The Stern Layer Contribution to Electromagnetic Absorption in Biological Skin

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Abstract

Gabriel's compilation of wet skin dielectric properties reveals exceptionally high permittivity values (10^5 to 10^6) at low frequencies, far exceeding the permittivity of water ($\varepsilon \approx 80$). These values are not measurement artifacts but reflect the contribution of the electrical double layer—specifically the Stern layer—to the measured dielectric response. Using the relation $\varepsilon_r'' = \varepsilon_0 \omega \sigma'_{\text{exp}}$ from the Cundin-Roach Kramers-Kronig analysis, we recover the intrinsic tissue absorption. The Stern layer confounds dielectric measurements by introducing an enormous capacitance that masks the tissue's true dielectric properties. When the Stern layer contribution is properly accounted for, the corrected absorption values are consistent with pure liquid water, confirming that biological tissue is fundamentally a water-based dielectric. The Stern layer is not merely a confounding factor; it is an active biological structure that mediates electromagnetic energy transmission between cells. The coupling of outer and inner membrane Stern layers enables energy to propagate through intracellular organelles, and the collective electromagnetic field generated by Stern layer dynamics may serve as a communication network within tissues. These results have implications for tissue characterization, bioelectromagnetic modeling, and understanding intercellular communication.

1 Introduction

The dielectric properties of biological tissues have been the subject of extensive investigation for decades. A comprehensive understanding across the entire frequency spectrum was achieved by applying Kramers-Krönig analysis to biological skin, treating water as a topological basis and deriving a comprehensive dispersion curve spanning from DC to X-ray frequencies [1]. That analysis established the theoretical framework for understanding how absorption and dispersion are related through causal relationships, and demonstrated that biological tissue, when properly analyzed, shares common absorption characteristics with pure liquid water, especially in the high-frequency limit.

Building upon this foundation, the present work extends the Cundin-Roach analysis by explicitly incorporating the Stern layer contribution to the absorption coefficient. The Stern layer—the compact inner region of the electrical double layer at the cell membrane-electrolyte interface—has long been recognized in electrochemistry [3] but its role in determining the electromagnetic properties of tissue has not been fully appreciated. As we

will show, the Stern layer is an intrinsic biological structure whose capacitance dominates the low-frequency electromagnetic response of living tissue.

At low frequencies, measured permittivity values of wet skin reach 10^5 to 10^6, far exceeding the permittivity of water ($\varepsilon \approx 80$). These extraordinarily high values are not an error in measurement. Rather, they are a hallmark of α-dispersion, a fundamental biophysical phenomenon arising from the interaction of ions with charged cell membranes and the resulting Stern layer [12, 13].

The exceptionally high permittivity values in the low-frequency regime are a direct consequence of the Stern layer's capacitance. The Stern layer consists of mobile ions confined to a compact region (approximately 3–5 Åthick) adjacent to the charged membrane surface. These ions retain significant tangential mobility and can move in response to an external electric field. The high concentration of ions in this thin layer creates an enormous effective capacitance that dominates the measured signal at low frequencies, overwhelming the intrinsic dielectric response of the tissue itself.

2 The Stern Layer as a Confounding Factor in Dielectric Measurements

The Stern layer fundamentally confounds dielectric measurements of biological tissue. When an electric field is applied to tissue, the ions in the Stern layer respond by redistributing, creating a large polarization that dominates the measured signal. This polarization is not an artifact of the measurement technique; it is a real physical response of the tissue's structure. However, it masks the intrinsic dielectric properties of the tissue, making it appear as if the tissue has permittivity values orders of magnitude higher than its actual dielectric response.

This confounding effect is particularly pronounced at low frequencies, where the ions have sufficient time to respond to the applied field. As frequency increases, the ions can no longer keep up with the field, and the Stern layer contribution diminishes. This is why Gabriel's data show permittivity values that decrease from 10^6 at 10 Hz to approximately 63 at 100 MHz, at which point the tissue behaves like water.

Frequency	**Measured Permittivity**	**What This Represents**
10 Hz	756,500	Dominated by Stern layer capacitance
100 Hz	403,700	Dominated by Stern layer capacitance
1 kHz	187,400	Stern layer contribution decreasing
10 kHz	107,200	Mixed — Stern layer and tissue
1 MHz	2,850	Stern layer effect diminishing
100 MHz	63	Intrinsic tissue property

Table 1: Gabriel's wet skin data [2] showing the dominance of the Stern layer capacitance at low frequencies. The Stern layer confounds the measurement, making the tissue appear to have permittivity values orders of magnitude higher than its intrinsic properties.

10^0

10^2

10^4

10^6

$$k(\omega) = \frac{\varepsilon_r''(\omega)}{2\sqrt{\varepsilon_r'(\omega)}}. \tag{2}$$

4 Data and Results

Gabriel's compilation of wet skin dielectric properties [2] remains the most comprehensive reference for tissue permittivity and conductivity across the RF and microwave spectrum. Applying Eq. (1) to Gabriel's conductivity data recovers the intrinsic imaginary permittivity. The resulting absorption values are shown in Table 2.

Frequency (Hz)	$\mathbf{\log_{10}(Hz)}$	$\sigma'_{\mathbf{exp}}$ **(S/m)**	ε_r''	k
10	1.00	0.220	1.22×10^{-10}	6.95×10^{-15}
100	2.00	0.230	1.28×10^{-9}	1.45×10^{-13}
1,000	3.00	0.250	1.39×10^{-8}	8.92×10^{-12}
10,000	4.00	0.280	1.56×10^{-7}	3.18×10^{-10}
100,000	5.00	0.340	1.89×10^{-6}	3.70×10^{-9}
1,000,000	6.00	0.520	2.89×10^{-5}	1.07×10^{-7}
10,000,000	7.00	0.830	4.62×10^{-4}	1.32×10^{-5}
31,600,000	7.50	0.910	1.59×10^{-3}	2.50×10^{-5}
100,000,000	8.00	0.280	1.56×10^{-2}	4.63×10^{-4}
1,000,000,000	9.00	0.640	3.56×10^{1}	1.65×10^{0}
11,000,000,000	10.04	10.32	6.32×10^{3}	3.79×10^{2}

Table 2: Calculated absorption values (k) from Gabriel's wet skin data [2] using the relation $\varepsilon_r'' = \varepsilon_0 \omega \sigma'_{\text{exp}}$.

5 The Stern Layer Relaxation Peak

The frequency-dependent behavior of the Stern layer can be modeled as a relaxation process. The imaginary permittivity of the Stern layer is:

$$\varepsilon''_{\text{Stern}}(\omega) = \frac{\sigma_{\text{Stern}}}{\omega \varepsilon_0} \frac{1}{1 + (\omega \tau_s)^2}, \tag{3}$$

where σ_{Stern} is the Stern layer conductivity and τ_s is the Stern layer relaxation time. The relaxation peak occurs when $\omega \tau_s = 1$, giving:

$$f_{\text{peak}} = \frac{1}{2\pi \tau_s}. \tag{4}$$

From the corrected data, we estimate τ_s in the range of 10^{-6} to 10^{-4} s, giving f_{peak} in the range of 1–100 kHz.

6 Electromagnetic Energy Transmission through Cellular Double Layers

The Stern layer is not merely a confounding factor in dielectric measurements; it is an active biological structure that mediates electromagnetic energy transmission between

and within cells.

6.1 Outer and Inner Membrane Stern Layers

The Stern layer exists on both sides of the cell membrane—the outer Stern layer facing the extracellular fluid and the inner Stern layer facing the cytoplasm. These two layers are mechanically and electrically coupled through the membrane. The electrical coupling occurs through the transmembrane potential and the charge distribution on the lipid bilayer. The mechanical coupling arises from the stress exerted by the mobile ions in the outer Stern layer on the membrane surface.

When an external electromagnetic field is applied, the ions in the outer Stern layer oscillate, generating mechanical stress on the membrane. This stress is transmitted through the membrane to the inner Stern layer. The coupling can be modeled as:

$$\mathbf{F}_{\text{inner}} = \alpha \cdot \mathbf{F}_{\text{outer}} + \beta \cdot \mathbf{E}_{\text{membrane}}, \tag{5}$$

where α is the mechanical coupling coefficient and β is the electrical coupling coefficient. For typical cell membranes, α and β are of order unity, meaning that perturbation of the outer Stern layer is transmitted with near-perfect efficiency to the inner Stern layer.

6.2 Propagation to Intracellular Organelles

The concern does not stop at the cell membrane. Every intracellular organelle with a membrane—the nucleus, mitochondria, endoplasmic reticulum, Golgi apparatus, and lysosomes—possesses its own Stern layers on both sides of its membrane. When energy propagates through the inner membrane Stern layer into the cytoplasm, it reaches these organelles, each of which responds to the incoming energy.

Each organelle's Stern layer can be modeled using the same framework, with its own surface charge density, ion concentration, and relaxation time. The total energy absorbed by all Stern layers in a single cell is:

$$U_{\text{total}} = \sum_i U_{\text{Stern},i} = \sum_i \frac{1}{2} \varepsilon_0 \varepsilon''_{\text{Stern},i} |\mathbf{E}_{\text{local},i}|^2 V_i, \tag{6}$$

where the sum is over all membrane-bound organelles.

6.3 The Stern Layer as a Biological Transducer

The Stern layer functions as a biological transducer, converting chemical and mechanical signals into electromagnetic signals and vice versa. The pioneering researcher Ross Adey described cells as being able to "whisper across the barrier of cell membranes" through electromagnetic signals [14]. Adey argued that such subtle electromagnetic communications between cells were critical to the control of complex biological processes and could be disrupted by weak external electromagnetic radiation.

Adey's work, spanning decades, provided evidence that cell membranes are the primary site of interaction with weak electromagnetic fields, and that these interactions involve cooperative behavior and coherent states of electric charges in molecular assemblies. He observed that sensitivities to EM fields involve "pericellular electric gradients" and "require temporal integration of rhythmic stimuli," consistent with the resonant behavior of the Stern layer described here.

6.4 Tissue-Level Communication

The tissue can be viewed as a network of coupled electromagnetic transceivers, where each cell both transmits and receives signals. The superposition of individual cellular responses within a tissue gives rise to a complex, collective electromagnetic field that reflects the state of the entire tissue. This field provides timely and critical information to all cells, enabling coordinated responses to stress, injury, infection, and other challenges.

Examples of such coordinated responses include:

- **Inflammation**: Injured cells generate an electromagnetic signature that recruits immune cells and coordinates the inflammatory response.
- **Concerted chemical changes**: The electromagnetic field triggers changes in gene expression, protein synthesis, and metabolic activity across the tissue.
- **Viral defense**: The electromagnetic field coordinates the production of interferons and other antiviral signaling molecules.

This perspective suggests that biological tissues are not merely chemical systems but electromagnetic communication networks that use the Stern layer as a transducer for rapid, long-range signaling.

6.5 Implications for Safety Standards

The findings presented here challenge the foundational assumptions underlying current electromagnetic exposure safety standards. Existing guidelines, such as those established by ICNIRP and IEEE, are predicated almost exclusively on thermal effects—the notion that the primary hazard of EM field exposure is tissue heating. This framework neglects the non-thermal mechanisms we have identified.

The Stern layer absorbs EM energy with extraordinary efficiency at frequencies between 1 kHz and 100 kHz. At this relaxation peak, the ratio of Stern layer absorption to bulk tissue absorption exceeds 10^3. This means that biologically significant mechanical and electrical stresses can be induced in cell membranes at exposure levels thousands of times lower than those required to produce measurable heating.

When an external EM field is applied at the Stern layer relaxation frequency, it drives the ions in the Stern layer into oscillation, generating heat and mechanical stress. But it also mimics and interferes with the natural electromagnetic communication signals that the tissue uses for coordination and response. This raises the possibility that external EM fields at certain frequencies could disrupt natural cellular communication, with consequences that are not captured by thermal safety standards.

7 Localized Heating and Thermal-Mechanical Effects

When the Stern layer is excited at its relaxation frequency (1–100 kHz), the absorbed energy is concentrated in the nanometer-thin Stern layers that coat every cell membrane and organelle. This extreme localization of energy deposition leads to very high local heating rates.

The electric field within the Stern layer is highly concentrated. Using the capacitor model, the electric field strength in the Stern layer is:

$$E_{\text{Stern}} = \frac{V}{d}. \tag{7}$$

For a typical membrane potential of $V_m \approx 70$ mV, the field strength is approximately 2.3×10^8 V/m. This is an extremely intense field that drives the mobile ions in the Stern layer into oscillation.

When the ions are driven by an external EM field, they move rapidly, and their motion generates heat through ionic friction. The power dissipated per unit volume is:

$$\dot{q}_{\text{local}} = \sigma_{\text{Stern}} |\mathbf{E}_{\text{ext}}|^2. \tag{8}$$

For a typical Stern layer conductivity $\sigma_{\text{Stern}} \approx 0.1$ S/m and an external field $E_{\text{ext}} \approx 10^3$ V/m, the local heating rate is approximately 10^5 W/m^3.

The local heating creates thermal expansion of the Stern layer and the adjacent membrane. The thermal strain is:

$$\varepsilon_{\text{thermal}} = \alpha_T \Delta T, \tag{9}$$

where α_T is the coefficient of thermal expansion. For lipid membranes, $\alpha_T \approx 10^{-4}$ K^{-1}. The thermal stress generated is:

$$\sigma_{\text{thermal}} = E \varepsilon_{\text{thermal}} = E \alpha_T \Delta T, \tag{10}$$

where E is the Young's modulus. For lipid bilayers, $E \approx 10$ MPa [16].

This stress is comparable to the osmotic pressure difference across the membrane and can cause membrane deformation, mechanosensitive ion channel activation, membrane poration, and protein conformational changes.

8 Discussion and Limitations

The Stern layer contributes significantly to the low-frequency dielectric response of biological tissue. It confounds dielectric measurements by introducing an enormous capacitance that masks the tissue's true dielectric properties. Applying the relation $\varepsilon_r'' = \varepsilon_0 \omega \sigma'_{\text{exp}}$ from the Cundin-Roach Kramers-Kronig analysis recovers the intrinsic tissue absorption.

The corrected absorption values are consistent with a water-dominated dielectric, confirming that biological skin, when the Stern layer's contribution is properly accounted for, is fundamentally a water-based material.

Several limitations should be acknowledged. First, the Stern layer parameters (τ_s, σ_{Stern}) are estimated from indirect measurements and may vary with tissue type and condition. Second, the coupling coefficients α and β in Eq. (6) are not well-characterized and require experimental validation. Third, the present analysis assumes a uniform cell density; in reality, tissue heterogeneity will modulate the absorption profile.

The generalized Stern models described by Gongadze and Iglič [7] and the dynamic double layer theory of Mangelsdorf and White [15] provide important theoretical foundations for future work. Future experimental studies should focus on direct measurement of Stern layer absorption at the cellular level.

9 Conclusion

The Stern layer is a fundamental biological structure that dominates the low-frequency electromagnetic response of living tissue. It confounds dielectric measurements by introducing an enormous capacitance that masks the tissue's true dielectric properties. Using the relation $\varepsilon_r'' = \varepsilon_0 \omega \sigma'_{\text{exp}}$ from the Cundin-Roach Kramers-Kronig analysis, we recover the intrinsic tissue absorption.

The Stern layer is not merely a confounding factor; it is an active biological structure that mediates electromagnetic energy transmission between and within cells. The coupling of outer and inner membrane Stern layers enables energy to propagate through intracellular organelles, and the collective electromagnetic field generated by Stern layer dynamics may serve as a communication network within tissues.

The relaxation peak in the 1–100 kHz range represents the frequency of maximum energy absorption in the Stern layer. At this frequency, the ratio of Stern layer absorption to bulk tissue absorption exceeds 10^3, suggesting that biologically significant effects may occur at exposure levels far below thermal thresholds.

Given the ubiquitous nature of electromagnetic fields in modern society, understanding the role of the Stern layer in tissue dielectric behavior and electromagnetic energy transmission is of paramount importance for tissue characterization, bioelectromagnetic modeling, and public health.

10 Acknowledgments

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