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The Collision between Wireless and Biology

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Abstract

This article examines the historical development of the concept of energy of activation, which has been used in the past to frame the belief that non-ionizing electromagnetic radiation is harmless at non-thermal levels.

The power and telecommunications industries have used two arguments to support their view that human exposures to non-thermal non-ionizing radiation is inoffensive. First, the radiation is non-ionizing. Second, the energy quanta of the radiation are too weak to overcome the competing energy of thermal motion. Those arguments rest on the Arrhenius equation (1889) and on the concept of energy of activation. Later scientific developments such as the Eyring equation (1935) and the Bennett-Chandler (1977-1978) equation on reaction rates, and the Second Law of Thermodynamics, recognized in living systems by Schrödinger as “negentropy”, all undermine these arguments.

The Second Law of Thermodynamics supplies the ionization claimed to be lacking, while some biological processes are independent of thermal motion. We contribute a new view of the physics and biology of non-ionizing electromagnetic radiation hygiene which explains many epidemiological, toxicological and scientific observations. The health effects of non-thermal non-ionizing radiation presently observed are in fact completely supported by physics. Furthermore, the expansion of wireless data rates is in direct conflict with preservation of a healthy environment.

Keywords

Electromagnetic Radiation; Heat; Health Impacts; Ionization; Telecommunications; Specific Absorption Rate.

List of Abbreviations

ADP. Adenosine Di-Phosphate.

ATP. Adenosine Tri-Phosphate.

C_f. Crest Factor.

COMAR. Committee on Man and Radiation.

ΔG. Change in Gibbs (free) energy.

ΔS. Change in entropy.

E_a. Energy of Activation.

IEEE. Institute of Electrical and Electronics Engineers.

ELF. Extra-Low Frequencies.

FCC. Federal Communications Commission.

GSM. Global System for Mobile Communications.

IARC. International Agency for Research on Cancer.

ICBE-EMF. International Commission on the Biological Effects of Electromagnetic Fields.

ICNIRP. International Commission on Non-Ionizing Radiation Protection.

LTE. Long Term Evolution.

MOSFET. Metal-Oxide Semiconductor Field Effect Transistor.

NTER. Non-Thermal Electromagnetic Radiation.

NTP. National Toxicology Program.

OXPHOS. Oxidative Phosphorylation.

ROS. Reactive Oxygen Species.

RF. Radio-Frequencies.

SAR. Specific Absorption Rate.

UPC1. Uncoupling Protein 1.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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The author declares that he has no competing interests.

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Authors' information

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Introduction

Technological electromagnetic radiation, the Extra-Low Frequencies from power systems (50 or 60 Hz), or the Radio-Frequency radiation from broadcasting and cellular phone networks, has spread rapidly in our environment in the last century. Should this radiation be controlled or confined to protect human health? The interesting scientific principles relevant to the discussion have been obfuscated by the powerful financial interests that were created as power and wireless deployments met with tremendous commercial penetration.

As a result, a controversy over health effects of non-thermal electromagnetic radiation (NTER) has been maintained for far longer than necessary.

Thinking based on Energy

IEEE (1991) and ICNIRP (1995) have used two arguments to claim that NTER is inoffensive.

Argument 1 is that NTER does not carry enough energy to ionize living tissues. Few atomic elements have ionization energies lower than 8 x 10^{-19} J, and this energy corresponds to an electromagnetic wavelength of 0.16 μm, in the near ultraviolet. Along the electromagnetic spectrum, typical Radio-Frequencies (RF) rate at 6.6 x 10^{-25} J, and Extra-Low Frequencies (ELF) even lower at 4 x 10^{-32} J. RF and ELF radiation are viewed as too weak to have any consequence.

Argument 2 is that the thermal energy of water molecules (~1.5 x 10^{-20} J) would completely overwhelm the smaller energies (6.6 x 10^{-25} and 4 x 10^{-32} J) applied by NTER to atomic ions in the body. Under the assumption that calcium ions, for example, were energized directly by NTER, collisions between calcium ions and water would have rapidly dissipated any contribution of NTER, setting up the so-called "kT paradox" (Binhi 2007).

These two arguments are used to claim that biological effects from NTER are impossible and can only be attributed to the high intensities connected with heating. The two arguments are loosely connected with the First Law of Thermodynamics, the conservation of energy, in the sense that if a phenomenon is going to happen, it must be propelled by a legitimate force or energy.
These assumptions have led to human safety testing based exclusively on heat. Quantification of electromagnetic heat injection in biological tissues was widely employed in radio-frequency radiation bioeffects research (Justesen 1975; Frey 1994) and in medical applications such as microwave ablation otherwise known as

oncological hyperthermia (Anghileri 1986) using the Specific Absorption Rate (SAR), in W/kg.

$$SAR = \frac{\sigma|\vec{E}|^2}{2\delta} = \frac{\omega\epsilon_0\epsilon_1|\vec{E}|^2}{2\delta} \quad (1)$$

σ is electrical conductivity in Siemens per meter, E the electric field inside the body in V/m, δ the density (kg/m^3), ω the angular frequency in radians per second, ε_0 the dielectric constant of free space, 8.85×10^{-12} F/m, and ε_1 the relative dielectric constant, a pure number.

IEEE/ICNIRP adopted the injected SAR and associated temperature rise as indexes of the biological impacts of electromagnetic field exposures, with a limit of 1 Kelvin above body temperature (IEEE C95.1-1982). A relation between SAR, temperature rise, and time of application was published by Guy in 1976.

$$SAR = 4{,}186\,\frac{c\,\Delta T}{t} \quad (2)$$

c is the tissue's heat capacity (kcal/kg x K), ΔT is the temperature rise (Kelvin), and t is the exposure time (second).

Equation 2 is valid as long as "t", the time of radiation exposure, is sufficiently small to ensure that dissipative influences for heat transfer are negligible.

Examples of "dissipative influences" are blood flow (perfusion) if the tissue is alive and conduction if the tissue is dead. Relevant dissipative times for whole body exposures were quoted as between 6 and 30 minutes (IEEE 1991).

Combining (1) and (2), we obtain the following.

$$\Delta T = \frac{\omega \epsilon_0 \epsilon_1 \left|\vec{E}\right|^2 t}{4{,}186 \times 2 \times \delta \times c} = K\omega \left|\vec{E}\right|^2 t \qquad (3)$$

According to an energy metric, the health impacts of electromagnetic radiation, whether sub-thermal or thermal, would generally increase in proportion to ω (the carrier frequency) and E^2 (the environmental electromagnetic field translated to its intensity in the body). But for IEEE/ICNIRP, K is too small for NTER health effects to be significant.

The critical safety tests on the effects of radiation on living beings retained by IEEE/ICNIRP were performed on a small number of rats (8) and monkeys (5), and over 40 to 60 minutes. This illustrates an *a priori* conviction that heat is the only possible agent of damage, and that health impacts of electromagnetic radiation cannot occur beyond one hour (Héroux 2023).

The procedure used in industry to homologate a portable phone simulates human tissues using a solution of sugar (45-56%), water (40.4-52.5%) and salt (1.4-2.5%) (FCC 1997). But as we shall see below, this thermal model cannot represent the metabolic activities or micro-anatomy of living tissue.

Arrhenius (for gases)

For IEEE/ICNIRP, chemical reactions must be triggerable by NTER to justify non-thermal effects, and these reactions have energy thresholds that are not met by either RF or ELF NTER.

In thermodynamic thinking, even biochemical reactions with negative Gibbs free energy ($\Delta G<0$, exergonic) do not occur spontaneously, and must be provided with an energy of activation to get started. The logic is that in any reaction, some bonds must be broken before new ones are formed.

In 1889, Arrhenius explained that most reactions require added heat energy to proceed by formulating the concept of *activation energy*, a barrier that must be overcome before two molecules react. The Arrhenius equation relates the activation energy (E_a) to the rate (k) at which a reaction proceeds.

$$k = Ae^{\frac{-E_a}{RT}} \qquad (4)$$

R is the universal gas constant, T is the temperature in Kelvin.

This equation can be used to support the energy comparisons used by IEEE/ICNIRP to deny NTER health effects: larger activation energies (E_a) are associated with ionization and water molecules than with those available from NTER.

But the Arrhenius equation, developed between 1860 and 1872, is quite limited. It is based on empirical observations in *gases*, and on their theoretical analysis, an energy averaging over a Maxwell–Boltzmann distribution, with E_a as a lower bound.

Eyring (for liquids)

An improved expression for chemical Reaction Rates was proposed by Eyring in 1935. Contrary to the Arrhenius equation, restricted to gases, its scope included condensed matter such as liquids or solids. The Eyring equation expresses the relationship between Reaction Rate (k) and the Gibbs (free) energy of activation, ΔG, which represents the energy needed for a reaction at constant pressure.

$$k = \frac{\kappa_t k_B T}{h} e^{\frac{-\Delta G}{RT}} \quad (5)$$

κ_t is the transmission coefficient of the transition state to the product (between 0 and 1), k_B is Boltzmann's constant, and h Planck's constant.

In liquid solutions, molecules must often be put in a contorted state to trigger a reaction, and the energy for such a change can come from the thermal movement of water molecules (~1.5 x 10^{-20} J). The molecules critical to living systems (protein, DNA, RNA) need to be stable, and would disintegrate if their activation energy was too low, so it is observed that temperature does not affect them, as long as it is within the physiological range.

Bennett-Chandler (enthalpy and entropy)

A further refinement on Reaction Rates was contributed by Bennett in 1977 and Chandler in 1978, which accounts for the energy involved in the formation of the "unstable intermediate", the activated complex that makes the final reaction possible. These activated conformational changes are important for biological macromolecules. The Reaction Rate (k) is then written as follows (Espenson 1981).

$$k = \frac{\kappa_t k_B T}{h} e^{\frac{-\Delta H}{RT}} e^{\frac{\Delta S}{R}} \quad (6)$$

The first factor represents collision frequency, ΔH the enthalpy of activation, and ΔS the entropy of activation related to the creation of the activated complex or transition state: positive ΔS indicates a dissociative, and negative ΔS an associative mechanism.

The Bennett-Chandler equation explicitly displays entropy (S). A fall in entropy ΔS must be accompanied by a rise in free energy ΔH. Although this equation was developed for a specific chemical reaction, it can be re-interpreted as a homeostatic expression for the collection of reactions happening in living systems.

Sustaining life (homeostasis) requires continual arranging of atoms and molecules into assemblies needed to repair, develop and duplicate living cells. Development of these complex structures decreases entropy (-ΔS), counteracting the universal tendency towards disorder and uniformity prescribed by the Second Law of Thermodynamics.

To remain consistent with the Second Law of Thermodynamics, self-organizing reactions that lower entropy values (life processes) *must* dissipate energy so as to increase entropy (+ΔS) elsewhere (Pascal 2023). This compensation is what Schrödinger described in 1944 as feeding on negative entropy, or "negentropy" (Schrödinger, republication 2010).

The energy needed comes from redox reactions that transfer electrons. These electron transfers inevitably involve some electron losses. It is these electron losses that are avidly captured by oxygen as Reactive Oxygen Species (ROS) and produce the increase in entropy required to at least balance the entropy lost to biosynthesis. The negative effects of ROS are controlled by enzymatic antioxidants such as superoxide dismutase, catalase and glutathione, and non-enzymatic antioxidants such as vitamin C and E, carotenoids, thiols, flavonoids and melatonin (Flora 2009).

About Argument 1

By requirement of the Second Law of Thermodynamics, living tissues are inevitably actively ionized and generate ROS through metabolic activity. The fact that life provides its own metabolic energy, activating reactions independently of the energy injected by electromagnetic fields, removes all objections to NTER health effects based on the First Law of Thermodynamics. Although living systems would be more vulnerable to NTER if it *was* ionizing, targets (ROS) are provided for the action of NTER by the very process of life itself, even if NTER is non-ionizing (Yakymenko 2016).

About Argument 2

Inorganic redox electron transfers between two atoms typically occur over very small distances, fractions of nanometers or nm (Vance 2000; Gauduel 2003). For scale, refer to the diameter of hydrogen (0.1 nm) and iron (0.25 nm) atoms as green dot and red dots in Figure 2.

But biology has made two evolutionary choices in its implementation of biological redox reactions as oxidative phosphorylation (OXPHOS).

The first is biomolecular: tunneling of electrons over multiple nanometers in series within large molecules (Figure 2).

The second is a micro-anatomical one in mitochondria that will be described in later sections: the transfer of electrons and protons over hundreds of nanometers to provide living systems with energy in the form of adenosine triphosphate (ATP).

This expansion of the physical size of electron and proton currents amplifies the interaction between external NTER and living processes.

These electron and proton currents thus provide a target for NTER without the need for external ionization, and these targets are inevitable according to thermodynamics.

Electrons in metallic conductors react at the speed of light to the application of voltage, but heating of the metallic ions lags behind because moving electrons need to collide repeatedly with metal atoms to heat them. This view is compatible with the Drude-Summerfeld model (Summerfeld 1927) of delocalized electrons (a degenerate Fermi gas) in metals. In living tissues, the light charge carriers (electrons and protons) are not tightly linked to the energy of atomic ions or molecules, particularly if the field is applied suddenly and for very short times (non-thermal), which is frequently the case for pulsed wireless communication signals.

The energy-generating redox reactions embodied by OXPHOS provide continuous electron and proton flows over 150 nm distances that amplify the vulnerability of living tissues to environmental NTER: these currents are 200 times the size of those in simple redox reactions, which were themselves thought to be vulnerable to NTER (Binhi 2007). The critical reactions of OXPHOS were provided by chemistry even at the origin of life and are designated as "metabolism" by biologists.

Life Reactions: Metabolism, Redox, ATP

"Metabolism" can refer to the sum of all chemical reactions that occur in living organisms, but more specifically to the chemical reactions that use food to produce the energy that we need to move, think, grow, and repair tissue damage.

Electrons supply the energy to run biological reactions. Electrons have more energy when they are in less electronegative atoms (such as C or H in our food, which we "oxidize"), and less energy when they are associated with a more electronegative atom (such as the oxygen we breathe, which we "reduce"). The electron movement from food to oxygen within the mitochondria in our bodies is called the *electron transport chain*. Because oxidation and reduction usually occur together, these pairs of reactions are called "redox" reactions. Redox is involved in all important biological processes, such as cellular respiration and photosynthesis. As electrons are passed from an electron donor (food) to an electron acceptor (oxygen) in the body, the energy difference is used to stock a pool of protons, and these protons are used to produce molecules of adenosine triphosphate (ATP). ATP carries releasable energy and diffuses throughout the cell to power its reactions ($\Delta G>0$, endergonic). Note that the energy available from a single molecule of ATP, 5.1×10^{-20} J, is approximately 3.4 times higher than a water molecule's kinetic energy.

Cells die without ATP. We know that 5 to 6 seconds without ATP generation causes severe arrhythmia and cardiac failure. If oxygen-carrying blood to the brain is blocked, a person passes out within 5 to 10 seconds, and dies within minutes, as ATP disappears, and its production is halted. Humans consume their own weight in ATP every day, and as it is broken down to adenosine diphosphate (ADP), the loss of one phosphoanhydride bond releases 26 kJ/mol. But since our body only contains about 50 g of ATP, each ADP molecule must be recycled to ATP from 500 to 750 times each day.

The following reaction, glycolysis, is actually a series of ten chemical reactions that require the input of two ATP molecules. This input is used to generate four new ATP molecules, which means that glycolysis results in a net gain of two ATPs.

$C_6H_{12}O_6$ (glucose) + 6 $O_2 \rightarrow$ 6 CO_2 + 6 H_2O

The reaction above yields two ATPs. But a process which combines the oxygen we breathe with fatty acids from our food yields 30 to 32 ATP molecules. Because the process requires oxygen and phosphorylates ADP to ATP, it is named oxidative phosphorylation (OXPHOS). We will see below that OXPHOS is totally dependent on continuous currents of electrons and protons to maintain metabolism (Mitchell 1966). This implementation of metabolism, OXPHOS, magnifies the size of the target of interaction with NTER beyond the free radicals required by the Second Law. All this *inevitable* metabolic activity is the essential distinction between living and inert materials and has been the focus of three Nobel prizes (Warburg 1931; Krebs 1953; Boyer, 1997).

Electron and Proton paths in Mitochondria

A single OXPHOS chain is made of many enzymes, some of which are very large molecules named Complexes I to V. Electrons and protons currents circulate continuously between Complexes.

Electron Current

Electrons available from our food enter Complex I (labeled red “1”) in Figure 1 and are carried away at Complex IV (labeled red “2”), where oxygen atoms accept the electrons, which are then passed on to water molecules. Electrons are propelled through molecules by tunneling (see Belevich 2010 for Complex IV) or diffusion through water (Castelvecchi 2021). The whole electron transport chain (I to IV) is of the order of 100 nanometers in length (Hirst 2018).

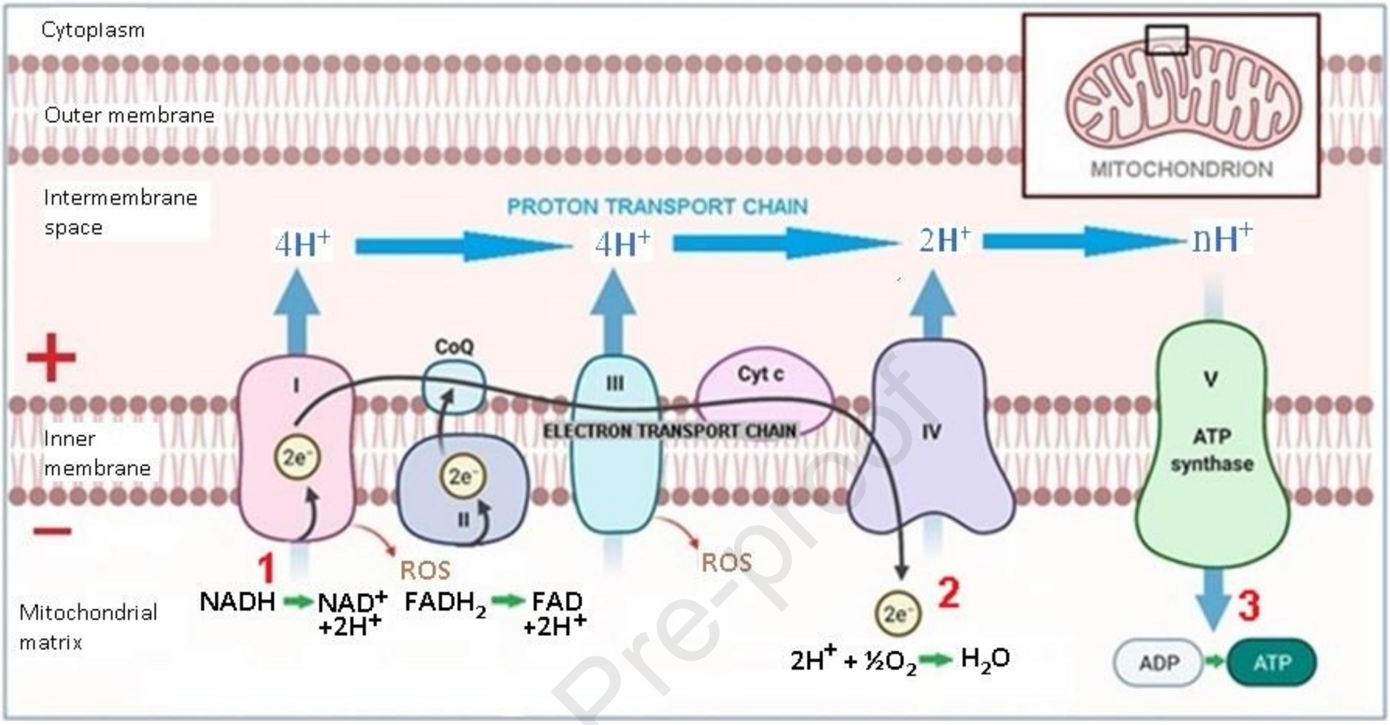

Figure 1. Electron and proton currents are traced in black and blue, respectively, within the OXPHOS chain. Molecular Complexes are labeled with black Roman numerals (I to V). The diagram is about 200 nanometers wide. Plus and minus signs in red indicate static polarization of the inner mitochondrial membrane.

Figure 2 shows the tunneling path of electrons across seven or more gaps in series (yellow arrows) through Complex I, otherwise known as NADH ubiquinone oxido-reductase. The enzyme aligns iron atoms (in red) for the transfer of electrons across gaps of less than 1.4 nm (Kuss-Peterman 2016).

The gap length is critical in determining the speed of electron transfer, as an increase of 0.1 nm means a 10-fold decrease in transfer speed (Moser 2010).

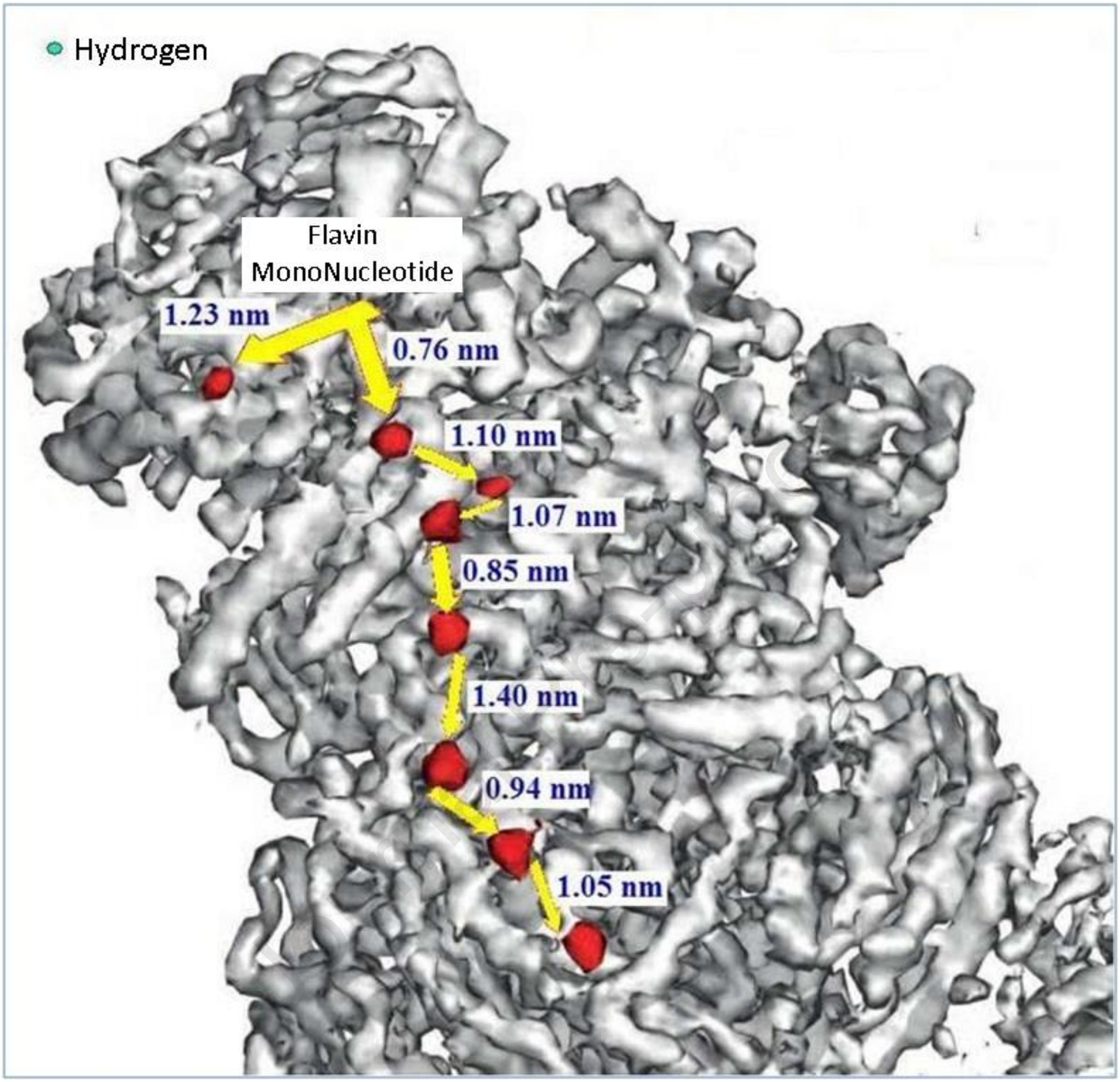

Figure 2. Electron jumps in Complex I (Vinothkumar 2014).

These traveling electrons are inevitably pulled on by external alternating electromagnetic fields, changing their position and circulation. Complex I itself, with a molecular weight of 950,000 Daltons, is 1.73 billion times more massive than an electron, forming an immovable reference to the NTER action on electrons. Perturbation of electron flow in Complex I and elsewhere allows the "smaller energies" of electromagnetic radiation to control large proton fluxes into the inter-membrane space of mitochondria.

Turning briefly to electrical engineering, small electric or magnetic fields impacting large currents should be familiar. Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFET, the most common transistor in digital circuits) use electric fields to control currents 2.9 x 10^{15} times larger. Spin tunnel junction magnetic sensors (Spin TJ 2024) offer detectabilities of 100 pT/Hz$^{1/2}$ at 1 kHz. The MOSFET and Spin TJ examples illustrate the large sensitivities that are achieved in semiconductor devices, and that could find analogs in biological systems.

This may explain why certain investigators (Hutter 2006) have documented human symptoms of electromagnetic radiation exposures at tens of µW/m^2.

Proton Current

The proton transport chain also starts at Complex I (labeled red "1") as well as at Complexes III and IV, and ends at Complex V, ATP synthase (labeled red "3"). This is where Adenosine Diphosphate (ADP) is upgraded to ATP, the energy currency of cells. The proton current flows in the inter-membrane space along the inner membrane, *without counter-ions*.

The protons keep the inner membrane under a typical voltage of 160 mV (+ and – in red in Figure 1), the highest static electric field (30 MV/m) of all eukaryote systems. The unusual strength of this polarization can be appreciated if we remember that most biological membranes puncture beyond 1000 mV. There is a difference of 1 in pH between the inter-membrane space and the mitochondrial matrix.

Entering ATPS synthase (Complex V), proton current flows towards a nano-confined alpha water channel with a structure similar to ice (Reiter 2011) that gives it exceptional tunneling conductivity. Complex V itself is a protonic motor (Yoshida 2002) driving a rotation which upgrades ADP to ATP. The proton transport chain covers distances of the order of 200 nm (Sjoholm 2017; Muhleip 2023).

OXPHOS Architecture

The electron transport chain that consumes glucose and other foods using oxygen releases energy (-ΔG), while the proton transport chain synthesizing ATP absorbs energy (+ΔG). Nature has every interest in making the electrical circuit in each of them as conductive as possible. This is why the OXPHOS Complexes I to V are tightly arranged in the cristae of mitochondria (folds of the inner membrane visible at top right of Figure 1).

This high conductivity also manifests when the protein UPC1 (also known as thermogenin) is activated in the inner mitochondrial membrane, creating "uncoupling". UPC1 is a channel that allows protons to pass from the inter-membrane space to the matrix without traveling through ATP synthase. By providing an alternate low energy route for protons ("shunt") to flow back into the matrix, UPC1 allows food energy to be dissipated as heat (Rousset 2004). This adaptive process is used to generate non-shivering heat in tissues known as brown fat (Nicholls 2021).

The Complexes of the electron transport chain are grouped together in super-complexes, while ATPS groups, critical to OXPHOS's optimal operation (Morowitz 1978; Bennett 2021), are a little further away (Muhleip 2023). The physical arrangement of the complexes (I to V) is variable over time according to physiological conditions and is altered in diseases such as Alzheimer's and Parkinson's (Novack 2020). Although OXPHOS units are only hundreds of nanometers in size, an enormous number are scattered through the human body ("multiple input" for NTER), as shown in the last column of Table 1: there are many cells in the human body, there are many mitochondria per cell (Figure 3), and there are many OXPHOS chains per mitochondrion.

Table 1. The total length of active currents that can be influenced by radiation is considerable.

Cells in human body	Mitochondria per cell	ATP Synthase molecules per mitochondrion	Number of 150 nm Conductors (Cells x Mito x ATPS) in human body
36 x 10^{12} (male) 28 x 10^{12} (female)	100[1]	100 - 5 000[2]	280 000 000 000 000 000 to 18 000 000 000 000 000 000
Total Length of Receiving Antenna Segments = 4.2 - 270 10^7 km			

[1] 5 for sperm; 200 for skin; 1 000-2 000 for liver; 1 600 for small intestine; 1 700 for muscle; 5 000 for heart muscle; 600 000 for human egg; 2 000 000 for brain cell. See Figure 3.
[2] Counting only active ATPS; total ATPS can be up to 100 times higher (Fahimi 2021).

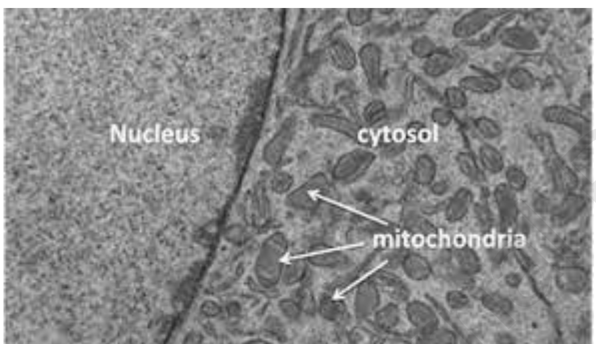

Figure 3. Micrograph shows the border of the nucleus of a cell and adjacent cytosol, which contains large numbers of mitochondria (Cameron 2013).

The last column of Table 1 shows that the human body hosts quintillions of conductors hundreds of nanometers in size, continuously bearing the electronic and protonic currents needed to maintain cellular energy. For scale, these small conductors carry electron and proton currents over distances 536 times larger than a molecule of water, which is only 0.28 nm in size.

Proton movement is expected to be favored by the exceptionally strong Stern layer formed on the mitochondrial inner membrane by the 160 mV polarization, which acts as a “skating rink” for the efficient transfer of the protons of metabolism.

Detailed modeling of the electrical properties of biological tissues shows that living matter has a dielectric constant across wide frequencies much larger than expected from the Debye dispersion of water (Cundin 2010).This analysis perceives a metallic (highly conductive) component hidden within the dielectric properties of biological tissues.

By weight, the human body is mostly water. In the visible part of the NTER spectrum, the absorption coefficient of water is exceptionally low, which means that under this radiation (light), the water matrix is mostly undisturbed. The situation is different in the GHz range and it is a commonly held engineering view that the high absorption of NTEM at such frequencies is beneficial, leading to poor penetration in living organism, but with the inconvenience that SAR concentrates, sometime to thermal levels, on delicate surfaces such as the eye (Levine 2009).

But at frequencies of Wi-Fi (5 GHz) and high band 5G (26 GHz), the absorption coefficients of water are respectively 1,000 and 10,000 times higher than in the visible (Segelstein 1981), perhaps leading to perturbations in the interactions of hydrated protein (Fogarty 2014).

Where the Environment Perturbs Metabolic Currents

Maxwell's equations are non-homogenous linear partial differential equations. Mathematically, the sum of any two solutions of these equations is itself a solution

(Crawford 1968). The principle applies to all waves, and specifically to electromagnetic waves, and says that when two waves overlap in space, the resulting wave is equal to the sum of the individual waves. This is widely known as the *principle of superposition*.

Since there is a field driving the electron and proton currents, this field will be perturbed by electromagnetic radiation coming from outside, specifically by radiation emitted by a cell phone, network tower, or power system.

Even though the static membrane polarizing fields are huge, the fields moving the electrons and protons are much smaller, which means than the alternating fields from NTER, can perturb the OXPHOS process. A multitude of points of action are possible: electron tunneling steps in Complexes, diffusion of electrons and protons in water, and tunneling of protons through ATP Synthase's special alpha channel.

Thus, the perturbation of the currents of metabolism by the currents induced by environmental NTER depends only on the two occupying the same space. That environmental NTER effectively modifies the biological fields of metabolism way below thermal levels is demonstrated by many reports, but we mention here two particularly clear ones, for ELF (Li 2013) and for RF (Sanders 1985).

When the Currents Stop

The free electrons and protons of metabolism should manifest in measurements of the dielectric properties of living tissues. Classical work on these dielectric properties investigated the dispersion over frequency of individual components such as water, protein, biopolymers and solvated biomolecules. Studies were also made of the electrical properties of biological membranes.

However, few measurements were made in tissues that were actually alive (Schwan 1956), and tissues samples were viewed as "fresh" even tens of hours after excision. Fleeting reference is made in the literature to delocalized electrons, protonic currents and to travel of electrons through molecules, but the overall mindset is the investigation of a passive circuit as opposed to an active (metabolizing) one. There is only a passing reference to the influence of physiological state on dielectric properties (Pethig 1979).

When oxygen supply is stopped to a living tissue, there is nothing to maintain this polarization, and detectable changes should occur.

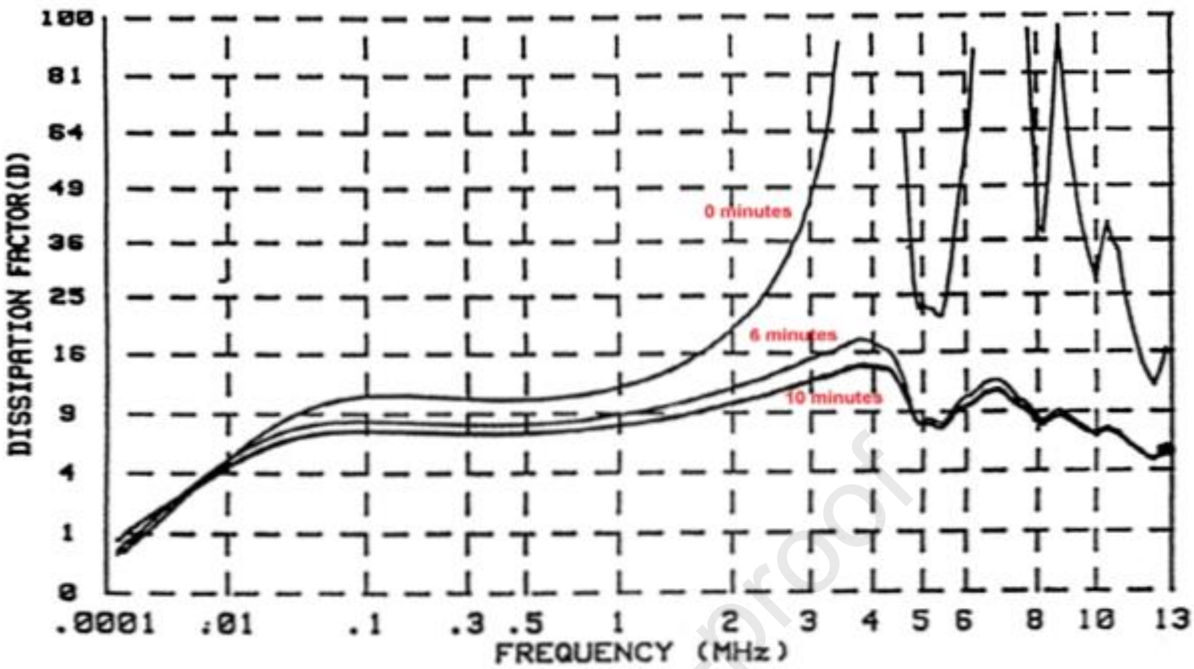

Figure 4. Dissipation Factor (D) dispersion across frequency (MHz) in the cortex of a rabbit following anesthetic overdose. Measured at 0, 6, and 10 minutes after overdose (Héroux 1993) .

Figure 4 shows a real-time measurement of the electrical dissipation factor in the brain cortex (~1 mm deep) of a rabbit. Following anesthesia, parietal craniotomy, removal of the dura and implantation of an impedance probe, the first (baseline) measurement is completed at 0 minutes. Immediately, an intra-peritoneal barbiturate overdose is then administered. The overdose inhibits the rabbit's respiratory center: blood flow and oxygen to the brain are stopped about 2 minutes later. Proton and ATP supply interruptions follow in short order, corresponding to the "6 minutes" trace in Figure 4. The relatively rapid measurements were provided by a Hewlett-Packard 4192A Impedance Analyzer.

What these results suggest is that within times that correspond to loss of consciousness under anoxia, dielectric properties of living tissues can change very drastically. The variable used in Figure 4 is the Dissipation Factor, R/X, familiar to engineers as tangent delta (tg $\delta = 1/Q$). This metric is used because of its low sensitivity to effective electrode area, to relative orientation between tissue fibers and electrode pair axis, yet is favorable to sensing small tissue electrical properties, as reactance (X) is the denominator (Héroux 1993).

The results reported in Figure 4 are not typical of what happens on interruption of blood perfusion in other body tissues, which vary widely in their speed of reaction to anoxia.

Table 2. Electrical Impedance changes in Rat tissues following Anoxia (Héroux 1991; Fahimi 2021).

Tissue	Impedance Change (Ohms / minute)	Mitochondria / cell
Muscle (n = 10)	0.436	1 700
Liver (n = 10)	6.15	1 000 – 2 000
Brain (n = 2)	128.7	2 000 000

The tissue impedance changes listed in Figure 2 are geometrical means across frequency (240 frequencies) of resistance and reactance values.

Since there is a rough dependance between Ohms/minute and number of mitochondria per cell, one can infer that impedance change rates reflect the dependency of the tissues on oxygen supply. Although these numbers are comforting for muscle and liver transplants, they augur poorly for brain transplants. Given the corresponding time frames between anoxia and impedance changes, it may be that syncope can be measured in Ohms.

It is therefore not surprising that the effects of NTER would occur most obviously in the nervous system in animal models (NTP 2019; Falcioni 2018) and in electromagnetically hypersensitive subjects (Belpomme 2023).

Crest Factors, Fields, and Time

The following equation is a re-write of equation 3 which represents the NTER impacts (in Kelvin) that can result from injection of small sub-thermal fields.

$$NTER\ impacts = K\omega\left|\vec{E}\right|^2 t = K_1\omega\left|\vec{E}\right|^2 \quad (7)$$

In equation 7, we eliminate time "t" by choosing for "t" the length on an LTE frame (10 msec), which fulfills the condition of equation 2 of low dissipative influences (10 msec = 0.000166 minute << 6 minute), and swapping K for K_1. But we are aware that wireless digital signals are made of successive pulses and not uniform over time. Consequently, to accurately represent the total range of activation energies that are enabled by a particular signal, one should consider the crest factor C_f of such signals. Under the assumption that transition thresholds of important biological reactions are uniformly distributed as a function of field intensity, we obtain.

$$NTER\ impacts = K_1 \omega \left|\vec{E}\right|^{2-4} C_f \quad (8)$$

Some investigators (Miclaus 2023) have examined such crest factors for 4G and 5G signals referenced to mean power, based on complementary cumulative distribution functions, and have quoted C_fs of 5 to 11 for 4G and 8.5 to 16.2 for 5G.

Equation 8 simply states that when higher energy levels are reached, even briefly, a wider range of physiological processes can be triggered.

The inclusion of a crest factor in equation 8 can also be justified from an engineering perspective, as rapid rise pulses such as a δ function have wide Fourier transforms, enabling them to disturb biological steps with different resonances or transition times, some of which may combine synergistically. Wireless transient signals are difficult to absorb for biological systems, simply because they occur at speeds beyond physiology, which is slower in practically all aspects of its controls such as hormones, cytokines or even action potentials.

A classic toxicological concept is now added to equation 8, “Area Under the Curve”. This concept simply expresses that the more sustained a stimulus is over time, the stronger the response. This is included by the factor “t*” in equation 9.

$$NTER\ impacts = K_1 \omega \left|\vec{E}\right|^2 C_f \ \mathrm{t}^* \quad (9)$$

This “t*” is Non-Thermal Time, different from the “t” in equation 7, because it has an athermal restriction. In other words, the variable integrates the presence of the stimulating field over time, but never in such a way as to significantly increase temperature (low duty cycle).

A last adjustment to equation 9 may be needed, as physiological reactions to transient events have been gauged by two enlightening metrics in other areas of science, such as mechanical vibration (Thuong 2011) . The rms method (with an exponent of 2, compatible with energy) and the root-mean-quad method (exponent of 4) tended to, respectively, underestimate and overestimate the discomfort of acceleration in mechanical vibration. The optimum evaluation method had an exponent of about 3.0 for 1-Hz motions and 3.5 for 8-Hz motions, which seems to indicate that a higher exponent is appropriate for more rapid phenomena.

$$NTER\ impacts = K_1 \omega \left|\vec{E}\right|^{2-4} C_f\ t^* \quad (10)$$

Shannon-Hartley Theorem

The Shannon–Hartley theorem establishes the capacity of a finite-bandwidth channel subject to Gaussian noise as follows.

$$Capacity\ \left(\frac{Bits}{second}\right) = Bandwidth\ (Hz) \times \left(\frac{Signal\ (Watts)}{Noise\ (Watts)}\right) \quad (11)$$

Since in practice wider bandwidths can be assigned for a similar number of channels when carrier frequency is higher, assuming a constant noise background, and a signal energy proportional to field squared, we obtain the following.

$$Functional\ Wireless\ Capacity = K_2 \omega \left|\vec{E}\right|^{2} \propto NTER\ impacts \quad (12)$$

In (12), K_2 includes crest factor C_f and non-thermal time t*.

It therefore appears that opportunities for greater wireless data transit, which depend on higher carrier frequencies and larger signal to noise ratios, which are closely related to crest factors, unavoidably imply larger NTER health impacts, even under conventional thermal and energy of activation thinking.

The analysis also pictures IEEE/ICNIRP views on NTER health effects as residing in the late 19th century.

Vulnerability of Life to General Radiation

What escaped the attention of many is that life's metabolism and design make it much more vulnerable to NTER than inert matter. Living tissue has mostly adapted to the Sun's radiation as well as to the static field of the Earth only through the course of 3.5 billion years of evolution. But this immunity is not complete, as we still sunburn and get cancer from ultra-violet radiation. A favorite model of biologists which is small enough to be seeped through by radiation, the fruit fly (*Drosophila melanogaster*), is far healthier under dark conditions, all other visible colors shortening life-span and locomotor activity by as much as 40% (Krittika 2022). Observations in human populations seem to confirm this, as chronic exposure to cell tower radiation has been linked in a small study to unrepairable genetic damage. Low dose GSM 900 and LTE radiations increased the incidence of a number of different types of chromosomal aberrations (Gulati 2024). The connection between metabolic disturbances by NTER, ROS generation and mutations is physiologically plausible.

But the levels of NTER from wireless techniques that we are experiencing now are totally unprecedented, and living systems have no defense against this new arrival (Bandara 2018).

Even for static fields, adverse cardiovascular outcomes have been linked to changes of 10 nT, 0.03% of the Earth's baseline (Zilli Vieira 2022).

Political History of NTER Health Effects

Nancy Wertheimer linked ELF magnetic fields to leukemia in children in 1979. That same year, the first commercial automated cellular network (1G), which used analog RF radiation, was launched in Japan by Nippon Telegraph and Telephone. Electrical and electronics industries were faced with hygiene and toxicological subjects in which they had no indigenous expertise. But they knew that exploration of these areas could significantly impact their operations.

Numerous research projects of different styles were pursued by industry focusing on ELF or RF which were expected, within industry, to placate the hypotheses and apprehensions of biologists and health specialists. As the results of these early studies were interpreted differently by different camps, the gulf between the views of industry and those of the health community on impacts of NTER became apparent. Those differences of opinion became entrenched, and in August 2007, the BioInitiative Report was published by a group of academics who challenged the views of industry. Industry's answer was swift (COMAR 2009).

IEEE is possibly the largest technical professional organization in the world with 450,000 members, and it could use its influence to promote its views to governments, particularly in the Western world. In the end, when faced with what it considered uncertain science, industry opted to deny effects of NTER in standards setting, acknowledging only electrocution, cardiac fibrillation, and shock for ELF (IEEE 2002) and heat effects for RF (IEEE 1991). Both focused on short term effects, substantially avoiding (Maisch 2009) the chronic health effects typically tackled by epidemiology.

Independently from this conflict, symptoms were increasingly experienced in human populations due to the enrichment of NTER exposures. Non-thermal protection limits have been published to alleviate the symptoms of NTER exposures in sensitive individuals (Belyaev 2016).

We believe it is time for industry to re-evaluate its positions on the basic hygiene of NTER. This is particularly urgent since industry has used dated arguments to develop a style of telecommunications relying heavily on wireless that has the potential to exert substantial public health impacts.

Biological Consequences

The huge scientific literature reporting biological impacts of NTER (ORSAA) can only be summarized here. The numbers presented in Table 3 should dispel any doubts on the opinion of the general scientific literature.

Perturbation of OXPHOS: Reactive Oxygen Species

Even under the best conditions, and without NTER exposure, the electron transport chain leaks at least 0.1-2% of the electrons it processes as ROS, mostly from Complex I. Henry Lai from the University of Washington has repeatedly compiled the electromagnetic radiation literature on biological effects (Lai 2018; Lai 2019; BioInitiative updates).

At the top of Table 3, we can see that a vast majority (89-90%) of articles in the literature investigating the connection between ELF or RF radiation and free radical or oxidative effects confirm the electron losses from exposures.

Table 3. Literature confirming Effects of Non-Thermal Electromagnetic Radiation (NTER).

Effect	Electromagnetic Fields	Number of Studies	% Positive (footnote)
Free Radical-Oxidative	Low Frequency	229	89%
Free Radical-Oxidative	Radio Frequency	225	90%
Free Radical-Oxidative	Radio Frequency	354	89% (1)
Neurological	Radio Frequency	435	77%
Reproduction/Development	Radio Frequency	335	83% (2)
Genetic Effects	Radio Frequency	466	70% (3)

[1]This includes 95% of 86 studies with a SAR $\leq$ 0.40 W/kg, ten times less than the 4.0 W/kg threshold of harm that IEEE/ICNIRP use in their RF radiation exposure limits.
[2]Among studies that reported significant effects, 56 studies used a SAR $\leq$ 0.40 W/kg, and 37 studies a SAR $\leq$ 0.08 W/kg.

[3] Including 79% of 144 studies of gene expression.

Yakymenko's review (2016) sampled 100 studies investigating oxidative effects: 93 of those confirmed induction by RF NTER, solidifying Lai's assessment. Among the 93, 4 were in humans, 17 in vitro, and 72 in animals and plants. Of note, a wide variety of NTER signals were effective at producing effects in plants (Kundu 2021a, Kundu 2021b; Porcher 2023; Porcher 2024).
Table 3 also summarizes general statistics on other aspects of NTER biological effects, specifically neurological, reproduction/developmental and genetic effects.

Health Consequences

Given that equation 12 above links wireless capacity to impacts, what does the current state of science suggest for a future heavy with NTER exposures?
The biological results reported above clearly support caution. There are in fact many mechanisms and diseases involved.

Given that leukemia was detected first, and that cancer is intensely studied, it is not surprising that there would already be substantial evidence that cancer can be induced both by the RFs of portable phones (NTP 2019) and cell towers (Falcioni 2018) as well as by ELF exposures.

The nervous system was prominent in both RF results, apparently because it is highly dependent on the supply of ATP.

Our own *in vitro* work on ELF (Li 2013) has shown that what is true for leukemia is likely true for other cancers, as NTER challenges a very basic physiological process, OXPHOS. This means that variable exposures to NTER will produce a fluctuating level of ATP production and a wider variety of daughter cancer cells (Li 2013), making an already existing tumor seed more malignant. This wide-ranging effect of NTER on carcinogenicity is confirmed by epidemiology (Dode 2011; Hardell 2013; Choi 2020).

An extensive body of biological data reported in the previous section confirms the link between NTER and free radicals. This is further supported both in individual *in vitro* studies on normal (Alipour 2022; Benavides 2023) and cancer cells (Li 2013), and in wide reviews (IARC 2013; Yakymenko 2016). ROS have long been related to chronic diseases such as Parkinson’s and Alzheimer’s (Houldsworth 2024) . So, NTER could play its role in keeping their incidences rising.

The case of diabetes positions NTER as an endocrine disruptor. NTER alters pH and ROS levels in important compartments of the human body. The ELF or RF fields are capable of interference with the activity of free protons in the intercellular interstitial fluid, resulting in impaired binding of insulin to the GLU4 receptor. The interference relates to the Grotthuss mechanism (Popov 2023), a basic proton exchange that occurs completely naturally in water and allows the measurement of pH even in pure water. Biological dysregulation appears to occur over 7 years (Héroux 2024).

The file on reproductive hazards from NTER is convincing, which means that unless NTER exposures are curbed, the worldwide decrease in fertility, particularly in males, will probably continue (ICBE-EMF 2022).

Many of these diseases have been labeled “diseases of civilization” (Milham 2010). They are of course multi-factorial, but some of them show good correlation with rises in human NTER exposures. For many of them, including diabetes (Milham 2013), there is hope that if exposures are controlled, the growth of prevalence could be reversed.

Reversibility

But some chronic consequences of NTER exposures may not be reversible. Applied to reproductive tissues, NTER action could undermine OXPHOS's efficiency, resulting in irreversible devolution (as opposed to evolution). OXPHOS currently yields 30 to 32 ATP molecules, but mitochondrial polymorphism and heteroplasmy are currently acknowledged as agents in progressive diseases such as aging and cancer (Smith 2022). The 13 genes resident in mitochondria (compared to 32,000 in the nucleus) are described as the "mitochondrial time clock", because this is where mutations accumulate the fastest in human genetics (Cabrera 2021).

Challenging the very basic process powering biological systems, especially at the genetic level, is a dangerous game. "Tamper with this reaction at your peril." (Lane 2015; evolutionary biochemist and winner of the 2015 Biochemical Society Award).

Conclusion

Modeling living tissues as sugar/water/salt, or as separate bio-molecular components such as protein, biopolymers and solvated biomolecules excludes the most essential element of the living process, which is the continuous traffic of electrons and protons maintained by metabolism.

These currents are required by the Second Law of Thermodynamics, and their vulnerability to NTER is enhanced by the anatomy of OXPHOS.

In a more complete model, and from the principle of superposition, oscillating electric or magnetic fields penetrating from the environment will alter the tissue's electron and proton currents. These can be far more easily disturbed by external electromagnetic fields than ionic species. To be biologically active, NTER does not need to produce ionized targets or electronic currents itself, but only to disturb those already provided by biology.

The present environmental perspective is sad given that a substantial engineering toolbox is available to mitigate NTER exposures: optical fiber, wire twisting, earthing practices, DC power. But a reversal of exposure tendencies will be difficult, as industry has long enjoyed the support of a critical actor, the military. The same wireless communication techniques used to enable maneuverability in war theaters can also be used for high data rate access in civilian environments. Innovations such as 5G are useful to the military. Consequently, the military support these developments with the goal of achieving superiority over their adversaries in a theater of war (Department of Defense 2020).

The alliance between industry and the military certainly has some practical advantages, but it has one major drawback.

If your environment is made to mimic a theater of war, it will not be a theater of health.

This paper addresses aspects of electron and proton dynamics in living systems. While it raises the subject of telecommunications signals crest factors, it ignores characteristics of common carrier modulations such as GSM and LTE, believed to be of importance in determining health impacts (NTP 2019). Refinement of modulations may minimize biological impacts, with the ultimate goal of controlling enough of those impacts to uncover new modulation schemes capable of reducing major health effects.

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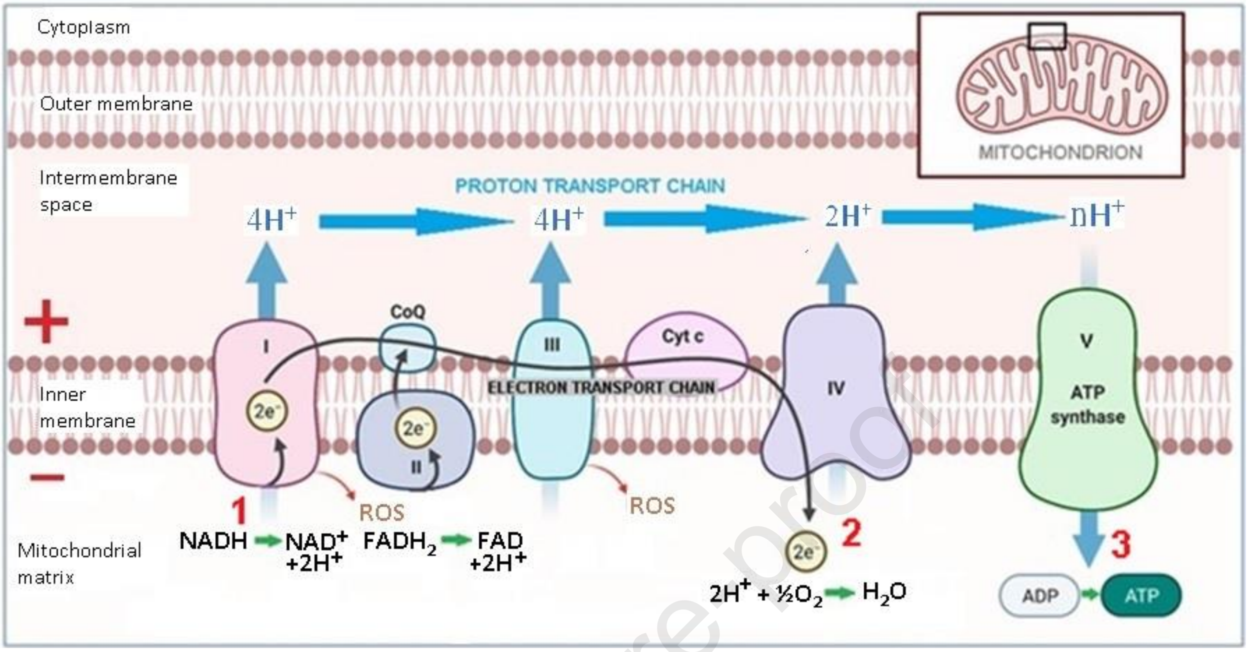

Figure 1. Electron and proton currents are traced in black and blue, respectively, within the OXPHOS chain. Molecular Complexes are labeled with black Roman numerals (I to V). The diagram is about 200 nanometers wide. Plus and minus signs in red indicate static polarization of the inner mitochondrial membrane.

1124 **Figure 2. Electron jumps in Complex I (Vinothkumar 2014).**

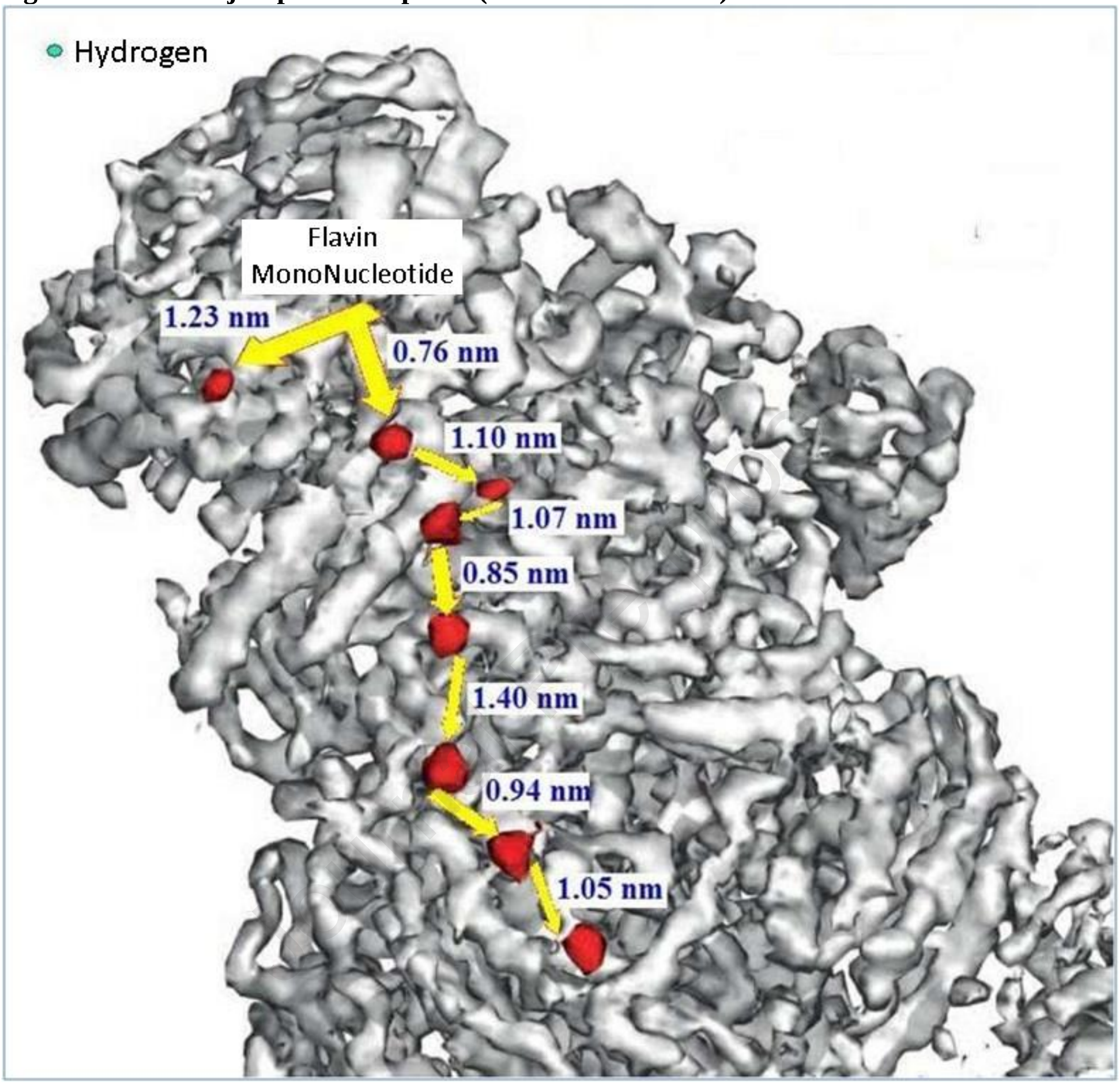

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Table 1. The total length of active currents that can be influenced by radiation is considerable.

[1] 5 for sperm; 200 for skin; 1 000-2 000 for liver; 1 600 for small intestine; 1 700 for muscle; 5 000 for heart muscle; 600 000 for human egg; 2 000 000 for brain cell. See Figure 3.

[2] Counting only active ATPS; total ATPS can be up to 100 times higher (Fahimi 2021).

Cells in human body	Mitochondria per cell	ATP Synthase molecules per mitochondrion	Number of 150 nm Conductors (Cells x Mito x ATPS) in human body
36 x 10^{12} (male) 28 x 10^{12} (female)	100[1]	100 - 5 000[2]	280 000 000 000 000 000 to 18 000 000 000 000 000 000
Total Length of Receiving Antenna Segments = 4.2 - 270 10^7 km			

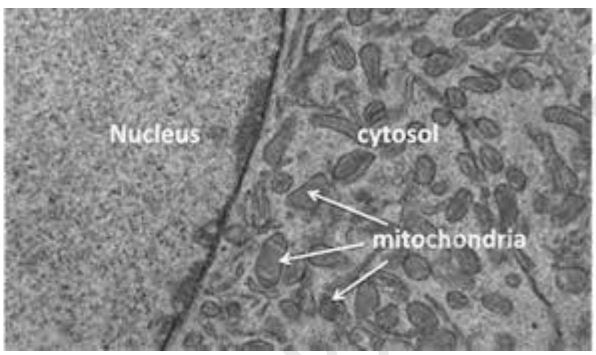

Figure 3. Micrograph shows the border of the nucleus of a cell and adjacent cytosol, which contains large numbers of mitochondria (Cameron 2013).

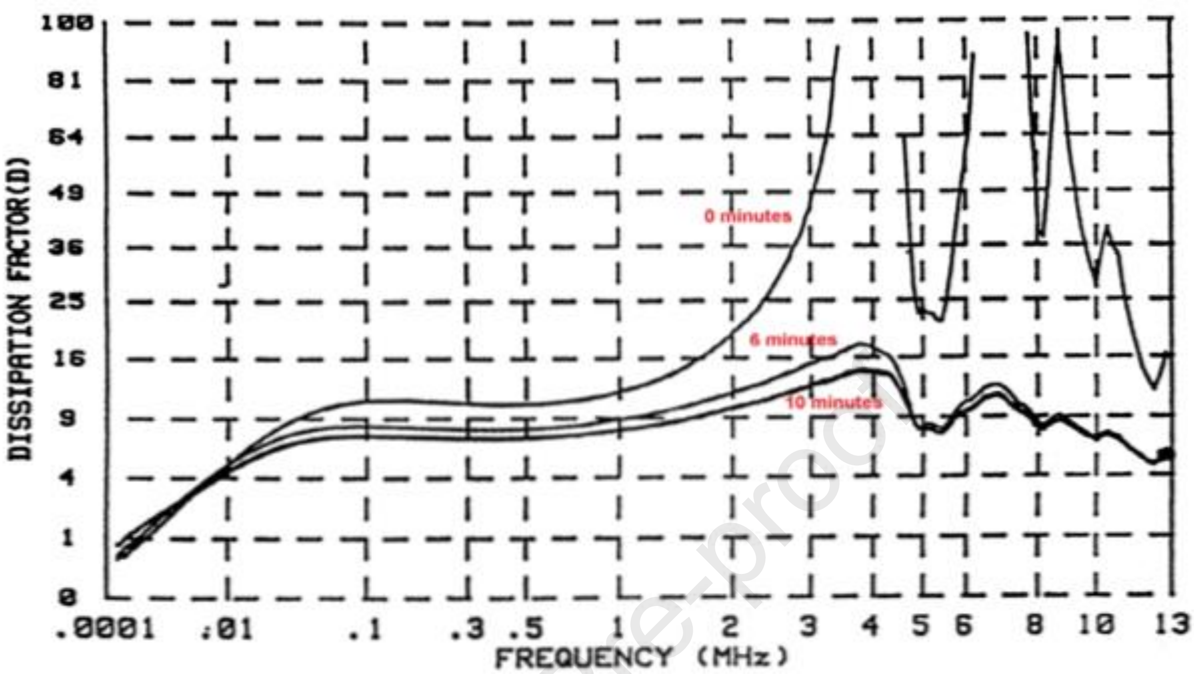

Figure 4. Dissipation Factor (D) dispersion across frequency (MHz) in the cortex of a rabbit following anesthetic overdose. Measured at 0, 6, and 10 minutes after overdose (Héroux 1993) .

Table 2. Electrical Impedance changes in Rat tissues following Anoxia (Héroux 1991; Fahimi 2021).

Tissue	**Impedance Change (Ohms / minute)**	**Mitochondria / cell**
Muscle (n = 10)	0.436	1 700
Liver (n = 10)	6.15	1 000 – 2 000
Brain (n = 2)	128.7	2 000 000

Table 3. Literature confirming Effects of Non-Thermal Electromagnetic Radiation (NTER).

Effect	Electromagnetic Fields	Number of Studies	% Positive (footnote)
Free Radical-Oxidative	Low Frequency	229	89%
Free Radical-Oxidative	Radio Frequency	225	90%
Free Radical-Oxidative	Radio Frequency	354	89% (1)
Neurological	Radio Frequency	435	77%
Reproduction/Development	Radio Frequency	335	83% (2)
Genetic Effects	Radio Frequency	466	70% (3)

[1]This includes 95% of 86 studies with a SAR $\leq$ 0.40 W/kg, ten times less than the 4.0 W/kg threshold of harm that IEEE/ICNIRP use in their RF radiation exposure limits.
[2]Among studies that reported significant effects, 56 studies used a SAR $\leq$ 0.40 W/kg, and 37 studies a SAR $\leq$ 0.08 W/kg.
[3] Including 79% of 144 studies of gene expression.