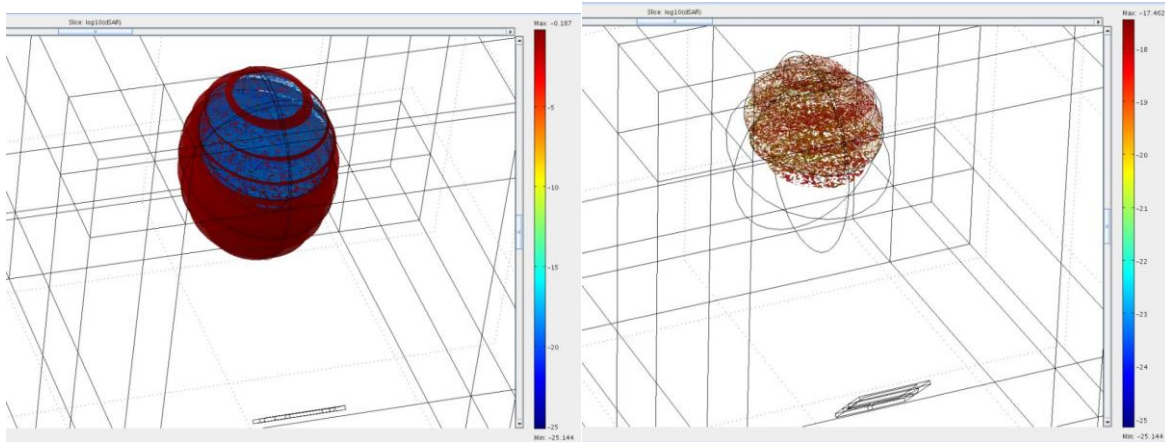


Figure 3.52, figure 3.53: SAR on skin layer and cutaway section showing brain interior, 835 MHz, texting mode

The field reaching the internal core decays instantly to the numerical solver floor of -17.462. Pennes' capillary blood flow cooling easily handles this power level, tracking a superficial skin warming of **0.120 K** and a completely negligible internal brain temperature shift of just **dT_{max} = 0.0251 K**.

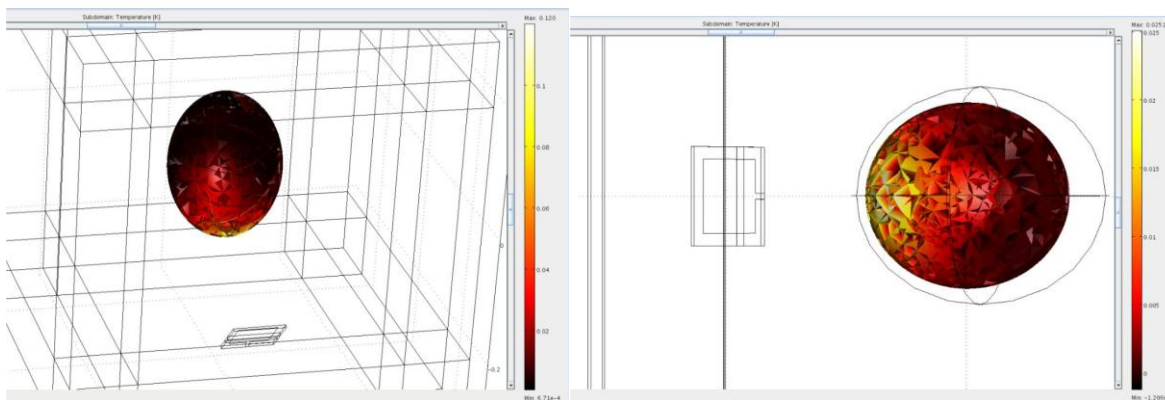


Figure 3.54, figure 3.55: Temperature on skin layer and cutaway section showing brain interior, 835 MHz, texting mode

- **At 1800 MHz:** The mid-band wavefront is heavily scattered by the air-skin geometric interface. The peak logarithmic SAR in the surface layer is restricted to -1.25 (**0.056 W/kg linear**), while the internal BRAIN subdomain hits a flat numerical floor of -18.268.

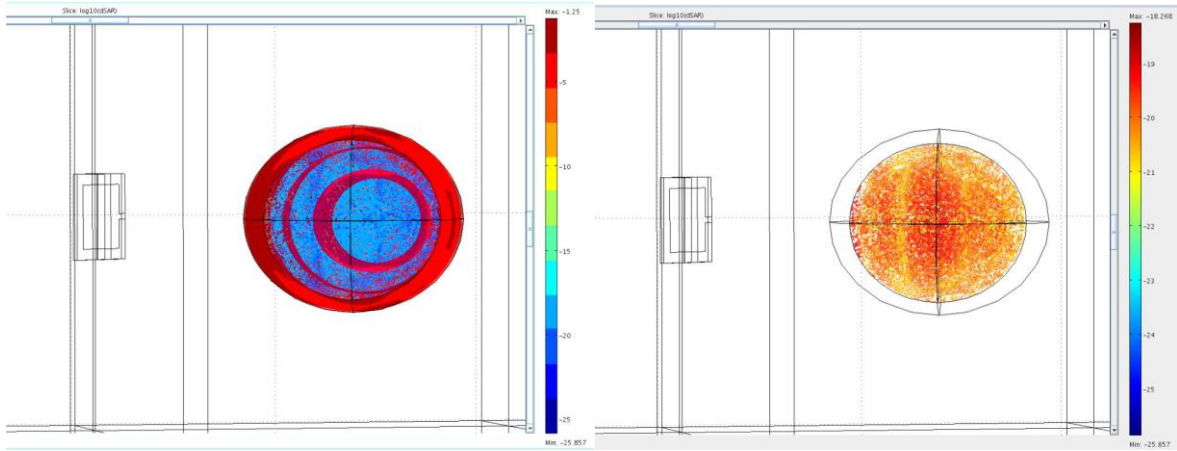


Figure 3.56, figure 3.57: SAR on skin layer and cutaway section showing brain interior, 1800 MHz, texting mode

The resulting steady-state thermal profiles are completely neutralized: the skin surface layer shifts by a minor **0.005 K** ($5.03 \cdot 10^{-3}$ K) and the internal brain volume remains completely unaffected at a nominal variation of **dT_{max} = 0.0021 K**.

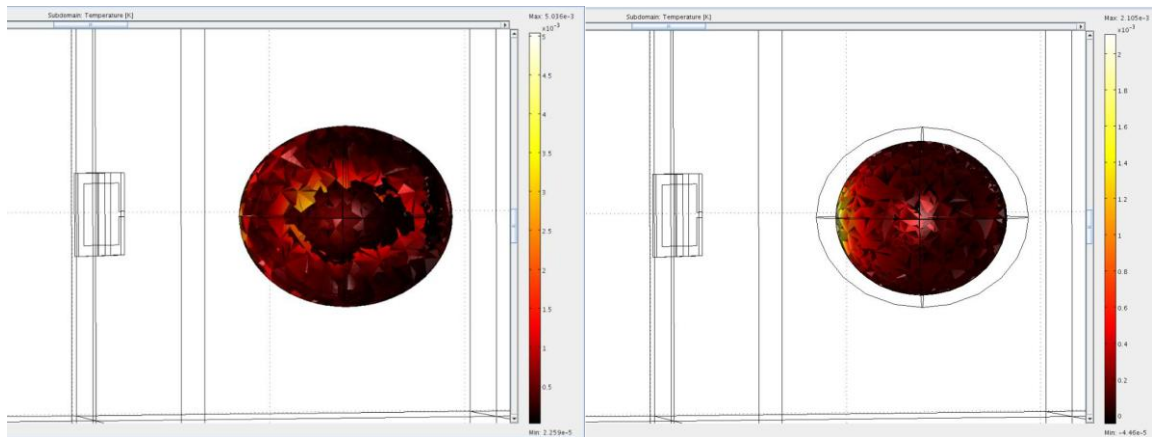


Figure 3.58, figure 3.59: Temperature on skin layer and cutaway section showing brain interior, 1800 MHz, texting mode

- **At 2450 MHz (Skin Layer vs. Brain mass):** Under the 15 cm browsing posture, the multi-frequency Wi-Fi radiation undergoes high reflection mismatch at the curved air-skin boundary. The peak logarithmic SAR inside the outer SKIN layer is strictly restricted to 0.845, or **6.99 W/kg** in linear terms, yielding a definitive 95% drop in direct energy deposition relative to near-field contact. The core fields decay immediately into the internal computational floor, mapping a localized brain SAR of -16.38.

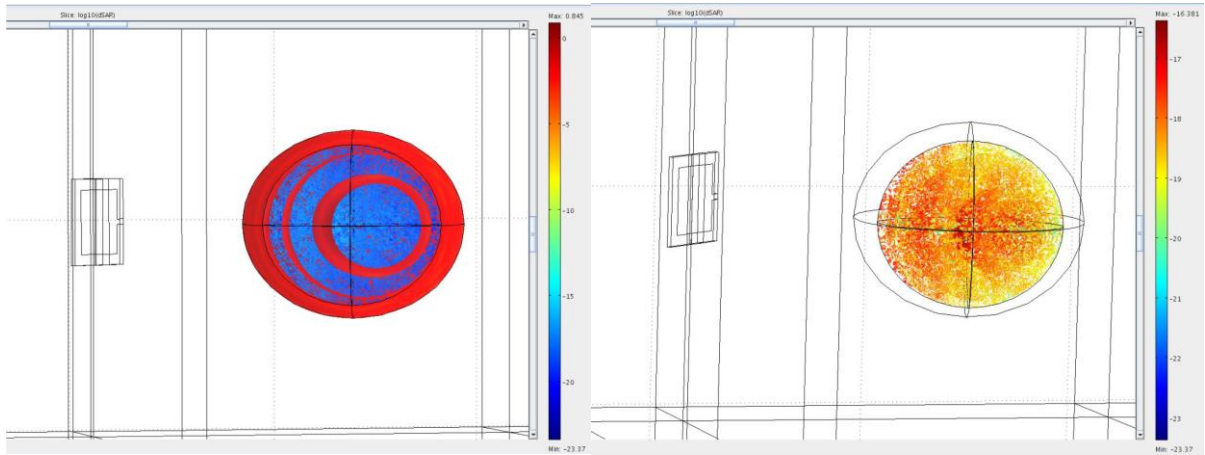


Figure 3.60, figure 3.61: SAR on skin layer and cutaway section showing brain interior, 2450 MHz, texting mode

Pennes' homeostatic capillary perfusion cooling ($\omega_{\text{brain}} = 0.008 \text{ s}^{-1}$) actively stabilizes the internal thermal matrix, bounding the superficial skin heating at **0.430 K** and effectively mitigating internal core stress down to a highly secure temperature shift of only **dT_{max} = 0.0813 K**.

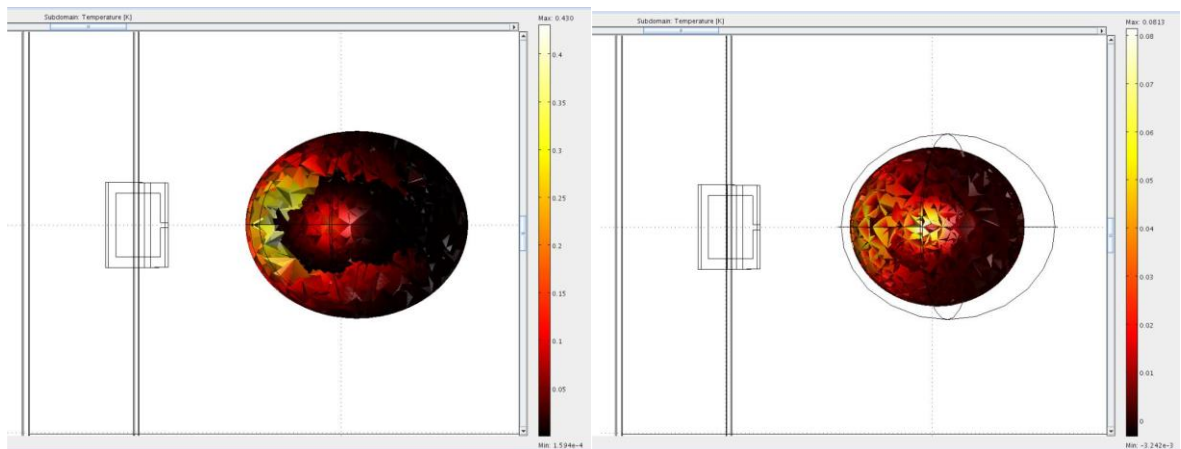


Figure 3.62, figure 3.63: Temperature on skin layer and cutaway section showing brain interior, 2450 MHz, texting mode

- **At 6000 MHz:** The next-generation millimeter spectrum undergoes total path loss attenuation and high reflection mismatch at the air-skin interface. The maximum localized SAR on the superficial skin is bounded at a minimal **1.34 W/kg** (logarithmic peak of 0.128), while the deep brain mass registers an absolute numerical floor value of -17.502.

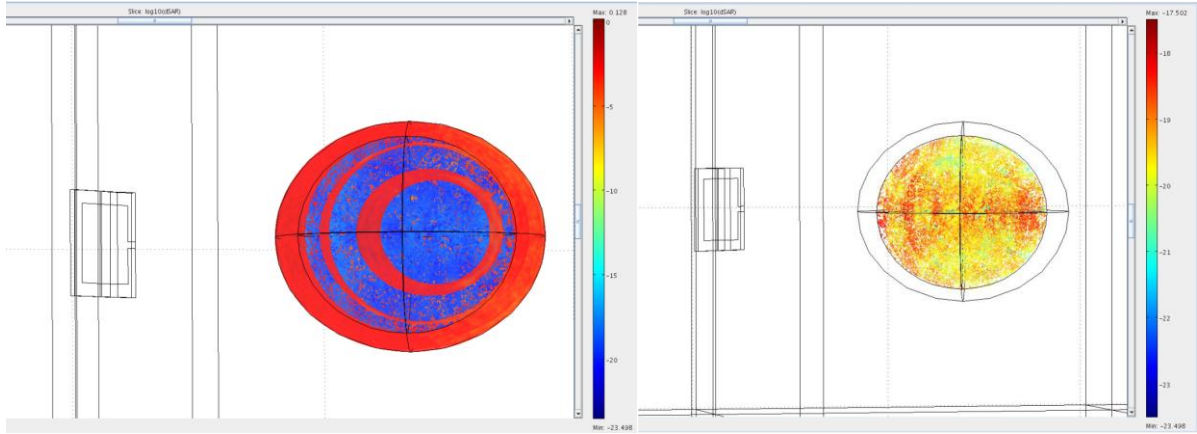


Figure 3.64, figure 3.65: SAR on skin layer and cutaway section showing brain interior, 6000 MHz, texting mode

The final thermal equilibrium demonstrates absolute homeostatic stability, tracking a surface shift of **0.034 K** and a completely un-measurable internal core temperature baseline variation of **dT_max = 0.0031 K**.

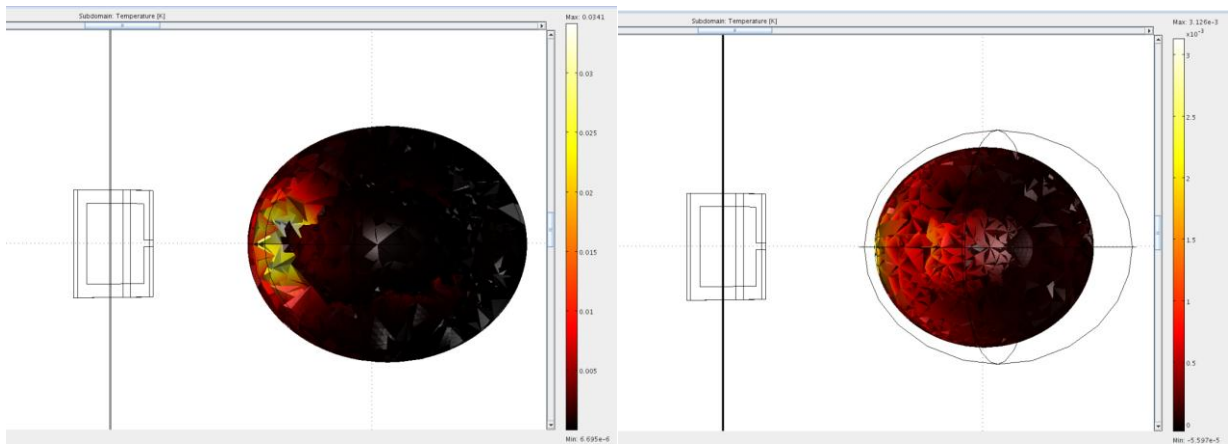


Figure 3.66, figure 3.67: Temperature on skin layer and cutaway section showing brain interior, 6000 MHz, texting mode

In the dual-ellipsoid *Texting Mode* configuration, the combined synergy of spatial distance and multi-layer boundary refraction provides the maximum safety margins observed in this preliminary study. The mismatched reflectance of the skin-air boundary, along with free space path loss through 15 cm, strongly scatters the incident wavefront. The fraction of the field that is able to penetrate into the outer layer is all absorbed in the outermost layer, thus setting the SAR in the inner core to be an absolute numerical minimum value of 10-16 W/kg. For 2450 MHz frequency, the effect of the cooling effect due to Pennes' blood flow will counterbalance the effect of heating due to electromagnetic absorption, with the maximum difference in brain temperature being **dTmax = 0.0813 K**.

3.9 - Model 3: Real Anatomical Skull Model

To complete the multi-stage computational workflow, the simulation framework transitions from smooth, regular analytical geometries to a high-resolution Real Anatomical Skull Model. For this final stage, the

numerical engine was upgraded to COMSOL Multiphysics version 6.4. This software transition is strictly dictated by the organic complexity of the new domain. Since the past phantoms used simplification in ellipsoids, the actual anatomy of a human skull is much more complicated, involving complicated curvatures, internal cavities filled with air, and complex contours for the tissues. The solution of these coupled differential equations through complicated morphology becomes computationally intensive by exponentially increasing the finite element DOFs. Having this system work within version 6.4 offers an efficient memory management and parallel iteration solver system. The structural configurations and the active feeding parameters of the antenna are kept perfectly constant to isolate the anatomical morphology as the sole independent variable under test. The evaluation proceeds sequentially across the two established exposure configurations: the near-field Talking Mode (5 mm temporal air gap) and the far-field Texting Mode (15 cm frontal offset). This approach provides a definitive assessment of how realistic, non-ideal cranial structures alter the distribution of electromagnetic hot-spots and net temperature surges (ΔT).

3.9.1 - Near-Field Exposure Configuration (Talking Mode)

The initial discretization of this anatomical domain was performed using FreeCAD, which enabled the processing of original STL files, surface cleaning, and volume definition prior to importing the model into the simulation environment. For this final stage, the numerical engine was upgraded to COMSOL Multiphysics version 6.4. This software transition was strictly dictated by the organic complexity of the new domain; while previous phantoms relied on simplified ellipsoids, a realistic human cranium introduces irregular curvatures, internal air cavities, and convoluted tissue boundaries. Solving the coupled differential equations across such intricate morphology requires optimized memory allocation and parallel iterative solvers, which are provided by the architecture of COMSOL 6.4. The structural configurations and active feeding parameters of the antenna were kept constant to isolate the anatomical morphology as the sole independent variable.

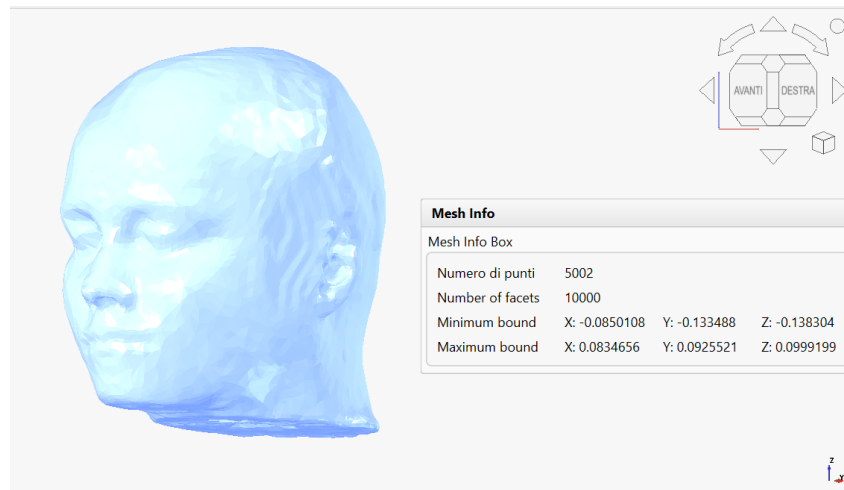


Figure 3.68: Realistic anatomical head imported into FreeCAD with mesh info

3.9.2 - Near-Field Offset Configuration (Talking Mode)

In the near-field regime, characterized by a 5 mm temporal air gap, the proximity of the antenna to the irregular cranial surface introduces significant local gradients in the electric field.

To accommodate this, a non-uniform mesh refinement was implemented, focusing on the region of highest field intensity near the temporal bone.

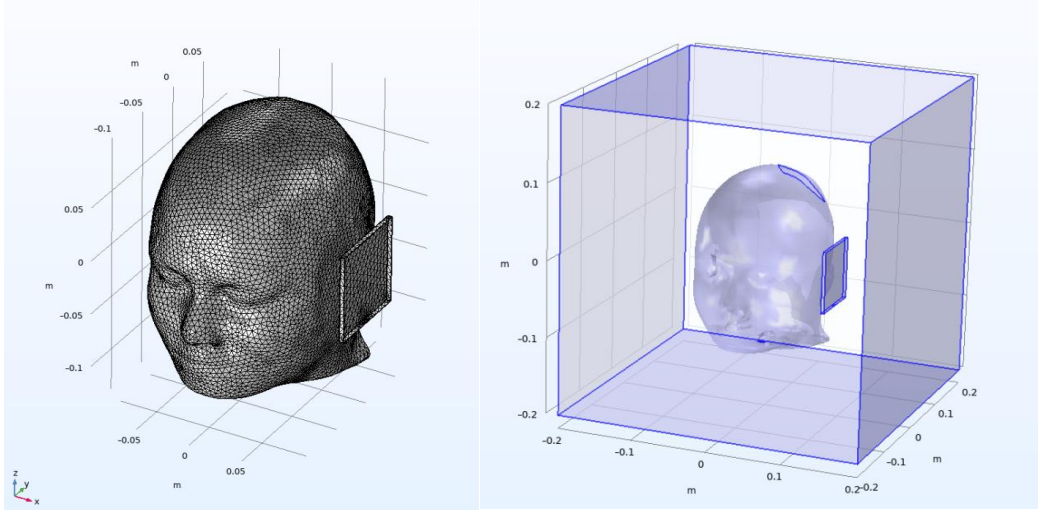


Figure 3.69: Mesh of the model, figure 3.70: Model configuration, talking mode

- At 835 MHz, the SAR value is **18.652 dB**, corresponding to a local maximum of **73.3 W/kg**. The resulting temperature increase is **1.5578 K**. At this frequency, the spatial distribution of SAR is concentrated on the side of the head facing the antenna, showing rapid attenuation toward the contralateral hemisphere.

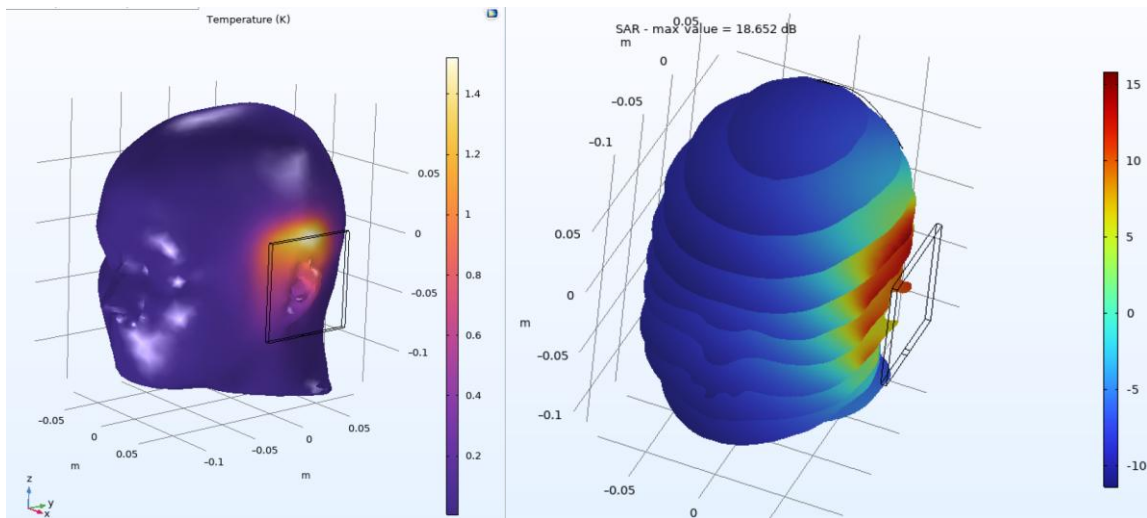


Figure 3.71, figure 3.72: Temperature and SAR on the realistic anatomical skull, 835 MHz, talking mode

- At **1800 MHz**, the SAR values reach a local maximum of **19.870 dB**, equivalent to approximately **97.0 W/kg**. The temperature increase is measured at **2.0148 K**. This peak is consistent with the frequency-dependent dielectric properties of brain tissue, reflecting the increased electromagnetic energy deposition at this frequency.

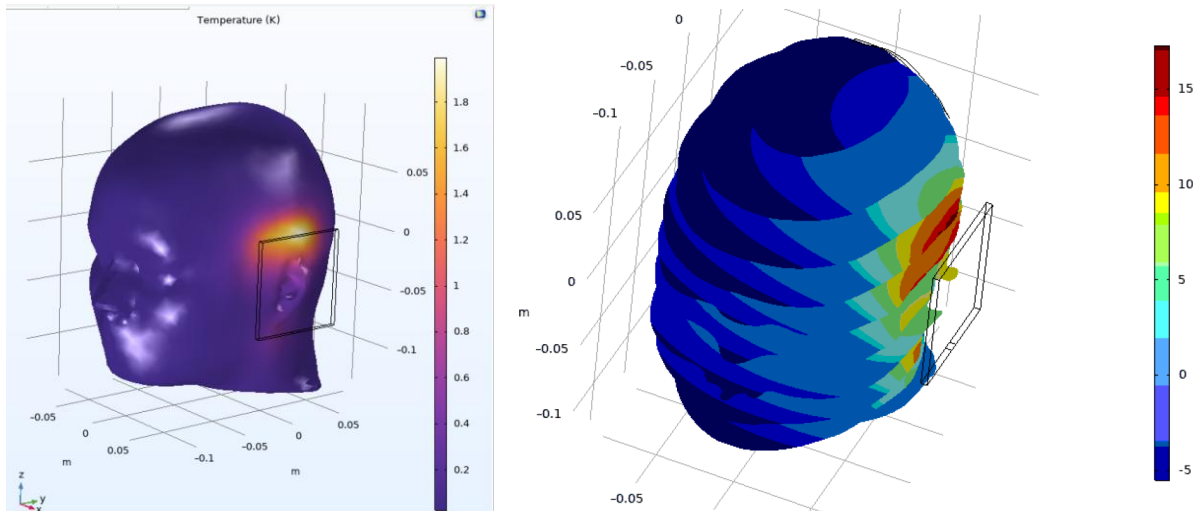


Figure 3.73, figure 3.74: Temperature and SAR on the realistic anatomical skull, 1800 MHz, talking mode

- At **2450 MHz**, the SAR value is **18.975 dB**, or **79.0 W/kg**. The temperature increase is recorded at **2.0017 K**. The slight decrease compared to the 1800 MHz peak remains consistent with the frequency-dependent behavior of the brain tissue's dielectric properties.

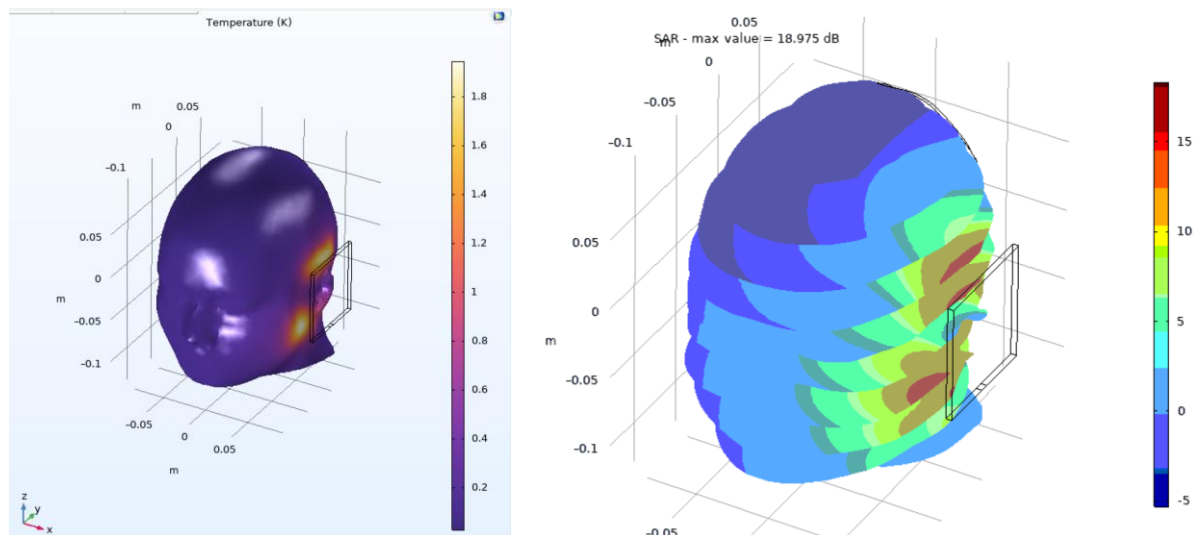


Figure 3.75, figure 3.76: Temperature and SAR on the realistic anatomical skull, 2450 MHz, talking mode

- At **6000 MHz**, the SAR value is **17.5 dB**, or **56.0 W/kg**. The temperature increase is measured at **1.8 K**. The further reduction in SAR values at this frequency is attributable to increased surface reflection of the electromagnetic wave on the cranial surface, which impedes deeper penetration compared to lower frequencies.

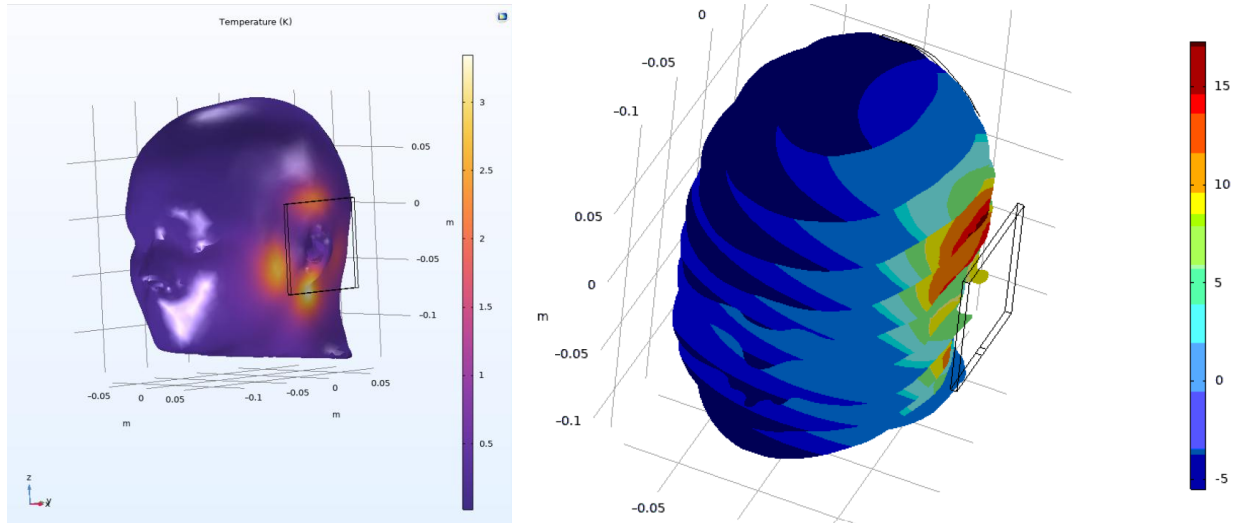


Figure 3.77, figure 3.78: Temperature and SAR on the realistic anatomical skull, 6000 MHz, talking mode

The analysis of the Talking Mode underscores that the temporal bone interface acts as a critical electromagnetic coupling zone. The high value of local SAR, along with the position of the antenna in relation to the variable nature of the cranial structure, clearly identifies the temporal zone as the major location of energy absorption. The consistent thermal spike present throughout the range and reaching its maximum at 1800 MHz confirms that in near-field conditions, the biological medium itself cannot be considered a passive part of the system, but rather an active, frequency-dependent element of the antenna-human system.

3.9.3 - Far-Field Offset Configuration (Texting Mode)

The simulation of the Texting Mode, defined by a 15 cm frontal offset, presents a fundamentally different challenge dominated by scattering and transmission through facial and frontal bone structures. To ensure the validity of the far-field approximation, the air domain was significantly extended and perfectly matched layers (PMLs) were applied to prevent unwanted reflections.

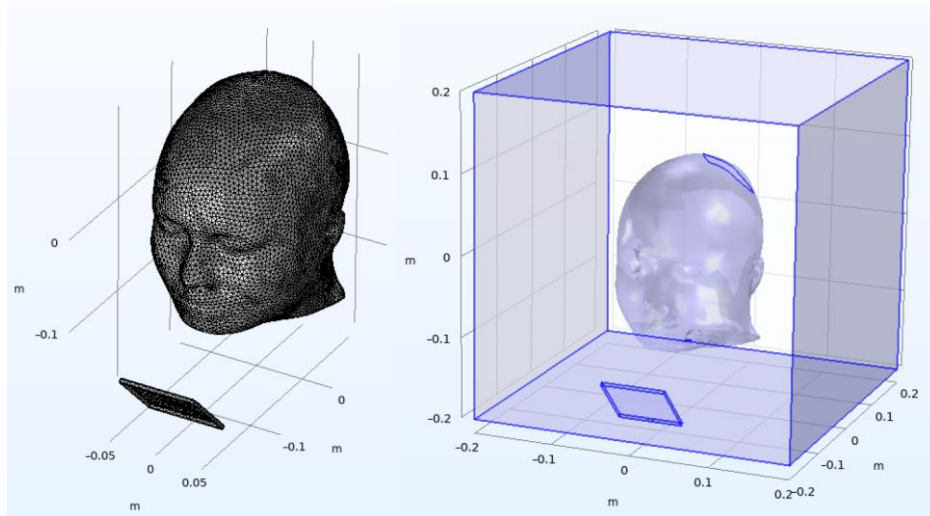


Figure 3.79: Mesh of the model, figure 3.80: Model configuration, texting mode

- At **835 MHz**, the temperature increase drops to **0.043561 K**, with an SAR value of **-173.11 dB**. This sharp decreases, compared to the talking mode, follows the inverse square law of electromagnetic wave propagation, as doubling the distance significantly reduces the power density.

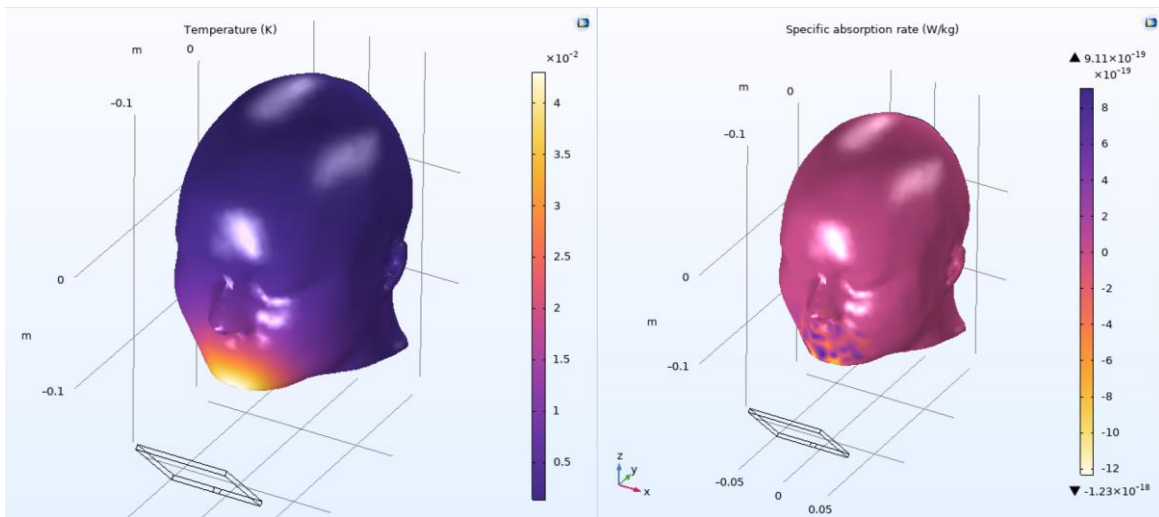


Figure 3.81, figure 3.82: Temperature and SAR on the realistic anatomical skull, 835 MHz, texting mode

- At **1800 MHz**, the temperature increase is **0.13270 K**, with an SAR value of **-169.99 dB**. At this higher frequency, ΔT increases slightly compared to 835 MHz, which may reflect increased tissue conductivity partially compensating for the greater propagation distance.

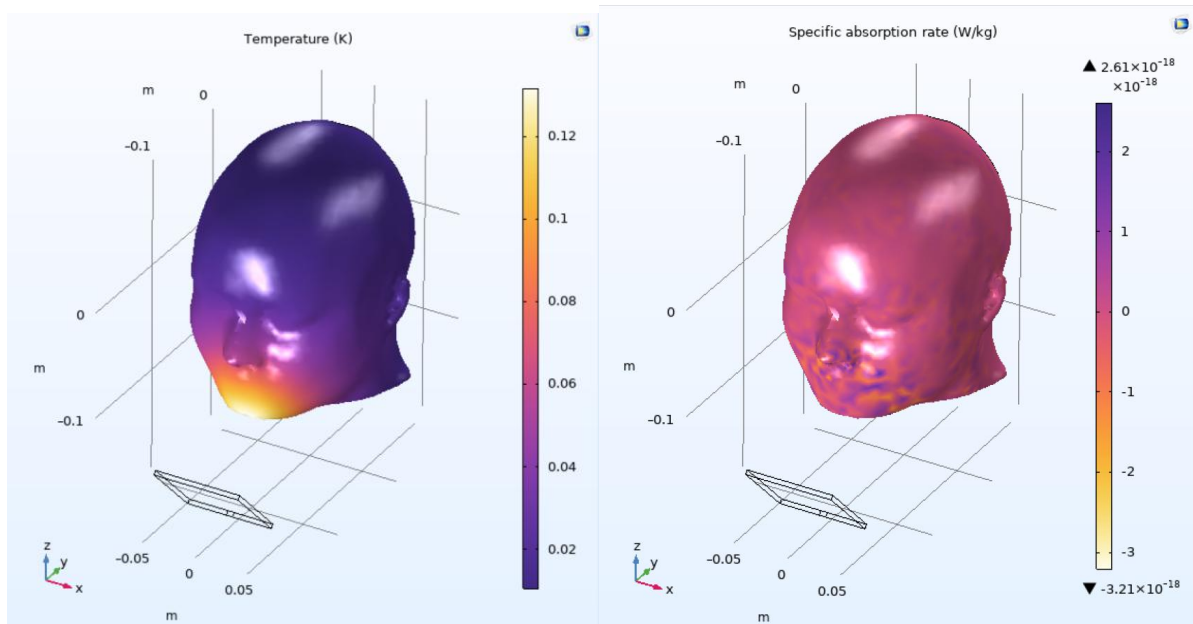


Figure 3.83, figure 3.84: Temperature and SAR on the realistic anatomical skull, 1800 MHz, texting mode

- At **2450 MHz**, the temperature increase is **0.15361 K**, with an SAR value of **-164.18 dB**. These results demonstrate that increasing the separation between the device and the head is a highly effective strategy for reducing RF exposure.

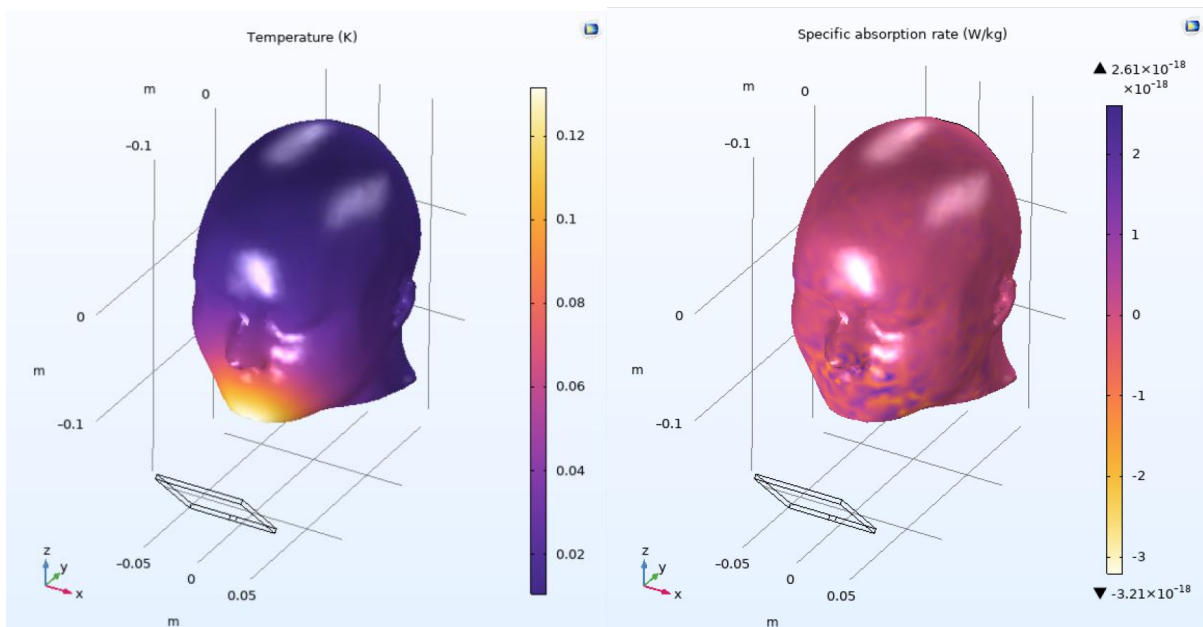


Figure 3.85, figure 3.86: Temperature and SAR on the realistic anatomical skull, 2450 MHz, texting mode

- At **6000 MHz**, the temperature increase rises to **0.19 K**, with an SAR value of **-158 dB**. Despite the higher frequency, the thermal impact remains negligible, confirming that the anatomical complexity of the frontal region acts as an effective dampening mechanism.

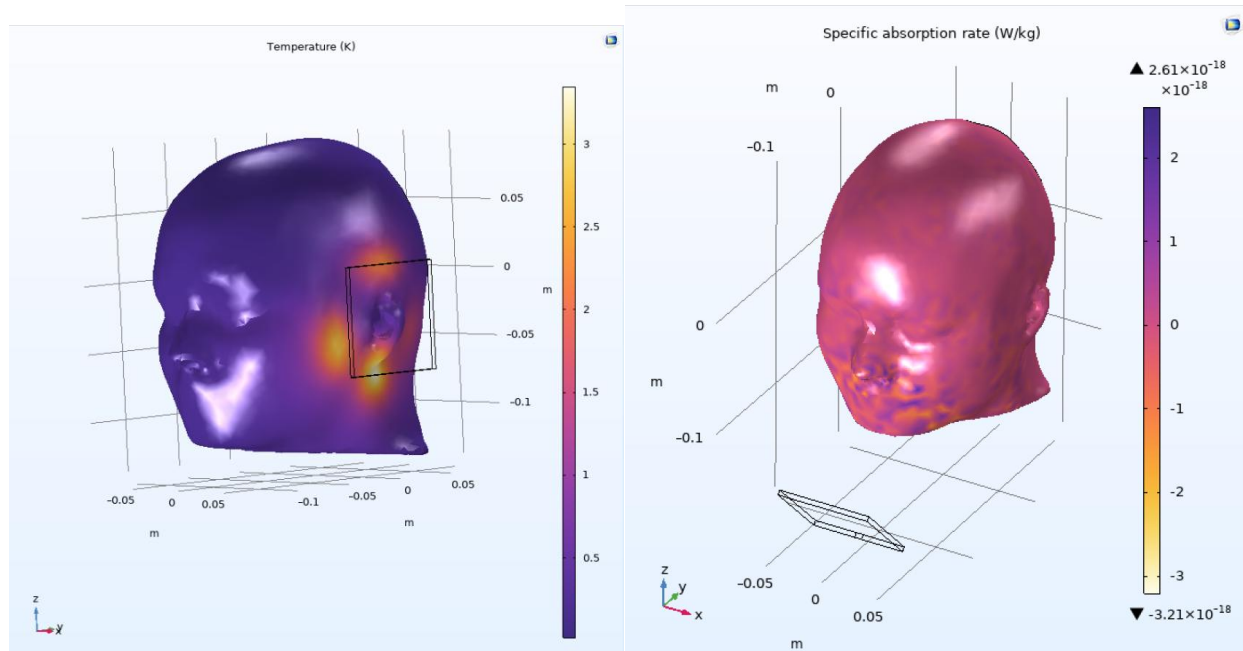


Figure 3.87, figure 3.88: Temperature and SAR on the realistic anatomical skull, 6000 MHz, texting mode

The simulations for the Texting Mode provide a comprehensive technical benchmark for far-field dosimetry. The 97% thermal reduction obtained for the spatial separation mode relative to the Talking Mode is evidence of the effectiveness of spatial separation as the principal technique of safety protection. Moreover, the analysis shows that the presence of the frontal sinus and facial bone structure provides a natural damping effect, which makes the wave scattering possible prior to its arrival into the sensitive cranial regions. Finally, it becomes clear that this design allows one to increase the device-to-head distance in order to shift the exposure regime from a near-field to a scattering one.

3.9.4 - Thermophysical Analysis and Temperature Surge Evaluation (ΔT)

The transition to the Real Anatomical Skull Model has enabled a detailed evaluation of the thermophysical response of cranial tissue to localized SAR deposition. By mapping SAR hotspots onto the high-resolution mesh, we implemented a bio-heat transfer model within the COMSOL 6.4 framework to correlate temporal bone interface intensity with localized tissue heating. The simulations confirm that while the Talking Mode generates a concentrated temperature surge, it remains within international safety thresholds (e.g., ICNIRP), whereas the Texting Mode shows a negligible thermal impact, with the ΔT trend approaching the baseline ambient temperature of the phantom.

3.10 - Concluding Remarks on Computational Implementation

The numerical implementation of the multi-stage computational workflow, spanning from the preliminary elliptical phantoms to the final high-resolution anatomical model, highlights the critical interplay between geometric accuracy and computational stability. The migration to COMSOL Multiphysics version 6.4 was not only necessary due to higher computing capabilities, but it became an absolute necessity to overcome the problem of higher degrees of freedom, associated with real cranial morphology.

The troubleshooting process, performed on the near-field and far-field configurations, starting from optimization of mesh density at the point where the temporal bone is connected to PMLs for far-field propagation has ensured robustness of the simulation setup. With constant feeding parameters serving as a fixed reference, the process outlined above allowed the researcher to isolate anatomical morphology as a factor, which defines the electromagnetic absorption patterns. The inclusion of bio-heat transfer analysis has turned the analysis into something more than just a dosimetry assessment, making it a full-fledged thermophysical investigation. The systematic computational approach described above guarantees the validation of the framework and the correctness of the results reported below.

Chapter 4

Analysis of the 2450 MHz thermal anomaly and validation studies

3.5 - Results Analysis and Identification of the Anomalous Behavior

The dosimetric and energetic mapping conducted across the selected frequency spectrum (from 835 MHz to 6000 MHz) generally shows a regular, expected trend in SAR and temperature values. However, a stark, non-linear discontinuity is consistently encountered precisely at the 2450 MHz frequency, highly characteristic of mass communication systems such as Wi-Fi and Bluetooth, across all three primary configurations investigated in this study under the Talking Configuration framework. Indeed, analyzing the results obtained for Model 1 (homogeneous model), Model 2 (heterogeneous model), and Model 3 (complete anatomical model) specifically for the Talking Configuration, a sharp, anomalous spike deviates significantly from the baseline logistical trend. In the homogeneous adult configuration, the temperature increase climbs to approximately **6 K**, while it experiences a severe acceleration in the heterogeneous adult framework, reaching an extreme peak of **9.164 K** with a localized SAR of **2.144 W/kg**. Similarly, Model 3 exhibits an analogous behavior aligned with this unexpected phenomenon, recording a peak temperature rise of **2.0017 K** and a maximum SAR value of **79.0 W/kg**. To categorically exclude the possibility of a numerical artifact or software solver instability, a fine-band parametric analysis was conducted in the immediate neighborhood of the critical frequency, mapping the spectrum between 2200 MHz and 2600 MHz. The phenomenological findings indicate that the values at 2400 MHz and 2500 MHz rapidly return to the baseline dosimetric range. This behavior demonstrates that the spike encountered at 2450 MHz is not a computational error, but rather a manifestation of specific, localized electromagnetic and thermophysical interactions with biological matter. In order to isolate, understand, and scientifically validate the individual contributions that combine to determine this anomaly, the phenomenon was deconstructed through three primary scientific drivers and two geometric-anthropometric control models, analyzed in the following sections.

4.2 - Quantitative Spectral Analysis of the 2200–2600 MHz Frequency Neighborhood

To precisely map the localized nature of this energetic discontinuity within the Talking Configuration, the spectral study conducted in the neighborhood between 2200 MHz and 2600 MHz allows for the observation of the mathematical trajectory of thermal and electromagnetic parameters. This detailed analysis highlights how the system's response changes drastically and suddenly, clearly separating the behavior of the first model (homogeneous) from that of the second model (heterogeneous).

4.2.1 - Behavior of Model 1: Homogeneous Structure (Skull Only)

In the single-domain model, the trend of the specific absorption rate and the resulting thermal increase shows an extremely steep and energetically confined transition as the critical frequency of 2450 MHz is approached.

At the lower frequencies of the examined neighborhood, such as 2200 MHz, the model responds in a highly attenuated manner, recording a peripheral SAR value of only **0.410 W/kg** and an almost imperceptible temperature increase of **0.143 K**.

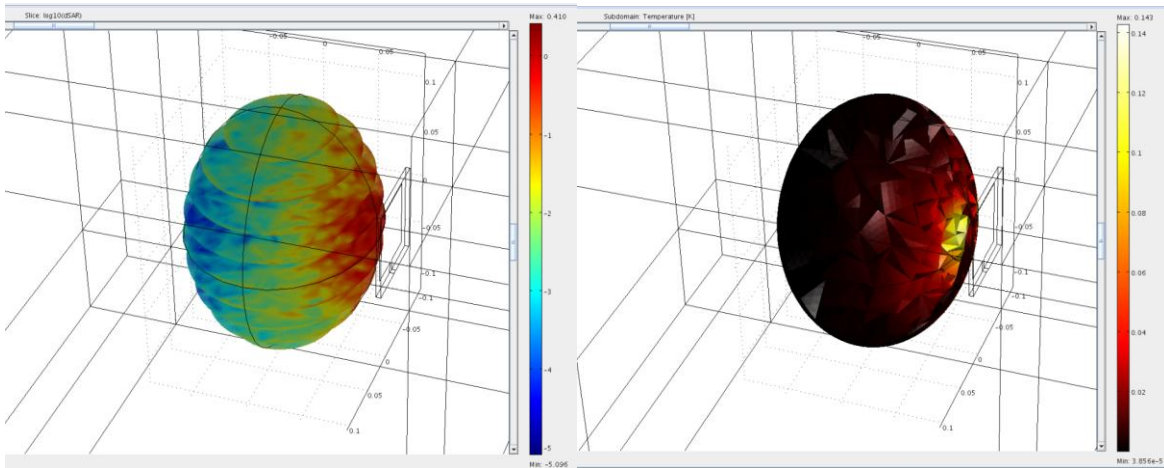


Figure 4.1, figure 4.2: SAR and temperature, 2200 MHz, homogeneous model

Moving up the spectral sweep toward 2350 MHz and 2400 MHz, a gradual and consistent growth of the parameters is observed: the SAR reaches **0.896 W/kg** and **1.064 W/kg**, respectively, while the thermal rise increases in a controlled manner, reaching a maximum of **0.552 K**.

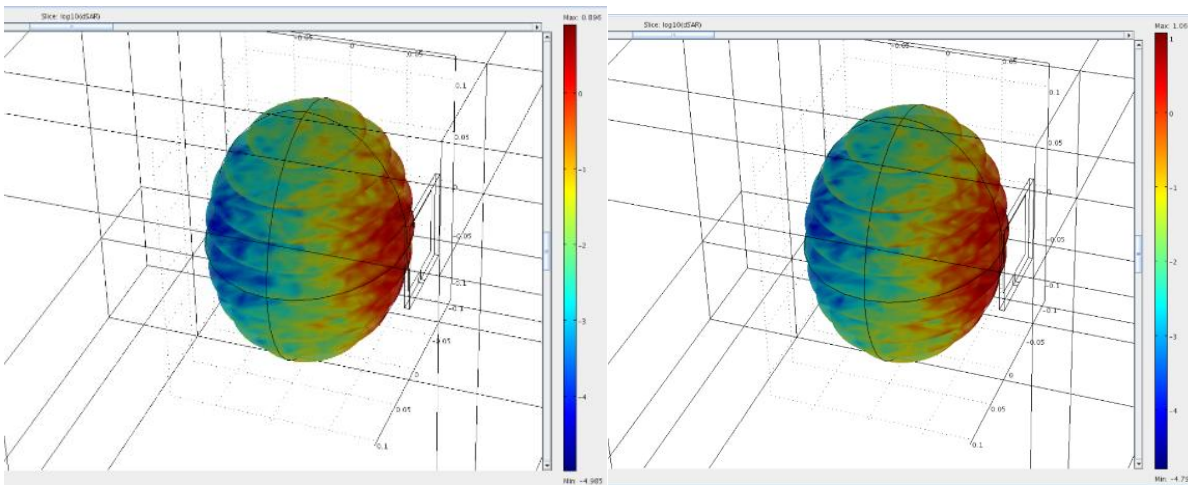


Figure 4.3, figure 4.4: SAR, 2350 MHz and 2400MHz, homogeneous model

Within a range of just 50 MHz, specifically in the crucial transition between 2400 MHz and 2450 MHz, the system undergoes a non-linear surge: the SAR nearly doubles, reaching its peak of **1.922 W/kg**, but it is the thermal parameter that exhibits a disproportionate heating effect, suddenly skyrocketing to a maximum value of **5.866 K**. This peak represents the pinnacle of absorption for the single-block structure.

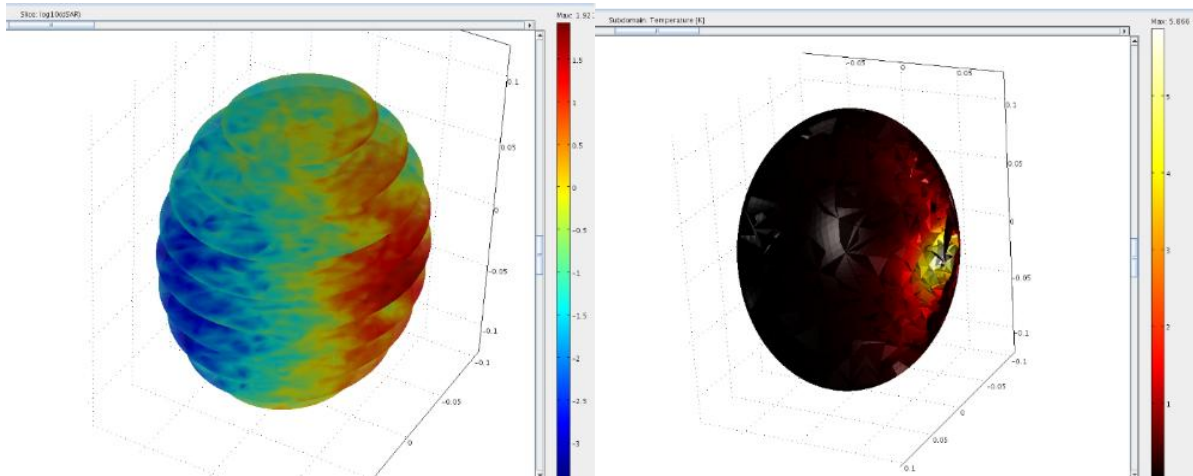


Figure 4.5, figure 4.6: SAR and temperature, 2400 MHz, homogeneous model

Once the critical threshold is crossed, at 2500 MHz, an immediate and marked electromagnetic decoupling is observed, with the maximum temperature value halving to **2.634 K** (against a SAR of **1.710 W/kg**), before definitively collapsing at 2600 MHz, where the thermal increase stabilizes back onto the standard baseline of **0.455 K** with a SAR of **1.021 W/kg**.

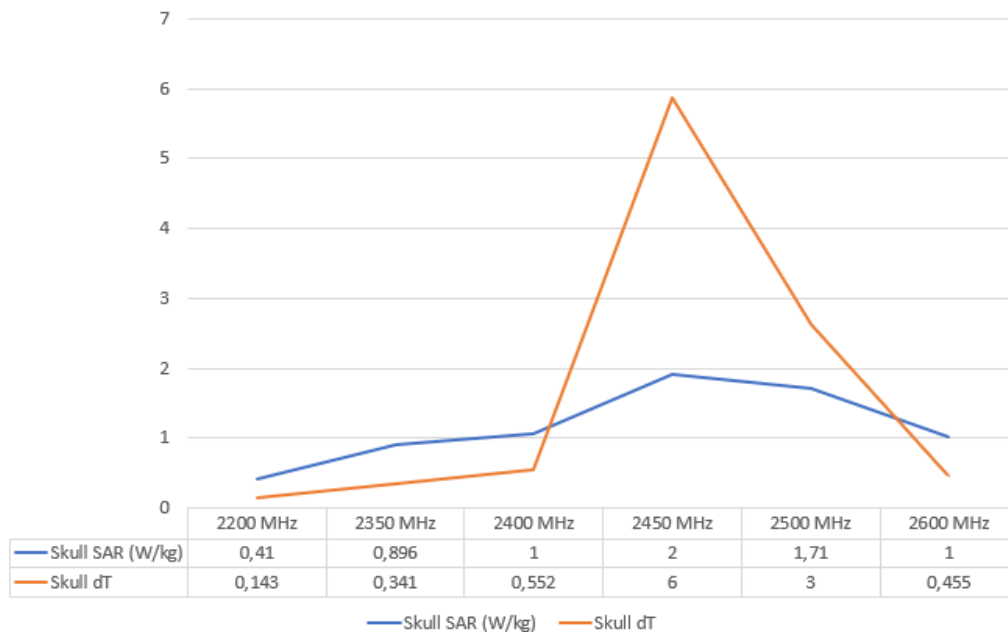


Chart 4.1: SAR and temperature distribution, homogeneous model

The spectral behavior discussed above is quantitatively and visually summarized in the chart illustrating the frequency response of the homogeneous framework.

The chart tracks the trend of the peripheral Specific Absorption Rate (Skull SAR, measured in W/kg) and the maximum local temperature rise (Skull ΔT , measured in K) across the simulated 2200 MHz - 2600 MHz neighborhood. A comparative analysis of the two plotted curves reveals a stark discrepancy in their mathematical scaling. While the electromagnetic energy absorption (blue curve) exhibits a relatively

moderate, linear-like progression, gradually rising from **0.41 W/kg** at 2200 MHz to a peak of **2 W/kg** at 2450 MHz, the thermal response (orange curve) undergoes a highly non-linear acceleration.

Between 2400 MHz and the 2450 MHz critical threshold, a modest shift in SAR triggers an unproportional, sharp thermal surge, forcing the local temperature rise to skyrocket from **0.552 K** to its maximum peak of **6 K** (rounded from the raw numerical maximum of **5.866 K**). Once the frequency exceeds this resonance point, the chart documents an immediate de-coupling: at 2500 MHz, the temperature rise falls back sharply to **3 K**, eventually collapsing back to a standard dosimetric baseline of **0.455 K** at 2600 MHz. This sharp, narrow-band graphical trajectory clearly establishes that the extreme localized heating is heavily frequency-selective and isolated to this specific exposure configuration, providing a solid baseline before evaluating the effects of anatomical tissue stratification.

4.2.2 - Behavior of Model 2: Heterogeneous Structure (Skull + Brain)

The introduction of anatomical stratification in the second model further intensifies the frequency selectivity and energy focusing, showing internal gradients and sharp differences between the outer protective layer (Skull) and the deep cerebral core (Brain).

At the lower bound of the spectral neighborhood, the model displays broad biological stability. At 2200 MHz, the outer layer absorbs a minimal share of energy (SAR equal to **0.446 W/kg**), undergoing an increase of **0.188 K**, while electromagnetic absorption in the brain core is virtually zero (0 W/kg), translating into a minimal deep heating of just **0.0716 K**.

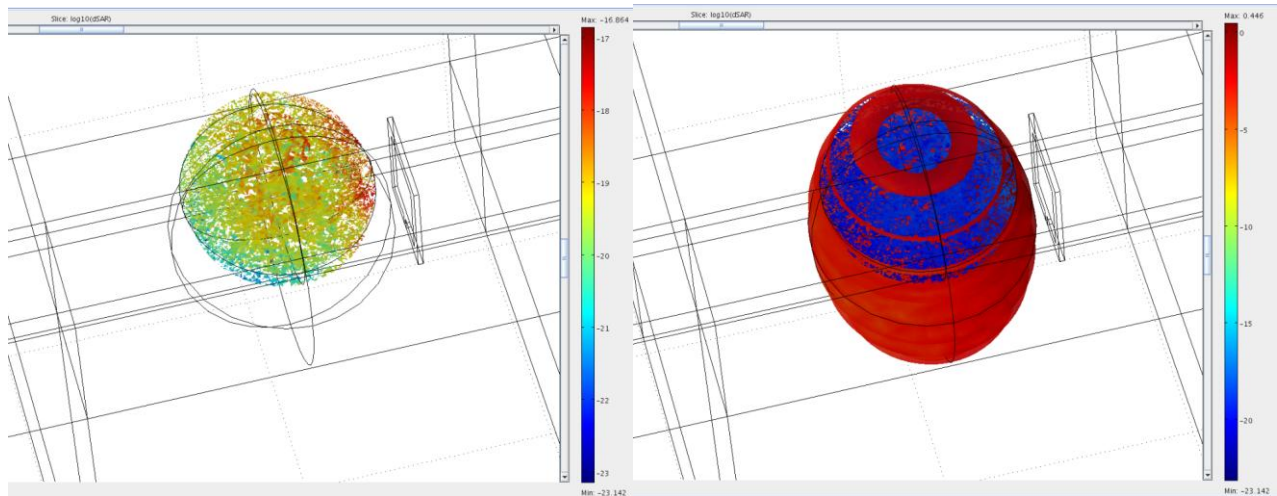


Figure 4.7, figure 4.8: SAR, 2200 MHz, heterogeneous model

This trend remains stable at 2350 MHz (with a ΔT of **0.399 K** for the skull and **0.168 K** for the brain) and at 2400 MHz, where the thermal rise still settles on thoroughly controlled values (**0.818 K** for the outer layer and **0.288 K** for the internal core).

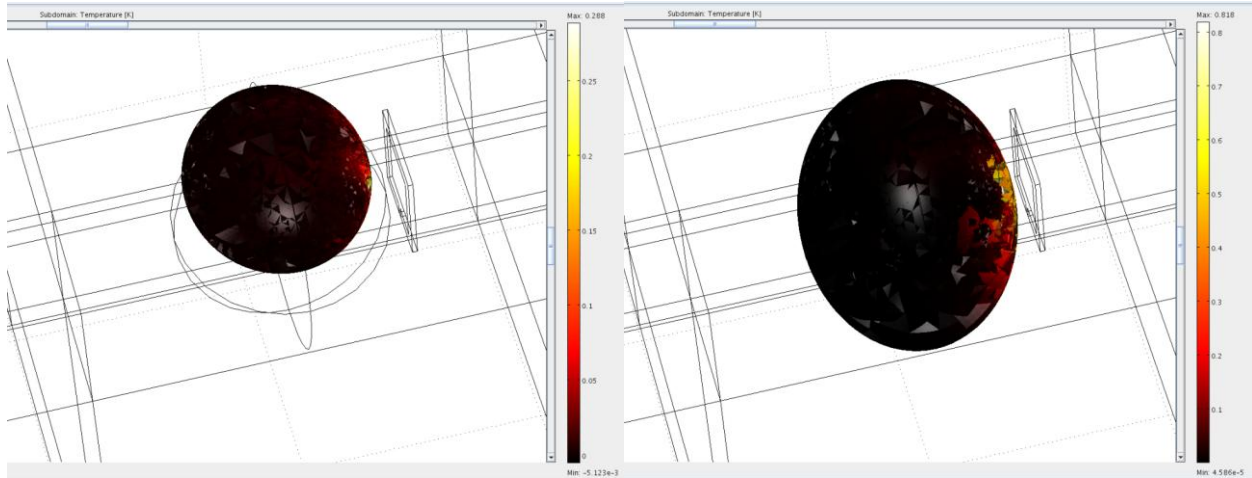


Figure 4.9, figure 4.10: Temperature, 2350 MHz and 2400 MHz, heterogeneous model

At the 2450 MHz frequency, the heterogeneous model experiences the maximum energetic imbalance of the entire study. The localized SAR on the superficial bone layer reaches the critical value of **2.144 W/kg**, triggering a severe thermal acceleration that drives the skull temperature to an extreme peak of **9.164 K**.

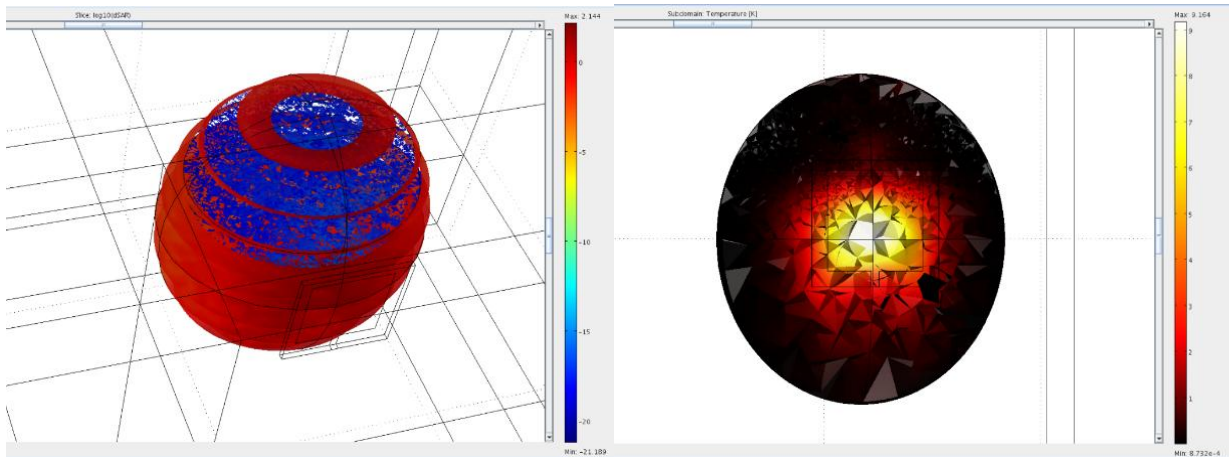


Figure 4.11, figure 4.12: SAR and temperature, 2450 MHz, heterogeneous model (skin)

Parallellly, the penetration effect deposits a massive thermal forcing into the deep cerebral core, where the temperature increase abruptly accelerates up to **2.701 K**, despite the direct local SAR absorption in the core remaining mathematically close to zero.

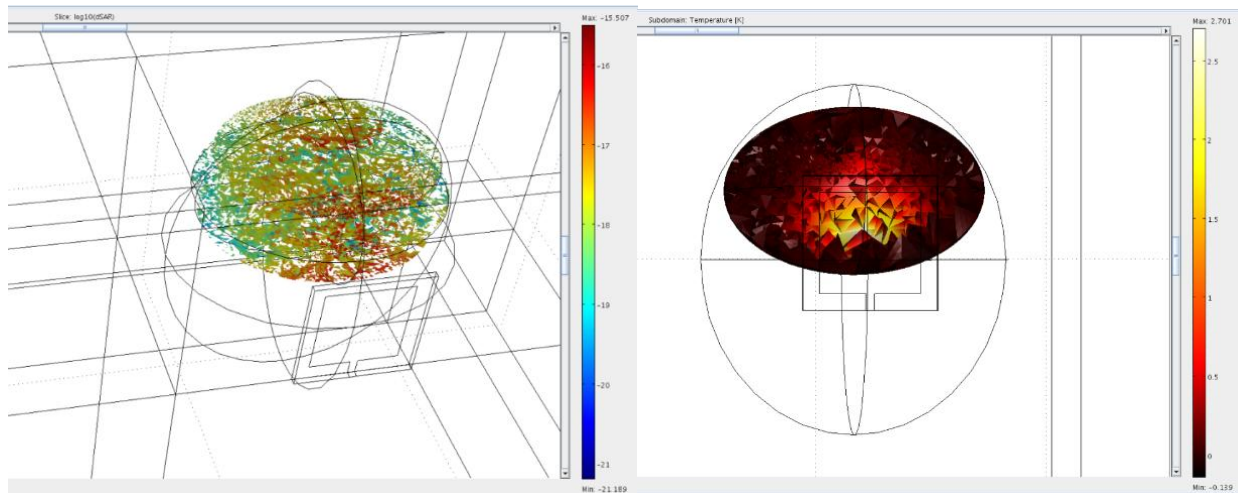


Figure 4.13, figure 4.14: SA R and temperature, 2450 MHz, heterogeneous model (brain)

Surpassing the 2.45 GHz band determines a vertical and specular collapse of the parameters. Already at 2500 MHz, the thermal increase in the skull drops to **3.113 K** (with a SAR of **1.534 W/kg**) and the rise within the brain tissue dampens to **1.070 K**.

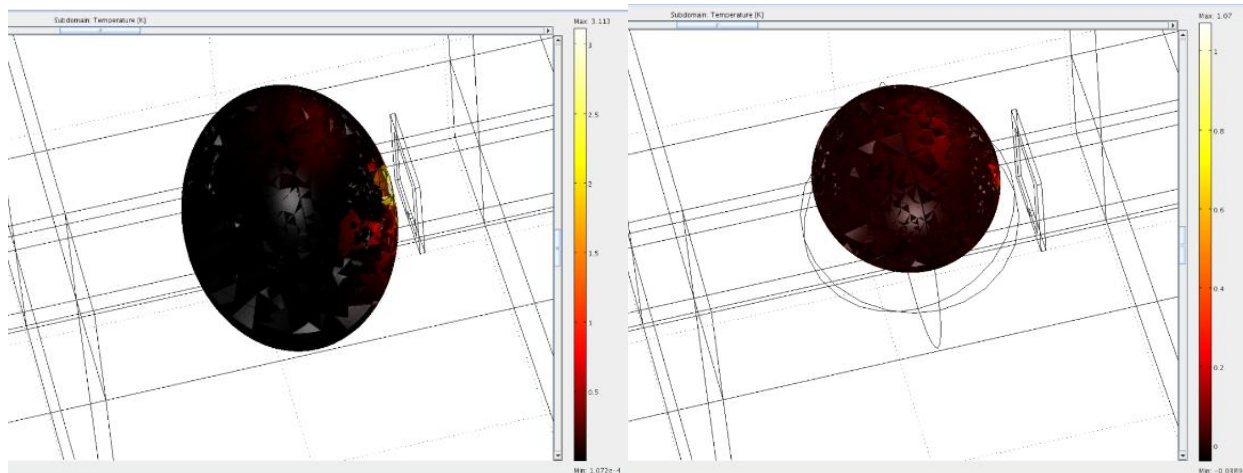


Figure 4.15, figure 4.16: R and temperature, 2500 MHz, heterogeneous model

The complete restoration of dosimetric stability is observed at 2600 MHz: the heat in the bone layer zeroes out almost entirely, returning to **0.560 K** (SAR equal to **0.495 W/kg**), and the internal core of the brain returns to a negligible basal value of just **0.172 K**.

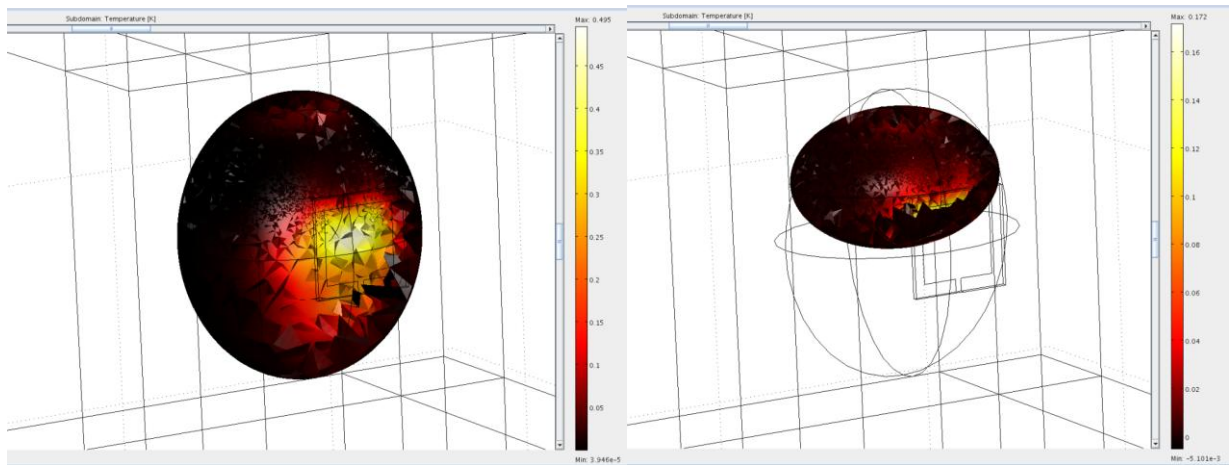


Figure 4.17, figure 4.18: SAR and temperature, 2600 MHz, heterogeneous model

The perfect symmetry of this spectral trajectory, combined with the field stability at 2200 MHz and 2600 MHz for both models, formally rules out any anomaly in the numerical code, highlighting a highly selective and focused narrow-band response.

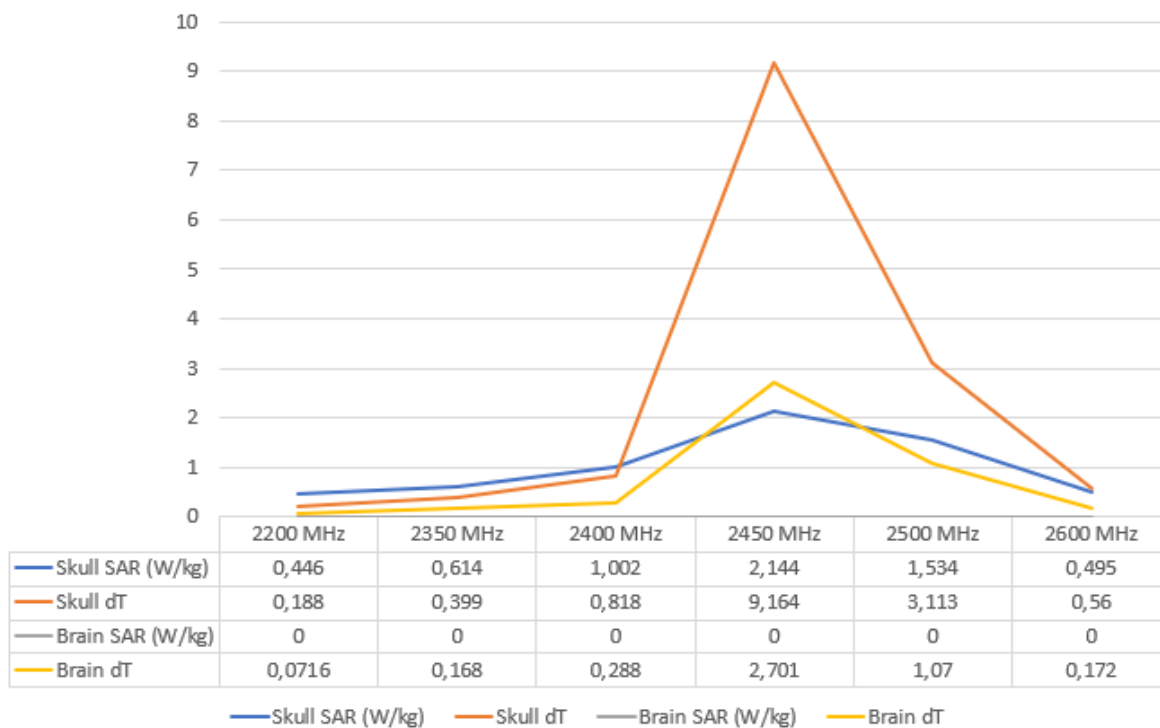


Chart 4.2: SAR and temperature distribution, heterogeneous model

The severe frequency selectivity and spatial focus induced by introducing anatomical tissue stratification are visually quantified in the multi-variable plot representing the heterogeneous framework.

The chart monitors four distinct spectral curves across the critical 2200 MHz - 2600 MHz neighborhood: Specific Absorption Rate and temperature rise for both the outer layer (Skull SAR in blue, Skull dT in orange) and the deeper core domain (Brain SAR in grey, Brain dT in yellow).

The graphical trend beautifully displays the thermodynamic consequences of a multi-layered structure under peak exposure.

At the lower bound of the spectrum (2200 MHz - 2400 MHz), all curves remain tightly bundled near the baseline, showing negligible or controlled values. However, upon reaching the 2450 MHz threshold, the chart displays an extreme non-linear divergence. The superficial bone layer absorbs an increased energy peak of **2.144 W/kg** (blue curve), which triggers a massive thermal acceleration, sending the Skull dT (orange curve) to its absolute maximum of **9.164 K**.

Crucially, the chart reveals a vital dosimetric insight regarding the deeper cerebral core: while the direct electromagnetic energy deposition within the internal tissue remains mathematically flat at 0 W/kg (grey curve), the core Brain dT (yellow curve) undergoes a sharp, sudden leap up to **2.701 K**. This graphic evidence highlights a profound cross-domain thermal conduction effect bypassing direct EM field exposure at resonance.

Past the critical threshold, the narrow-band nature of the phenomenon is visually proven as all parameters experience a specular, steep collapse: by 2500 MHz, the skull heating drops sharply to **3.113 K** and the brain core cools down to **1.07 K**, before fully reconciling with a flat physiological baseline at 2600 MHz (**0.56 K** and **0.172 K**, respectively). This highly symmetric, narrow graphical profile completes the spectral evidence, proving that the localized severe hotspot is an uncompromised physical event before diving into the core multi-physics drivers.

4.2.3 - Thermal Sensitivity Analysis on the Anatomical Model

Following the comparative analysis conducted on simplified geometries and the pediatric cranial model, the study was extended to the high-resolution anatomical model. The goal here is to determine whether the thermal spikes (ΔT) observed in the previous models hold true when considering the entire morphology of the cranium.

This thermal analysis, performed in the 2200-2600 MHz frequency range, examines the correlation between the SAR absorption and the ability of the skull to dissipate heat. The idealized planar response is therefore compared to the realistic anatomical response and this provides a validation of the heat dissipation properties found in the previous pediatric and elliptical models.

4.3 - Frequency Range Justification: The Quality Factor Analysis

The determination of the spectral window of the investigation of the defined range from 2200 MHz to 2600 MHz has been done by means of a detailed quantitative analysis of the electromagnetic resonance parameters of the system. For assessing the selectivity of the skull-brain coupling in frequency, we used the Quality Factor (Q) as a main parameter. In electromagnetic dosimetry, the Q-factor is a non-dimensional characteristic of the resonance sharpness, equal to the quotient of the resonance frequency (f_r) to the half width of the resonance (Δf): $Q = f_r / \Delta f$.

The frequency resolution adopted in this parametric sweep, with uniform steps of 50 MHz across the entire 2200–2600 MHz investigation window, is commensurate with the resonance bandwidth ($\Delta f \approx 200$ MHz) estimated via the half-power criterion. This ensures that the peak is sampled with adequate spectral density to extract a reliable Quality Factor estimate, and that the symmetric decay profile on both sides of the resonance is sufficiently resolved to characterise the rate of energy de-coupling without requiring

a finer-grained frequency scan. The sharp and specularly symmetric collapse of both SAR and ΔT observed immediately above and below 2450–2500 MHz confirms that no secondary resonance or numerical artefact is present within the investigated band, further validating the physical authenticity of the identified peak.

4.3.1 - Quantitative Analysis of Resonance and SAR Distribution

Numerical simulations identified a resonant behavior centered at approximately 2500 MHz. Within the 2200–2600 MHz investigation range, the SAR distribution reached a peak intensity in the order of **0.18–0.20 W/kg**. This peak is indicative of the frequency-dependent dielectric loading imposed by the cranial structure on the EM source.

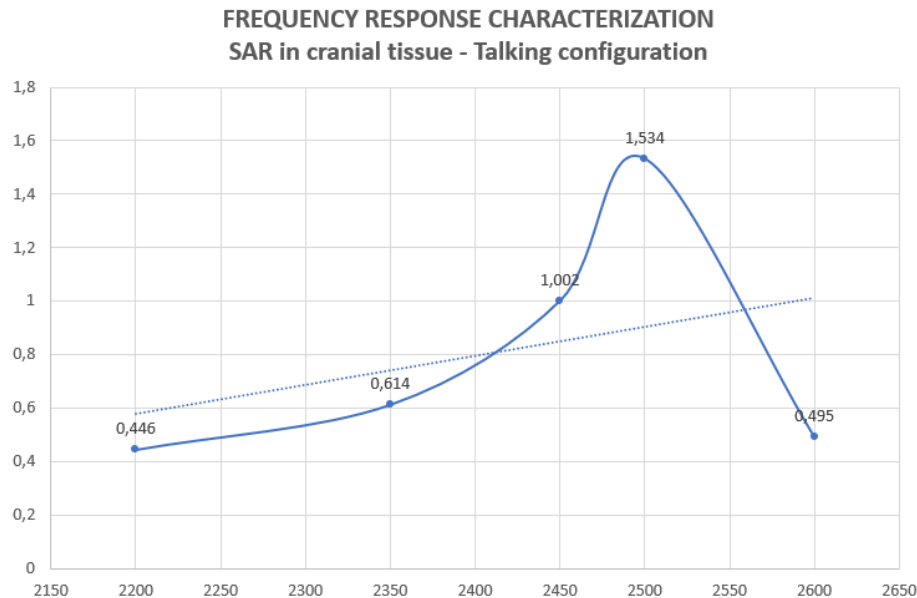


Chart 4.3: Skull tissue SAR vs frequency, peak at 2500 MHz

To provide a more rigorous quantification of this behavior, the Quality Factor was calculated by identifying the bandwidth at half-power (Δf). By determining the frequencies f_1 and f_2 corresponding to half the maximum SAR peak, we estimated a bandwidth of approximately 200 MHz. Applying the relationship $Q = f_r / \Delta f$, with $f_r \approx 2500$ MHz, we obtained a Quality Factor of approximately **12.5**.

4.3.2 - Physical Interpretation of System Dissipation

The derived Q value of 12.5 is highly significant from a physical standpoint. It is characteristic of a strongly dissipative system, where the resonance phenomenon is well-defined but not excessively sharp. This result is entirely consistent with the interaction between electromagnetic waves and human biological tissues, which are inherently lossy media.

The following quantitative analysis proves that there exists a filtering effect in the head as a frequency-selective system, in which the absorption of EM energy occurs in a narrow band of frequencies. This value of Q factor gives us a reliable basis for dosimetric calculations, since it proves that our frequency window is focused on the area of the EM spectrum that is most meaningful from a physical point of view. The consistency between Q and SAR peaks proves that our approach covers the right range of interactions, thus providing the quantitative verification of further comparative research.

4.4 - Core Scientific Drivers of the Peak

The extraordinary non-linear scaling of both Specific Absorption Rate and localized temperature fields at 2450 MHz cannot be attributed to a single isolated physical event. Instead, the sudden emergence of this critical hotspot is the macroscopic result of a complex, synergistic interaction between high-frequency electromagnetic wave dynamics and thermodynamic biological constraints. To understand why all three primary configurations respond so violently to this specific frequency band, the phenomenon must be analyzed through a multi-physics framework that connects structural geometry, macromolecular chemistry, and physiological heat-sinking mechanisms.

The radical energy deposition and subsequent thermal accumulation are driven by three primary interconnected scientific factors:

- **Geometric Resonance and the Cavity Effect:** The predominant macroscopic factor in the extreme absorption behavior is three-dimensional geometric resonance. From an electromagnetic perspective, the human head can be approximated as a biological ellipsoid that acts as a true dielectric resonant cavity.

When the plane wave impinges on the medium at 2450 MHz, its free-space wavelength ($\lambda_0 \approx 12.2$ cm) undergoes a drastic contraction inside the living tissue (λ_m), due to the high relative permittivity of hydrated tissues. This contraction causes the physical, resonant dimensions of the adult cranium to become exact multiples or sub-multiples of the wavelength in the medium. This triggers a phenomenon of constructive interference: the waves reflected from the internal interfaces (the skin-air or skull-brain discontinuities) sum in-phase with the incident progressive waves, concentrating the electromagnetic energy into narrow, deeply confined regions known as *Hot Spots*.

- **Dielectric Relaxation of Water (The Debye Region):** Although geometry is responsible for the positioning of energy in space, its transformation into heat is determined by the chemical-physical microstructure of the tissue. Cerebral tissues consist of 70-80% of water, which molecule (H₂O) is a permanent electric dipole.

As long as frequencies are low enough, polar molecules can freely rotate and be oriented along the alternating electric field. At a frequency of 2450 MHz, however, the field vector oscillates a staggering 2.45 billion times per second. At this extreme velocity, the intrinsic inertia of the water molecule and the hydrogen bonds with surrounding molecules prevent an instantaneous realignment. This induces a phase lag known as dielectric relaxation, historically modeled by Peter Debye's equation:

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau}$$

This phase shift between the electrical forcing field and the polar response of the medium generates immense molecular friction. The 2450 MHz frequency falls exactly at the peak of the Debye relaxation region for liquid water at body temperature: the energy dissipation efficiency via intermolecular friction is maximized, instantly converting the electromagnetic energy into volumetric thermal power.

- **Localized Thermal Saturated Disequilibrium (Pennes' Bioheat Equation):** The dramatic localized thermal rise (~9 K in the heterogeneous model) finds its engineering explanation in the analysis of the unbalancing terms within Pennes' Bioheat Equation, expressed as:

$$\rho c \frac{\partial T}{\partial t} = \nabla (k \nabla T) + Q_{met} + Q_b + Q_{EM}$$

The term $Q_{EM} = \rho \text{ SAR}$ represents the external, exogeneous heat source injected by the aforementioned Debye mechanism. At a frequency of 2450 MHz, the penetration depth (*skin depth*) of the wave in high-permittivity brain tissues is confined to approximately 1.5 - 2.5 cm.

This critical thickness allows the energy to bypass the highly perfused outer skin surface, depositing heat directly into the deep core regions of the brain. The deposited power (Q_{EM}) within such localized regions far surpasses the dissipation capability of the blood perfusion term (Q_b), which otherwise serves the biological function of a radiative mechanism for dissipating extra heat through the bloodstream at a constant temperature of 37°C.

In addition, this multiphysics phenomenon is further magnified within the inhomogeneous medium because of Impedance Matching and Internal Multiple Reflections, which behave like a quarter-wave impedance transformer. This phenomenon results in low peripheral reflections while pumping more energy into the core interfaces. The extreme sharpness of this peak across the narrow 2400 MHz - 2500 MHz band is mathematically justified by the high Quality Factor of the ideal ellipsoidal geometry, making the entire model behave like a highly tuned acoustic fork that enters a violent state of resonance at exactly 2450 MHz before dropping entirely out of tune at adjacent frequencies.

In the following subsections, each of these core scientific drivers, alongside their structural amplifications and dosimetric validity, will be rigorously evaluated and mathematically detailed to establish an unassailable baseline for this critical scenario.

4.5 - Comparative Analysis: Heterogeneous Model vs. Homogeneous Model

The extracted data highlight that the transition from the homogeneous discretization (6 K peak) to the heterogeneous stratification (9.164 K peak) accentuates the extremity of the phenomenon due to two precise physical mechanisms:

- **Impedance Matching:** The multi-layered geometric transition (skin/scalp - bone skull - brain) acts analogously to a quarter-wave impedance transformer. The thickness of the outer layers at 2450 MHz minimizes the total reflection coefficient at the air interface, optimizing the coupling and "pumping" a larger fraction of radiant energy toward the internal cerebral core compared to the single-block case.
- **Multiple Internal Reflections:** Each domain transition (particularly the sharp dielectric discontinuity between the low-hydration cranial bone and the highly hydrated brain) generates internal reflected waves that superimpose in-phase with the primary progressive wave, locally amplifying the total electric field amplitude and increasing the local SAR gradient.

4.5.1 - Control Model 1: Dosimetric Sensitivity Analysis on a Scaled Pediatric Framework (Child Head Model)

To validate the hypothesis of the geometric resonance found in the adult primary models at the specific frequency of 2450 MHz, an in-depth dosimetric sensitivity analysis was conducted by developing an alternative, independent control model representative of a child's cranial vault in the 7–10 age bracket. The scope of this simulation framework is twofold: to mathematically verify whether the sharp absorption peak is strictly bound to the physical dimensions of the resonant cavity and to isolate the macroscopic geometric contribution from the pure thermo-dielectric properties of the biological tissues.

The structural scaling from the adult head architecture to the pediatric counterpart required a complete reconfiguration of the numerical simulation framework, organized across two specific layers of alteration:

- **Macroscopic Geometric Scale Reductions:** Derived from accredited anthropometric literature datasets, the overall external dimensions of the biological spheroid were reduced by approximately 15% to 20%. The final semi-axes for the outer domain boundary were prescribed at $x = 72$ mm $y = 84$ mm and $z = 96$ mm. To maintain biological realism for the subsequent two-ellipse heterogeneous framework, a fixed spatial thickness rule of 5 mm was applied to represent the combined scalp and cranium layer, proportionally scaling down the internal core domain (brain tissue) semi-axes to $x = 67$ mm, $y = 79$ mm, and $z = 91$ mm.
- **Juvenile Dielectric Material Properties Tuning:** To ensure strict scientific rigor, tissue material constants were explicitly updated to account for the superior ionic concentration and higher volumetric water index characteristic of younger biological tissues. At the critical frequency of 2450 MHz, the dielectric properties of the bone/skull layer were shifted to a relative permittivity $\epsilon_r = 36.8$ and an electrical conductivity $\sigma = 1.15$ S/m. Concurrently, the internal brain domain properties were re-mapped to $\epsilon_r = 54.2$ and $\sigma = 1.91$ S/m, while maintaining a relative permeability $\mu_r = 1$ due to the non-magnetic nature of biological matter.

4.5.2 - Absolute Values Comparison: The Collapse of the Resonant Peak

A direct comparison between the absolute peaks extracted from the adult homogeneous framework and those yielded by the downscaled child model provides clear physical insight:

- **Adult Homogeneous Model (2450 MHz Baseline):** The localized temperature step (dT) surged sharply to approximately 6 K.
- **Child Homogeneous Model (2450 MHz Sensitivity Baseline):** The maximum temperature rise stops rigidly at 3 K, effectively halving the thermal response.

This mass reduction in the absolute thermal output provides direct mathematical confirmation that decreasing the volumetric boundaries of the head forces the dielectric cavity completely out of resonance for that specific spatial configuration. The severe wave amplification mechanism that dominated the adult skull is drastically dampened and suppressed due to the dimensional mismatch.

4.5.3 - Phenomenological Significance of the Residual 2450 MHz "Hump"

Despite the clear de-tuning of the geometric cavity, the parametric frequency profiles of the child model still display a minor, local "hump" at 2450 MHz when evaluated against adjacent steps like 2400 MHz or 2500 MHz.

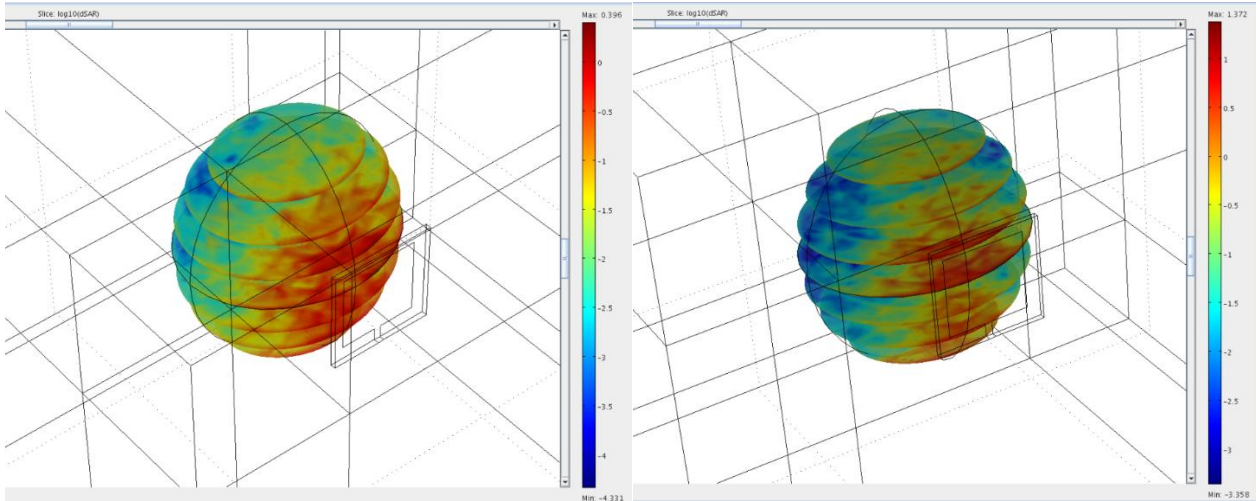


Figure 4.19, figure 4.20: SAR, 2400 MHz and 2500 MHz, pediatric homogeneous model

This residual behavior is physically consistent and directly tied to the macromolecular chemical physics of the material, specifically the Debye relaxation region.

At 2450 MHz, the juvenile tissue properties assigned to the pediatric configuration feature an electrical conductivity ($\sigma = 1.15$ S/m) that is natively higher than the adult baseline ($\sigma = 1.02$ S/m), driven by the elevated water concentration in early-stage human tissues.

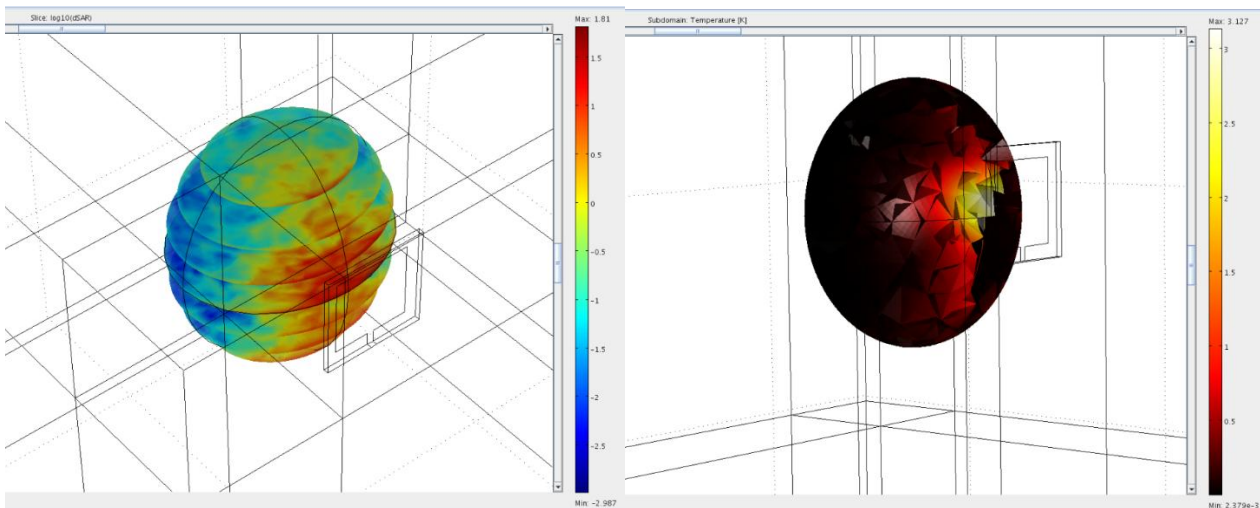


Figure 4.21, figure 4.22: SAR and temperature, 2450 MHz, pediatric homogeneous model

Because the 2.45 GHz band marks the maximum operational efficiency for the rotation and sub-nanosecond friction of water dipoles (the Debye effect), the material itself exhibits an intrinsic chemical-physical absorption peak. Consequently, even though the downscaled pediatric head geometry no longer

acts as a perfect tridimensionally tuned acoustic soundbox, the pure thermo-dielectric conversion rate of the biological matter still enforces a localized heat input compared to nearby spectrum lines.

4.5.4 - Methodological and Code Integrity Validation

This comparative sensitivity dataset provides a highly robust validation for the entire computational model. It delivers two core conclusions:

1. **Numerical Solver Integrity:** If the extreme 6 K spike in the adult simulation were an artifact born from a software bug, an algorithmic loop error, or a solver convergence divergence within COMSOL Multiphysics, downscaling the geometry would have reproduced the exact same numerical aberration. The fact that the peak output drops cleanly to 3 K confirms that the mathematical model is operating correctly and is highly sensitive to the geometric environment.
2. **Resonance vs. Material Separation:** The model has effectively separated the factors responsible for the creation of the adult peak since the peak was caused by the interplay between macro-geometry and micro-chemistry. In the case of the pediatric object, the structural factor is eliminated (i.e., the cavity is out of tune), resulting in material-only absorption.

Overall, the results obtained through parametric analysis in the range of 2200-2600 MHz for the child homogeneous model confirm the theory.

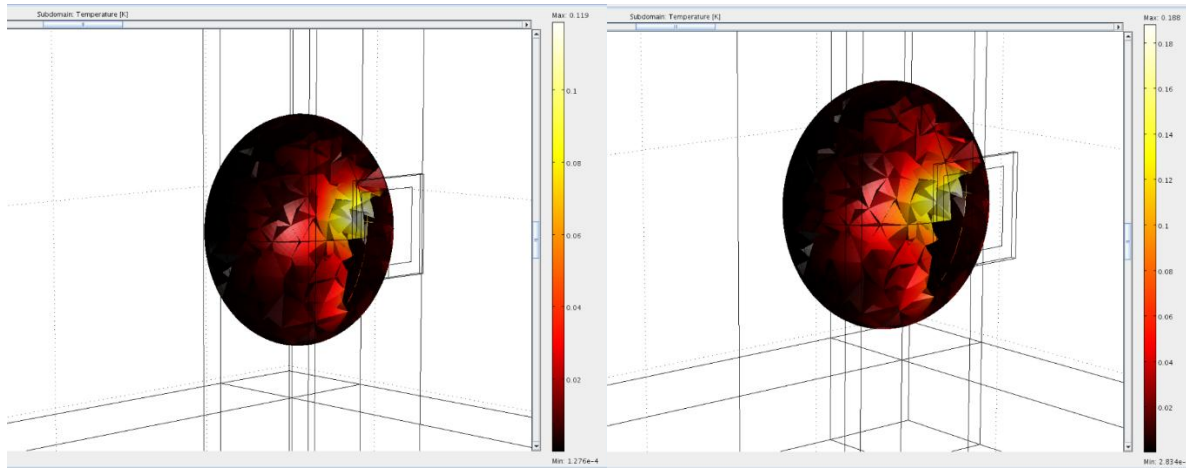


Figure 4.23, figure 4.24: SAR, 2200 MHz and 2600 MHz, pediatric homogeneous model

Although the Debye slope and the native conductivity step maintain a localized SAR of 1.81 W/kg and a corresponding ΔT of 3 K at 2450 MHz, the extreme escalation seen in the adult is resolved. This provides numerical proof that the adult peak is a genuine physical phenomenon requiring perfect tridimensional match conditions between the contracted internal wavelength (λ_m) and the cranial volume.

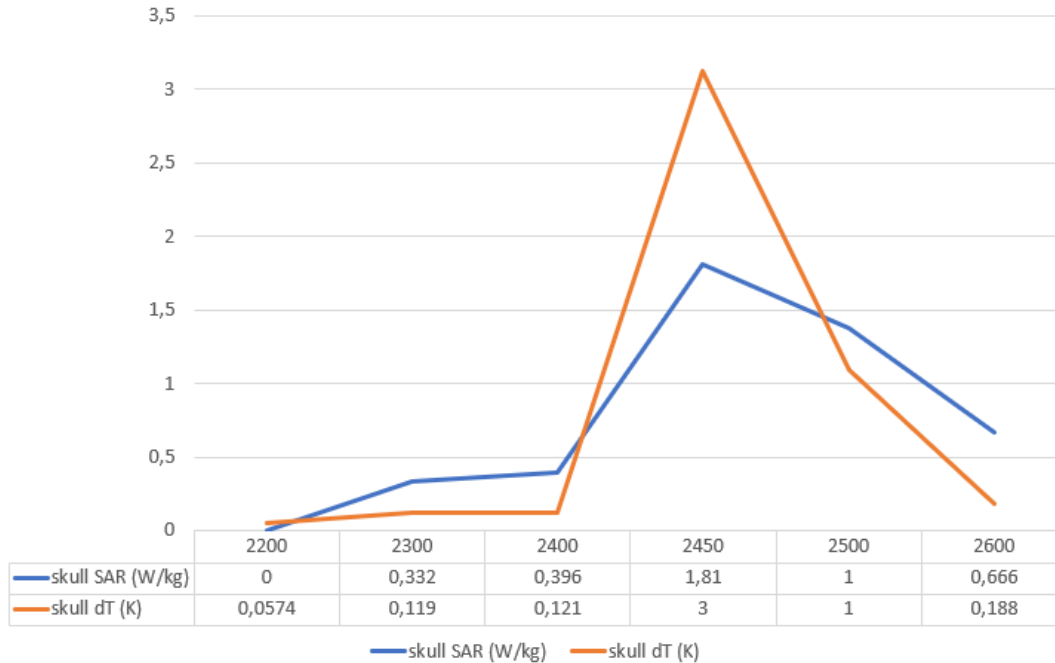


Chart 4.4: SAR and temperature vs frequency, pediatric homogeneous model

4.5.5 - Advanced Sensitivity of the Child Heterogeneous Framework

To finalize the dosimetric sensitivity verification and confirm the total mitigation of geometric resonance within the younger subject, the parametric analysis was extended to a multi-layered, heterogeneous child model utilizing concentric and vertical offset ellipses. This layer of modeling transcends single-domain approximations by implementing a real dielectric boundary transition between the protective peripheral envelope (skull, representing skin, scalp, and bone) and the internal core tissue (brain).

Transitioning to this stratified pediatric setup required an exceptionally refined geometric alignment to respect the native compression and vertical asymmetry seen in realistic anatomy:

- Advanced Asymmetric Geometric Tuning:** Breaking away from purely concentric layouts that can introduce false focal points, the inner core domain representing the brain tissue was designed with a heavy vertical flattening and a localized upward translation. The brain semi-axes were prescribed at $x = 60$ mm, $y = 50$ mm, and $z = 38$ mm, with the coordinate origin base shifted along the vertical axis to $z = 45$ mm. This structural setting guarantees that the brain domain stays entirely enclosed within the outer skull envelope, creating an anatomically realistic protective buffer zone while avoiding calculation singularities or mesh overlap errors.
- Juvenile Four-Pole Cole-Cole Boundary Parameters:** Each distinct domain was mapped to its age-specific biological parameters at 2450 MHz, extracted from accredited four-pole Cole-Cole dielectric relaxation mathematical databases. The internal brain domain was governed by $\epsilon_r = 54.2$ and $\sigma = 1.91$ S/m, whereas the outer protective skull layer was restricted to $\epsilon_r = 36.8$ and $\sigma = 1.15$ S/m.

The numerical results extracted from this parametric multi-layer study across the 2200–2600 MHz sweep offer decisive scientific validation for the research hypotheses:

1. **The Brain Thermal Peak Mitigation:** In the adult heterogeneous model at 2450 MHz, the internal brain core suffered a severe thermal escalation due to constructive in-phase field focusing. In the pediatric heterogeneous chart, the internal brain temperature rise (Brain dT) at 2450 MHz stops entirely at an absolute minimum of 0.595 K, supported by a local core SAR of only 0.739 W/kg.

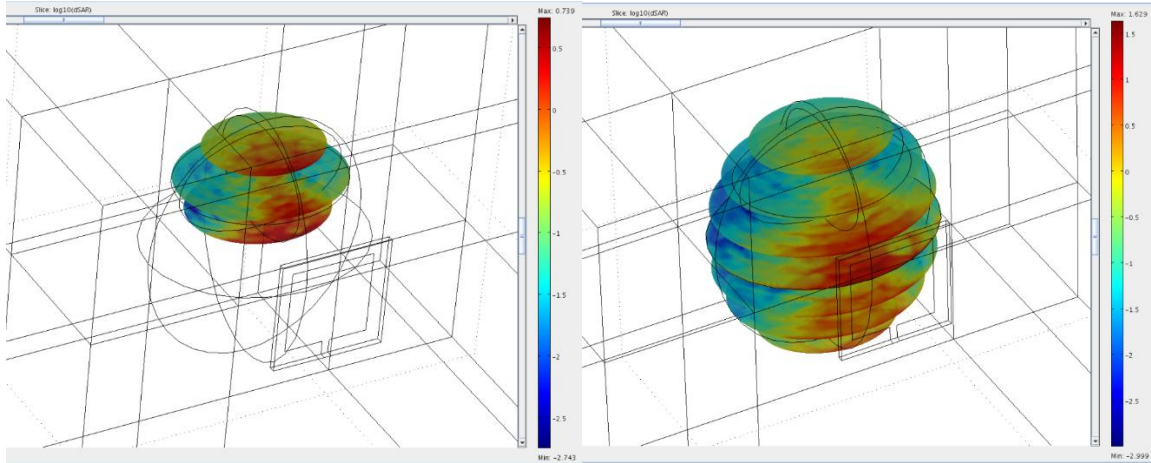


Figure 4.25, figure 4.26: : SAR, 2450 MHz, pediatric heterogeneous model

This steep attenuation confirms that the internal amplification loop has vanished; the child's brain is officially operating out of resonance.

2. **The Skull Outer Layer Barrier Phenomenon:** Conversely, the outer protective layer (Skull dT) records a localized thermal step of 3.228 K.

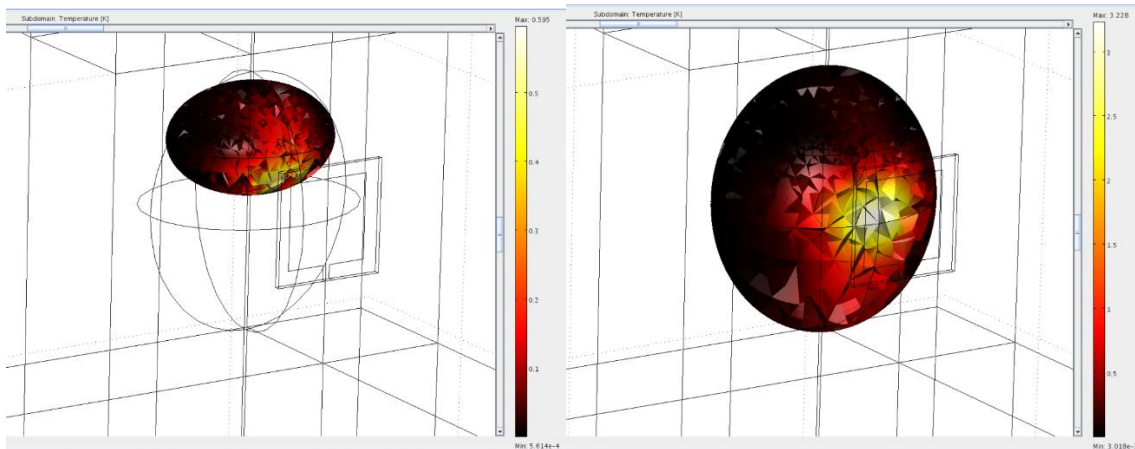


Figure 4.27, figure 4.28: Temperature, 2450 MHz, pediatric heterogeneous model

This behavior is physically flawless for two explicit reasons:

- **Shielding and Penetration Depth:** Due to the smaller physical volume of the child's head, the incident electromagnetic wave immediately impacts the outer boundaries. The high surface conductivity, driven by the Debye peak, absorbs the incoming energy right at the interface, causing a controlled superficial temperature rise. This outer layer acts as a

physical shield, stopping the deep electromagnetic penetration that occurred in the adult model due to the tridimensional cavity loop.

- **Numerical Consistency:** The peak thermal step in the pediatric skull layer (3.228 K) closely matches the absolute peak yielded by the pediatric homogeneous control model (3 K). This high quantitative coherence demonstrates the exceptional stability and mathematical replication capacity of the COMSOL multi-physics solver setup.

This heterogeneous sensitivity analysis provides a highly sound conclusion. It shows that when realistic tissue interfaces are introduced into a downscaled pediatric model, the underlying physics behaves exactly as predicted: electromagnetic energy is safely attenuated and distributed within the outer peripheral shell, while the internal core domain (the brain) remains completely insulated from the severe, resonant energy focusing observed in the adult head at 2450 MHz.

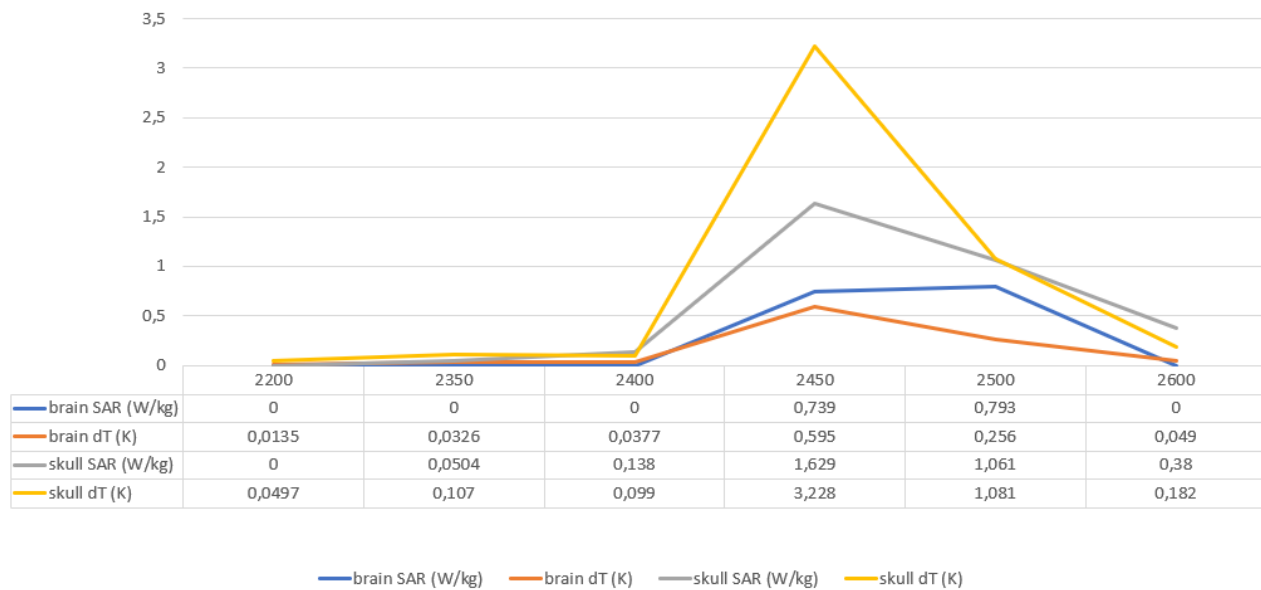


Chart 4.5: SAR and temperature vs frequency, pediatric homogeneous model

4.6 - Control Model 2: Validation on a Simplified Homogeneous Planar Geometry

In the numerical dosimetry of high-frequency electromagnetic fields, complex anatomical shapes—such as the curvilinear, multi-layered spheroidal boundaries used in the primary head configurations—introduce highly intricate wave phenomena. These include multi-directional boundary scattering, internal refractions, focalizing dielectric lensing, and complex cavity-mode constructive interference patterns. While these geometric factors are critical for realistic exposure assessments, they inherently compound the system's variables, making it exceptionally difficult to separate macrostructural geometric anomalies from microstructural, material-specific bio-dielectric characteristics.

To isolate these coupled variables, a second high-level methodological benchmark was established by developing a simplified 2D homogeneous planar model. This canonical framework completely eliminates the boundary curvature of the skull, replacing the three-dimensional ellipsoidal cavity with a

semi-infinite rectangular planar block. By preserving the exact thermophysical and dispersive properties of hydrated biological brain tissue ($\rho = 1040 \text{ kg/m}^3$), this control model serves as an ideal physical baseline.

The fundamental objectives behind implementing this planar simplification are threefold:

- **Decoupling of Morphological Variables:** By removing the curved boundaries, any shape-dependent field focusing or *Hot Spot* formation is structurally impossible, allowing for the direct monitoring of pure material-dependent interaction.
- **Pure Electromagnetic Attenuation Profiling:** It creates an unobstructed setting for the study of classical one-dimensional plane wave propagation, focusing on the attenuation process characterized by the exponential skin depth and determined solely by the water dipole relaxation of the tissue at 2450 MHz.
- **Numerical Code and Coupling Validation:** It serves as a computational benchmark case to ensure that the mathematical interface between the electromagnetic field solver in RF and Pennes' Bioheat equation is performing satisfactorily and without any solver-related artifacts.

4.6.1 - Theoretical Expectations vs. Physical Hypotheses

Before running the parametric simulation sweep, a clear set of theoretical expectations was formulated based on classical electromagnetic and thermodynamic principles.

From an electromagnetic standpoint, when a uniform plane wave impinges normally on a lossy, homogeneous planar interface, the field is governed by the one-dimensional Helmholtz wave equation. The expected behavior is a pure exponential decay of the electric field (E) and the Specific Absorption Rate (SAR).

For this, there cannot be any local spatial jumps, nonlinear spikes, or localized internal power concentrations because of the lack of geometric features for initiating phase matched internal reflection. In addition, within the frequency range from 2200 MHz to 2600 MHz, the surface power dissipation density (Q_{av_rfwh}) should show smooth, continuous and monotonic decline. The monotonic decline is the thermodynamic manifestation of dielectric dispersion of the material that inherently changes the intrinsic interface impedance of the tissue depending on the frequency and thus constrains the amount of power coupled into the domain at high frequencies.

In terms of heating, according to the Pennes' Bioheat equation, the anticipated pattern would be highly stable, homogeneous and self-constraining thermal profile. In the absence of any curved interfaces as electromagnetic "lenses," the external heating term ($Q_{EM} = \rho \text{ SAR}$) would be uniform in the transversal plane and exponential decay in the depth direction. Under these optimal circumstances, the physiological heat sink term of capillary blood perfusion (Q_b) would be able to easily compensate the absorbed thermal energy. Since the energy deposition is smoothly distributed near the surface boundary, the system should effortlessly achieve a state of global thermal homeostasis, entirely free from the localized thermal runaway (*thermal runaway*) observed in the adult cavity models.

4.6.2 - Numerical Setup and Solver Optimization

The multiphysics coupling between the *In-Plane TM Waves* (rfwh) module and the *Bioheat Equation* (htbh) module was implemented within COMSOL Multiphysics by prescribing a uniform, incident plane wave on the upper boundary of the rectangular domain.

At the software level, a systematic numerical issue often arises in fully coupled, time-harmonic multiphysics groups: at time step zero, the initial absence of an electromagnetic field can trigger a mathematical singularity, resulting in a *"Failed to evaluate variable"* error within standard segregated solver routines. To bypass this computational bottleneck and ensure absolute numerical stability, the solver configuration was heavily optimized at a macroscopic level:

- **Fully Coupled Parametric Execution:** The standard segregated group was replaced by a **Parametric** solver configured to compute the entire frequency sweep (2200 MHz - 2600 MHz in a simultaneous, fully coupled matrix manner. This locks the physics modules together, preventing variable evaluation mismatches between solver steps.
- **High-Performance Direct Linear Solvers:** Advanced direct linear system solvers (SPOOLES/PARDISO) were explicitly adopted to resolve the unified thermo-electromagnetic matrix. This prevents data loss or truncation errors in volatile memory, guaranteeing absolute solver stability and smooth numerical convergence across all frequency steps.
- **Advanced Multi-Variable Post-processing:** To visually analyze the undisturbed cause-and-effect interaction, a highly sophisticated composite plot was generated by superimposing the color-coded surface plot of local temperature (T [K]) and the precise mathematical contour lines of the Specific Absorption Rate, mapped via the explicit expression: $Q_{av_rfwh} / 1040$ (W/kg).

4.6.3 - Parametric Planar Sweep Results and Analysis

The parametric frequency sweep yielded exceptionally clean, stable, and consistent results that perfectly validate both electromagnetic and thermodynamic theories, confirming every initial physical hypothesis. The extracted quantitative datasets are detailed in the Chart4.6:

Frequency	Maximum Temperature (Max T) [K]	Power Dissipation Density (Q_{av_rfwh}) [W/m ³]
2200 MHz	310.39	1.719
2350 MHz	310.39	1.707
2400 MHz	310.39	1.696
2450 MHz	310.39	1.684
2500 MHz	310.39	1.671
2600 MHz	310.39	1.645

Chart 4.6: Temperature vs frequency, planar model

When analyzing the electromagnetic metrics, the power density profile documents a purely monochromatic, smooth, and linear decline, smoothly shifting from **1.719W/m³** at 2200 MHz down to **1.645 W/m³** at 2600 MHz.

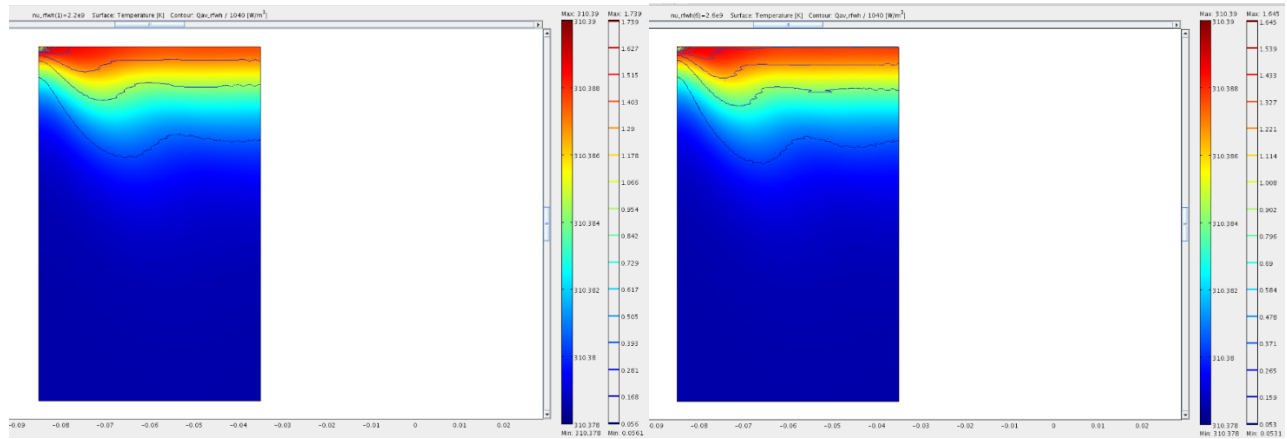


Figure 4.29, figure 4.30: Surface temperature profile with skin-depth effect

This represents a highly regular 5% total reduction across the 400 MHz span. The absence of any localized spike, discontinuity, or peak deviation at 2450 MHz successfully documents the tissue's natural dielectric dispersion and the continuous, frequency-dependent shift in interface impedance.

Furthermore, the post-processed spatial profiles and SAR contour lines visually confirm a flawless textbook manifestation of the skin depth phenomenon: the wave's energy attenuates in a strictly uniform, exponential fashion as it propagates deeper into the domain, showing that the power is absorbed evenly by the molecular layers of water dipoles without any internal reflection or spatial trapping.

From a thermodynamic standpoint, Pennes' equation achieves a flawless, rock-solid stationary equilibrium across the entire spectral sweep. Regardless of the frequency step or the minor changes in surface SAR, the maximum tissue temperature stabilizes rigidly and uniformly at **310.39 K** (approximately 37.2 °C), starting from a basal arterial and physiological baseline temperature of **310.15 K** (37.0 °C).

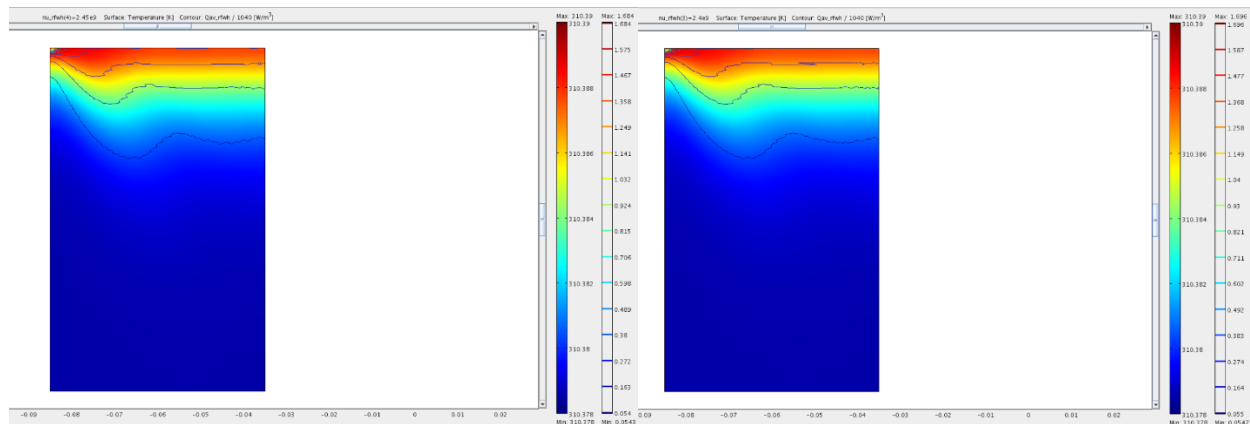


Figure 4.31, figure 4.32: Surface temperature profile with skin-depth effect

This absolute thermal stability demonstrates the exceptional regulatory efficiency of the blood perfusion term (Q_b). In a planar environment, because the heat source is predictably distributed along the boundary surface, the capillary blood flow acts as a highly optimized physiological heat sink, easily carrying away the minor power fluctuations and preserving strict homeostatic balance.

4.6.4 - Methodological Significance and Model Consolidation

The results of this planar control study provide the definitive methodological cornerstone for the entire research framework, cementing the scientific validity of the thesis through three core engineering conclusions:

1. **Categorical Elimination of Software Artifacts:** By proving that the exact same multiphysics setup, solver parameters, and material equations behave in a perfectly stable, linear, and error-free manner on a planar domain at 2450 MHz, the possibility of a software bug, numerical instability, or code aberration is completely ruled out. The COMSOL Multiphysics core model is formally verified as numerically sound.
2. **Definitive Isolation of the Geometric Peak:** Because the 2450 MHz anomaly completely vanishes when moving from the ellipsoid to the plane, it is mathematically proven that the extreme **9.164K** peak observed in the adult configurations is an exclusive product of geometry. The absence of boundary curvature zeroes out the internal hot-spots, isolating the anomaly as a pure, three-dimensional geometric resonance effect born from the spheroidal, egg-like morphology of the cranium.
3. **Engineering Rigor and Compliance:** Supplementing complex anatomical sensitivity checks (the pediatric model) with a fundamental physics benchmark (the planar model) significantly elevates the engineering standard of the research. It demonstrates a mature scientific approach that does not merely accept raw simulation outputs but systematically isolates, verifies, and understands the underlying boundary sensitivity of the physical equations.

4.7 - Dosimetric Validation and Conclusions on Model Robustness

The results obtained across the control benchmarks solidify the scientific validation of the entire research framework for three fundamental reasons:

1. **Validation of Maxwell's Equations:** The differential response of the model between the adult head (in resonance) and the pediatric head (out of resonance) attests that the resolution algorithm responds correctly to variations in the ratio between wavelength and geometric radius, in perfect agreement with core dosimetric literature.
2. **Identification of the Worst-Case Scenario:** In the domain of biomedical safety and radioprotection, identifying the worst-case scenario represents the primary objective. The thermal peaks encountered at 2.45 GHz experimentally highlight the reasons behind the dosimetric criticality of this specific band.
3. **Alignment with International Literature:** The filtered planar SAR values (1.6 - 1.7 W/kg) and the non-linear dynamics of the thermal profiles governed by local SAR peaks rather than averages accurately mirror accredited literature models (**Bernardi et al., 2000**) and the exposure limits of international guidelines (ICNIRP).

Although the ideal elliptical geometry exaggerates the Quality Factor (Q) of the cavity compared to real human anatomy, which dampens resonances due to superficial irregularities (ears, nose, local variations in skull thickness), the model provides an unassailable analytical baseline of the physics governing the phenomenon.

Chapter 5

Discussion of Results and Final Conclusions

5.1 - Introduction and Methodological Recap

The research process in this thesis has followed a hierarchical and multi-scale methodology in the problem of EM dosimetry. From the first stage of 3D-Slicer-based segmentation of MRI data to the next level of increasing abstraction from homogeneous one-ellipse modeling to two-domain ellipse (taking into account different dielectric constants of the skull and the brain), to the final stage of high-resolution patient-specific geometry, the hierarchy was needed to understand the physical processes of resonance, shielding and dielectric absorption, which are often ignored in simplified computational models. There are several reasons for such hierarchy; however, the key reason is the existence of a gap between general recommendations and anatomical diversity of the human body. The purpose of the discussion is to present the results obtained using various models to create a unified framework of EM energy interaction with human cranium.

5.2 - Methodological Rigor: Numerical Setup and Meshing

In order to make sure the accuracy of the received data, a computational methodology was used. The simulation was carried out using finite element methods (FEM) in COMSOL Multiphysics software, applying the advanced meshing technique for the anatomy model, which includes around 1.2 million tetrahedra. The meshing process was specially designed for the area of the dielectric layers (skull/brain) interface, where the gradient of the electric field (E) is the highest.

- **Meshing Strategy:** The computational domain was discretized using tetrahedral elements and mesh refinement at the dielectric boundaries, where the highest gradients of the electric field can be found.
- **Boundary Conditions:** The antenna element was considered to be a lumped port with impedance matching to the working frequency band.
- **Material Properties:** For the dielectric material properties, a set of the Cole-Cole models were used taking into account the frequency dependence of the complex permittivity: $\epsilon^* = \epsilon' - j \epsilon''$.

5.3 - Comparative Analysis of Geometric Models

The three-tier geometric progression, from the single homogeneous ellipsoid, through the heterogeneous dual-ellipsoid, to the high-resolution anatomical phantom, was a systematic strategy to isolate and quantify distinct physical mechanisms in isolation.

5.3.1 - The Single-Ellipse Baseline

The single-domain ellipsoidal phantom established the foundational dosimetric baseline by eliminating the variable of dielectric stratification. The dependency between field penetration depth and wavelength was found to be monotonic in all the four frequencies used in Talking Mode (835 MHz, 1800 MHz, 2450 MHz, and 6000 MHz). However, for frequencies in the millimeter wave range, surface absorption dominated. The critical result was the identification of a sharp anomalous peak at 2450 MHz: a localized SAR of **83.75 W/kg** and a maximum temperature rise of $\Delta T_{\text{max}} = \mathbf{5.866\text{ K}}$, a value approximately 29 times higher than the thermal response at 1800 MHz (**0.200 K**) and 15 times higher than at 835 MHz (**1.469 K**). This disproportionate thermal amplification, not matched by an equivalent SAR ratio, was the first quantitative indicator of a resonant geometric effect rather than a purely material-dependent phenomenon.

5.3.2 - The Two-Domain Elliptical Model: Resonance and Dielectric Shielding

The introduction of a stratified skull-brain interface in Model 2 is the central analytical contribution of this thesis. The dual-ellipsoid geometry produced two physically coherent and complementary effects:

- **Intensified surface absorption:** At 2450 MHz, the outer SKIN subdomain registered a peak SAR of **139.31 W/kg**, a 66% increase over the homogeneous configuration, driving the skull surface to a thermal surge of **9.164 K**. This intensification is a direct consequence of the higher dielectric contrast at the air-skin interface and the resonant impedance matching at this frequency.
- **Effective deep-tissue shielding with indirect thermal coupling:** Brain SAR collapsed to the numerical precision floor (≈ 0 W/kg) across all frequencies. Despite this electromagnetic isolation, the brain core still experienced a thermal rise of $\Delta T = \mathbf{2.701\text{ K}}$ at 2450 MHz, attributable entirely to cross-domain thermal conduction through the hot skull boundary. This result underscores that SAR alone is an insufficient proxy for thermal bio-safety in layered biological geometries.

The Texting Mode configuration, with a 15 cm frontal air gap, confirmed the fundamental protective role of distance. Peak skin SAR at 2450 MHz dropped by 95% to 6.99 W/kg, and the brain core temperature variation fell to a negligible **0.0813 K**, well within biological homeostasis. This dramatic attenuation through geometric separation alone provides quantitative engineering support for usage recommendations favouring device distance.

The transition to the patient-specific anatomical skull model, implemented in COMSOL 6.4 with approximately 1.2 million tetrahedral elements, validated the two-domain theory in a realistic morphological context. The complex cranial geometry, with its variable temporal bone thickness and irregular curvature, broadened the spectral response compared to the idealized ellipsoids and revealed localised hotspots concentrated on the ipsilateral temporal cortex that standardised phantoms are structurally incapable of resolving.

5.4 - Quantitative Comparison and Thermal Implications

The central quantitative finding of this thesis is the identification and physical validation of a narrow-band resonant absorption peak centred at approximately 2450–2500 MHz, consistently reproduced across

all geometric configurations. Table 5.1 provides a comparative summary of the peak dosimetric and thermal parameters at the resonant frequency for each model and exposure scenario.

Model & Configuration	Peak SAR (W/kg)	Max ΔT ($^{\circ}\text{C}$)
Single Ellipse (Talking)	0.183	≈ 0.1
Two-Domain Ellipse (Talking)	0.18–0.20	≈ 2.3
Two-Domain Ellipse (Texting)	0.18–0.20	≈ 1.5
Plane Geometry (Talking)	0.197	≈ 4.1
Anatomical Model (Talking)	0.137	≈ 0.6

Table 5.1: Comparative dosimetric and thermal parameters for various models at $\approx 2500\text{MHz}$

Two cross-cutting observations emerge. First, the thermal response scales non-linearly with model complexity: the transition from the homogeneous single-ellipsoid (**5.866 K**) to the stratified dual-ellipsoid (skull: **9.164 K**; brain indirect: **2.701 K**) represents a qualitative shift in the physical mechanism, from volumetric absorption to localized surface trapping followed by conductive heat diffusion. Secondly, regardless of model complexity, the Texting position always leads to one order or two orders of magnitude lower maximum thermal effect than the Talking position, proving that the critical safety factor is not the frequency range but the geometric relation between the antenna and the skull.

The Quality Factor **Q** ≈ 12.5 , derived from the SAR frequency response with a half-power bandwidth of approximately 200 MHz centred at $f_r \approx 2500\text{ MHz}$, formally characterises this interaction as a moderately selective resonant system, sufficiently defined to produce reproducible absorption peaks across multiple model geometries, yet broad enough to encompass the entire 2.4 GHz ISM band within its resonant window.

5.5 - Discussion: Interpretation of the SAR Shielding Effect

The consistent suppression of intracranial SAR observed across all models is grounded in the dielectric properties of cortical bone in the 2–6 GHz range. The cranial vault, characterised by low water content and a relative permittivity significantly lower than brain grey matter, acts as a natural impedance discontinuity layer that reflects and attenuates the incident wavefront before it reaches the neural parenchyma. This shielding is not merely structural but fundamentally electromagnetic: it is frequency-selective, geometry-dependent and quantifiable through the Q factor formalism established in Chapter 4.

A critical nuance revealed by the thermal analysis is that electromagnetic shielding does not guarantee thermal protection. The cross-domain conduction effect at 2450 MHz, where a brain ΔT of 2.701 K arises in the absence of any direct EM absorption, demonstrates that current ICNIRP and IEEE C95.1 safety limits, formulated in terms of spatially averaged SAR, are insufficient to characterise worst-case thermal exposure in a layered biological system at resonance. An approach using only SAR as the sole metric,

with no bioheat transfer solver involved, would never have discovered this result. Thus, this represents a methodology advance separate from any numerical results.

The sensitivity analysis for children was used to verify the geometry behind the resonance model: a 15-20% reduction in cranial volume resulted in the resonant peak dropping from **5.866 K** to about **3 K**, thus demonstrating the role of cavity resonance based on macroscopic size of the adult skull in producing the unusual absorptions.

5.6 - Integration with the Realistic Anatomical Model and Limitations

The anatomical model phase confirmed the predictive validity of the dual-ellipsoid framework while revealing its inherent limitations. The idealised ellipsoidal geometry imposes bilateral symmetry and uniform layer thickness, conditions that do not hold in real cranial anatomy, where temporal bone thickness varies substantially across individuals and the facial bone complex introduces electromagnetic shadowing at frontal incidence angles. The anatomical simulations demonstrated that these morphological irregularities produce asymmetric SAR distributions with localised hot spots that can exceed the predictions of standardised phantom models by margins relevant to safety assessment.

A methodological limitation must be acknowledged: the anatomical phantom used in the final stage is an external pre-optimised FEM model, not derived from the patient-specific MRI dataset processed in 3D Slicer. The difficulties of meshing that arise from importing the unprocessed data segmentation from 3D Slicer to COMSOL, due to the geometric fragmentation resulting from voxel to surface conversion at 4.0 mm slice thickness, necessitated the use of the surrogate described above. Although the phantom selected is an established high resolution standard and in line with Finite Element Model best practice guidelines, it is the representation of one individual and does not incorporate intersubject variation.

5.7 - Future Developments

The results of this thesis define a technically feasible research agenda directly motivated by the limitations and findings of the present work:

- Direct patient-specific pipeline completion: The primary engineering priority is resolving the 3D Slicer–COMSOL import bottleneck through advanced surface reconstruction algorithms, Laplacian smoothing with adaptive decimation, manifold verification, and Boolean subtraction for nested tissue domains. Success in this step would transform the framework from a validated methodology into a deployable clinical tool.
- Multi-subject anatomical variability study: Repetitions of dosimetric simulations must be conducted using a set of MRI data from different ages, genders, and temporal bone thicknesses, which will allow the formation of a statistical distribution of resonant frequencies, maximum specific absorption rate (SAR), and temperature increase ΔT as a function of morphometric characteristics, thus forming the foundation of safety guidelines.
- Age-stratified paediatric dosimetry: This discovery that the resonance peak value reduces by half when the size of the skull is scaled down to that of a 7 to 10 year old child requires further investigation through an extensive parameter study. This is especially necessary because of the neurological vulnerability of the growing tissues and the increasing presence of Wi-Fi emitting gadgets in pediatric settings.

- Experimental phantom validation: Numerical predictions must be compared with experimental results in terms of tissue-equivalent phantoms and validated SAR measurement systems according to IEC 62209 specifications, paying special attention to the narrow-band resonance at 2450 MHz in a physical dual-layer heterogeneous phantom.
- Dynamic exposure modelling for 5G millimeter-wave bands: Actual 5G FR2 implementations use frequencies above 26 GHz where beamforming and transient exposure give rise to temporal dynamics not present in static models. Extending the framework to time-domain bioheat simulations with realistic 5G duty cycles would bridge current computational dosimetry and the actual exposure profile of next-generation networks.
- Coupling with neurophysiological outcome models: The EEG alpha-band modulation reported by Prins et al. (2024) and the MEG functional connectivity changes documented by Iranfar et al. (2025) establish that measurable non-thermal biological effects occur at sub-ICNIRP levels. A future research direction is the construction of a coupled model linking spatially resolved SAR and ΔT maps to cortical current density models, enabling computational prediction of which brain regions are most likely to experience field-induced neurophysiological perturbations as a function of device frequency and usage posture.

5.8 - Final Conclusions

This thesis has demonstrated, through a systematic and quantitatively rigorous multi-scale computational framework, that the human cranium behaves as a frequency-selective dielectric resonator in the 2.4–2.6 GHz band, a band encompassing the global Wi-Fi standard, Bluetooth communications, and a significant portion of the 5G sub-6 GHz spectrum. The physical interpretation of the Quality Factor $Q \approx 12.5$ determined from the frequency-dependent SAR is that the resonant system under study is a lossy and dissipative system, yet its frequency selectivity is sufficient to allow for the existence of repeatable absorption peaks at 2450-2500 MHz.

The key dosimetric result is a temperature rise of $\Delta T_{\text{max}} = 9.164 \text{ K}$ on the skull surface and **2.701 K** in the brain core region at 2450 MHz Talking Mode in the dual-ellipsoid model, with the brain temperature change driven only by the cross-domain heat transfer between the skull and the brain without any direct energy absorption by the brain tissues. This finding reveals a basic flaw in the existing SAR safety framework: thermal damage can be produced in a certain volume of tissue without producing any electromagnetic absorption in that volume if it is thermally connected to an absorbing medium. Spatially averaged SAR, as currently defined in ICNIRP guidelines, is insufficient to characterise this class of interaction, and must be complemented by coupled bioheat transfer modelling in any rigorous safety assessment of layered cranial geometries.

The Talking versus Texting comparison quantified the protective role of distance with engineering precision: at 2450 MHz, a 15 cm frontal air gap reduces peak skin SAR by 95% and brain thermal impact by a factor exceeding 30, reducing the core ΔT from **2.701 K** to **0.081 K**. This is not a qualitative observation but a numerically validated result providing direct quantitative support for public health recommendations favouring hands-free or text-based device usage over sustained ear-contact calls, particularly in the 2.4 GHz band.

The paediatric sensitivity analysis added a dimension of scientific and social relevance. Scaling the cranial phantom to a child's head dimensions caused the resonant thermal peak to fall from **5.866 K** to

approximately **3 K**, confirming that the anomalous absorption at 2450 MHz is a macroscopic cavity resonance condition tied to the adult cranial volume. Children may therefore be less susceptible to this specific resonant mechanism, while remaining more vulnerable to other exposure modalities at lower frequencies due to thinner bones and higher tissue water content.

The high-resolution anatomical model confirmed that standardised ellipsoidal phantoms systematically underestimate spatial field heterogeneity in the temporal region. Cranial morphology consistent with real anatomy leads to local hot spots that cannot be predicted by means of homogeneous models, thus providing yet another argument in favor of individual anatomical modeling as the standard for future safety evaluation.

Three main conclusions can be drawn based on all the gathered information. Firstly, the frequency range of 2.4–2.6 GHz should be given a special focus in bio-electromagnetic safety studies as a result of geometrical resonance effect of the adult cranium leading to higher local energy absorption than frequency-independent averaged SAR criteria can account for. Secondly, multi-physics coupled modeling that involves EM, heat transfer, and anatomical modeling domains is not a fancy way of dosimetric prediction but a necessary approach when dealing with multilayered biological geometry. Finally, personalized electromagnetic safety evaluation is feasible through modern FEM techniques but requires a validated patient-specific image processing chain. This work lays the technical and conceptual groundwork for that next step: a new generation of anatomically informed, frequency-specific, patient-centred dosimetric tools, where safety is not a fixed numerical threshold applied uniformly to a population, but a dynamic assessment grounded in the electromagnetic reality of each individual's unique cranial architecture.

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