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Analysis of Health and Biophysical Risks Related to Exposure to Microwave Radiation and Hyperfrequency in Urban Environments: An Approach Electromagnetics and Foundations of Radiation Protection

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ABSTRACT

The ubiquity of wireless technologies in urban environments leads to a significant increase in human exposure to artificial electromagnetic fields, particularly in the microwave and high-frequency bands (300 MHz to 300 GHz). This scientific article, structured according to the academic standards of the National Pedagogical University (UPN), examines the biophysical interactions between these non-ionizing waves and biological tissues. Using Maxwell's macroscopic equations, we model the penetration, propagation, and attenuation of waves in the human body, characterized by its dielectric properties (complex permittivity and conductivity). The analysis focuses on thermal effects, quantified by the Specific Absorption Rate (SAR), as well as potential non-thermal mechanisms at the cellular level. Finally, concrete radiation protection recommendations adapted to the context of the Democratic Republic of Congo are formulated.

KEYWORDS: *Microwaves, Maxwell's equations, Specific Absorption Rate (SAR), Biophysical effects, Radiation protection, UPN.*

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I. INTRODUCTION

The rapid development of wireless telecommunications, broadcasting, radar, and household appliances has profoundly altered the contemporary electromagnetic environment. Urban populations, particularly in Kinshasa, now live in a continuous "bath" of radiation of varying frequencies, grouped under the terms microwaves and hyperfrequencies, with frequencies ranging from 300 MHz to 300 GHz. Unlike ionizing radiation (X-rays or gamma rays), these waves do not possess sufficient quantum energy to break chemical bonds or directly ionize atoms. Nevertheless, the interaction of electromagnetic waves with living matter generates complex biophysical phenomena. The question of potential risks to human health remains a subject of scientific debate and major public concern. At the National Pedagogical University, the analysis of environmental risks related to electromagnetic waves is part of a rigorous approach that aims to combine fundamental mathematical and physical modeling with real-world health data.

This article aims to elucidate the physical basis of these interactions. We will use Maxwell's equations to describe the behavior of fields at the interface and within biological tissues. We will then address the quantification of absorbed energy via the Specific Absorption Rate (SAR), analyze the documented health consequences, and propose appropriate protection strategies.

II. FUNDAMENTAL PHYSICAL FORMALISM: MAXWELL'S EQUATIONS AND BIOLOGICAL ENVIRONMENTS

To understand how microwaves penetrate the human body, it is essential to postulate that living tissue behaves, from an electrical point of view, like a dispersive, dissipative, and heterogeneous material medium. Maxwell's macroscopic equations govern the propagation of the electric field $\boldsymbol{E}$ and the magnetic field $\boldsymbol{B}$ in this medium:

$$\nabla \cdot E = \rho / \varepsilon$$

$$\nabla \cdot B = 0$$

$$\nabla \times E = -\, \partial B / \partial t$$

$$\nabla \times B = \mu_0 \,(J + \varepsilon\, \partial E / \partial t)$$

Where $\boldsymbol{\varepsilon}$ represents the permittivity of the medium, $\boldsymbol{\mu_0}$ the magnetic permeability of vacuum, $\boldsymbol{\rho}$ the free charge density and $\boldsymbol{J}$ the induced conduction current density, defined by the local Ohm's law: $\boldsymbol{J = \sigma E}$, with $\boldsymbol{\sigma}$ the electrical conductivity of the tissue.

II.1. Complex permittivity and dielectric losses

Under the influence of a high-frequency alternating electromagnetic field, water molecules (which constitute a large fraction of tissues) undergo a forced alternating orientation. This dielectric relaxation phenomenon results in a complex permittivity $\boldsymbol{\varepsilon^*}$:

$$\varepsilon^* = \varepsilon' - j\,\varepsilon''$$

The real part $\boldsymbol{\varepsilon'}$ represents the tissue's capacity to store electrical energy, while the imaginary part $\boldsymbol{\varepsilon''}$ encompasses energy losses due to molecular friction and ionic conduction. The overall equivalent conductivity of the middle is then written: $\boldsymbol{\sigma\_eq = \sigma + \omega\varepsilon_0\varepsilon''}$, where $\boldsymbol{\omega = 2\pi f}$ corresponds to the angular frequency of the wave.

II.2. Attenuation and depth of penetration

Solving the wave equation shows that the amplitude of the electric field decreases exponentially as it penetrates the human body. The penetration depth (or skin thickness) $\boldsymbol{\delta}$, representing the distance at which the field amplitude is divided by $\boldsymbol{e}$, is expressed as:

$$\delta = 1 / (\omega \sqrt{[\, (\mu\varepsilon'/2) * (\, \sqrt{(1 + (\sigma\_eq/(\omega\varepsilon'))^2}\,) - 1\,)\,]})$$

This fundamental relationship highlights that the higher the frequency $\boldsymbol{f}$ or the conductivity $\boldsymbol{\sigma}$, the shallower the penetration depth. Thus, very high-frequency microwaves (e.g., 5G at 26 GHz or airport scanners) are stopped primarily by the skin, while lower frequencies (around 900 MHz to 2.4 GHz) penetrate more deeply into internal organs.

III. BIOPHYSICAL INTERACTION AND QUANTIFICATION: THE SPECIFIC ABSORPTION RATE (SAR)

The key measurement used in biophysics and radiation protection to assess the energy dose deposited by microwaves in the body is the *Specific Absorption Rate (SAR).* It is expressed in watts per kilogram (W/kg).

The SAR is directly proportional to the square of the amplitude of the internal electric field induced at the point considered:

$$DAS = (\sigma\_eq \cdot |E\_int|^2) / (2 \cdot \rho\_m)$$

Where $\boldsymbol{\rho\_m}$ is the density of the target biological tissue (kg/m³). The dielectric properties vary greatly depending on the water content of the organs, as illustrated in the table below:

Table 1: Average dielectric properties of various human tissues at a frequency of 2.45 GHz.

TYPE DE TISSU	TENEUR EN EAU (%)	PERMITTIVITÉ RELATIVE (E')	CONDUCTIVITÉ (Σ EN S/M)	PROFONDEUR DE PÉNÉTRATION (MM)
Muscle	Élevée (~75%)	52,7	1,74	19,3
Cerveau (matière grise)	Élevée (~80%)	48,9	1,81	18,1
Tissu adipeux (graisse)	Faible (~15%)	5,3	0,11	78,4
Os compact	Très faible (~10%)	11,4	0,38	45,2

IV. Health consequences and pathological effects

The effects of microwaves on the body are generally classified into two distinct categories, although their boundaries are still the subject of extensive research.

IV.1. Thermal effects (proven)

When the SAR exceeds a certain threshold (approximately 4 W/kg for the whole body), the body's thermoregulatory mechanisms (sweating, vasodilation) are overwhelmed, leading to a rise in local or systemic temperature. Organs with limited blood supply, such as the **lens of the eye, are particularly vulnerable.** The **testicles** are particularly vulnerable because they cannot efficiently eliminate excess calories through the bloodstream. Intense exposure can therefore lead to the development of early cataracts or impaired spermatogenesis.

IV.2. Non-thermal or athermal effects (suspected)

Numerous epidemiological and cellular studies suggest the existence of effects occurring at exposure levels well below regulatory thermal thresholds. Although the exact physical mechanisms are not fully understood, several biophysical avenues are being explored:

- **Cellular disturbances:** Alteration of cell membrane permeability and alteration of calcium ion fluxes (***Ca^{2+}*)**.
- **Oxidative stress:** Increased production of free radicals, which can indirectly damage cellular DNA.
- **Neurological effects:** Subjective disorders reported by some populations (headaches, asthenia, insomnia, fatigue), described as electromagnetic hypersensitivity syndrome.

V. Safety standards and radiation protection strategies

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has established basic restrictions to protect populations from any harmful thermal effects. Table 2 summarizes these general thresholds.

Table 2: ICNIRP recommended limits for public exposure (100 kHz - 300 GHz).

TYPE D'EXPOSITION	DAS POUR LE CORPS ENTIER	DAS LOCALISÉ (TÊTE ET TRONC)	DAS LOCALISÉ (MEMBRES)
Professionnelle (travailleurs)	0,4 W/kg	10,0 W/kg	20,0 W/kg
Public général (population)	0,08 W/kg	2,0 W/kg	4,0 W/kg

V.1. Radiation protection guidelines and their application in the DRC

In order to minimize exposure in the Congolese urban environment (characterized by the sometimes haphazard installation of cell towers in the immediate vicinity of homes or universities), it is necessary to apply the general principles of radiation protection adapted to non-ionizing waves:

- **The distance principle:** The intensity of the electromagnetic field decreases inversely proportionally to the square of the distance ($1/r^2$) in free space. Keeping phones away from the brain (using a hands-free kit) drastically reduces the local SAR (Specific Absorption Rate).
- **Time management:** Limit the duration of communications in areas of poor reception (where the phone increases its transmission power to the maximum).
- **Environmental regulations:** Require telecommunications operators to conduct regular technical audits of the power density of cell towers located near residential and school areas (e.g., Mont-Ngafula).

CONCLUSION

This biophysical study demonstrates that while microwaves do not possess the ionizing destructiveness of high-energy waves, their interactions with biological tissues via dielectric dissipation remain substantial. Maxwell's equations, coupled with complex permittivity models, allow for the rigorous mapping of energy absorption quantified by the SAR (Specific Absorption Rate). Faced with continuous technological deployment, the precautionary principle and the strict application of radiation protection regulations are essential pillars for ensuring safe technological development in the Democratic Republic of Congo.

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