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Literature Review on Human Bioeffects of Electromagnetic Energy: A Complex Systems Perspective

by Scott E Kerick

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14. ABSTRACT

This report reviews the literature on biological effects of engineered and natural electromagnetic (EM) energy systems across spatiotemporal scales spanning orders of magnitude from a complex systems perspective. I first review the EM frequency spectrum and define complex systems and complexity. I then review multiple parameters giving rise to the complexity of EM energy systems and how these parameters dynamically interact to produce complex human bioeffects across molecular, cellular, tissue, organ, and system levels over time scales from milliseconds to years. Finally, I discuss outstanding issues and questions and suggest conceptual and analytical approaches for advancing future research from a more integrative and holistic perspective.

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electromagnetic energy systems, directed energy weapons, human bioeffects, complex systems, integrative, holistic

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1. Introduction

During 2016–2018, several US Government personnel were suspected to have been subjected to directed energy (DE) phenomena of unknown origin (i.e., acoustic, electromagnetic [EM], laser) in Havana, Cuba, and Guangzhou, China (National Academies of Sciences, Engineering, and Medicine 2020). Neuroimaging evaluation of 40 Havana victims revealed decreased whole brain white matter volume; smaller frontal, occipital, and parietal lobe white matter volumes; lower mean diffusivity in the inferior vermis of the cerebellum; lower mean functional connectivity in auditory and visual subnetworks; and greater ventral diencephalon and cerebellar gray matter volumes versus healthy controls (Verma et al. 2019; see also Swanson et al. 2018; Nelson 2020; Lin 2021). These neural symptoms were associated with cognitive, affective, vestibular, oculomotor, and sleep dysfunction accompanied by headaches, dizziness, and disorientation. However, the variable symptoms across patients and the variable length intervals from reporting of incidents to clinical evaluation make clear determination of the source and its effects difficult.

Since 2018, 130 US intelligence agents, diplomats, and other Government officials have reported similar experiences in Russia, China, Vienna, and inside the United States.[*] Advancing our understanding of the bioeffects of weaponized directed EM energy, or directed energy weapons (DEWs), is needed to defend against such attacks, as well as to rehabilitate those who have been attacked to recover from the devastating neurological consequences. However, the main issue with DEW attacks is that they are covert with little evidence as to who perpetrated the attack and by what means; they are silent, invisible, have virtually unlimited ammunition, and are indefensible to unsuspecting victims under attack. According to *National Defense Magazine*'s interview of James Giordano (2017), a professor in the Departments of Neurology and Biochemistry and chief of the Neuroethics Studies Program at Georgetown University Medical Center: "Such weapons could be used clandestinely against a political leader, for example, to ultimately destabilize a society . . . I think what you are beginning to see is a greater likelihood for targeting the brain in these ways—both in regard to its structure and its functions, which includes cognitions, emotions and behaviors—in ways that are going to be disruptive on a variety of scales from systems in the individual to systems in the social and political" (Magnuson 2018). This profound statement suggests the need for insightful new scientific approaches to understand, prevent, and mitigate the complex effects of DE systems.

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[*] https://www.newyorker.com/news/news-desk/vienna-is-the-new-havana-syndrome-hotspot

There is limited publically available (unclassified) research on the bioeffects of DEWs, or the weapons systems themselves, although research has been ongoing for decades. Laser research and technology have been under development in the US since the space race in the 1960s and research in microwave physics dates back even further to atomic energy programs in the 1930s (Geis 2003). In 1996, the Non-Lethal Weapons Program was established to provide the US Military options where nonlethal force is preferred over lethal force (LeVine and Rutigliano 2015). More recently, the Air Force Research Laboratory (AFRL) has been the leader in DE technology and development of the active denial system (ADS) in the US (LeVine 2009). The ADS was designed to "weaponize millimeter waves as a non-lethal directed energy weapon into a configuration that would be militarily useful" (LeVine 2009, p. 3). According to Schneider (2007, p. 42), "The ADS employs millimeter wave technology to repel individuals without causing injury. This capability enables users to stop, deter, and turn back adversaries without the use of lethal force. The system also disrupts an assailant's ability to effectively use a weapon. The ADS provides the ability to control outbreaks of violence, minimize collateral damage, and ultimately saves lives."

According to Gunzinger and Dougherty (2012), nonlethal DEWs are safe, legal, and treaty-compliant for applications of area denial, crowd dispersal, and static security among other related missions. However, the potential for abuse of DEWs has already been evidenced as reported by Verma et al. (2019) and others. There has long been concern about such abuses by human rights advocates. Buch and Mitchell (2012, p. 22) reported:

> Unethical regimes or personnel could easily deny abuses of ADS, as the device leaves no physical evidence of its use. In addition, because ADS is a new and radiation-based technology, there is fear that exposure could lead to long-term health effects . . . All of these organizations speculate that states and non-state actors alike could easily abuse non-lethal weapons with impunity, given that they leave no physical trace. In a 1997 report, Amnesty International alleged that twelve states, including the United States, had abused CEDs [conducted energy devices]. Additionally, Human Rights Watch and United Nations officials worry that there has been insufficient testing of the long-term medical effects of non-lethal weapon use, especially testing that examines how non-lethal weapon exposure will interact with pre-existing medical conditions.

Giordano (2017) also warns of ethical and legal issues of "neuroweapons", in particular in the hands of nonstate actors operating outside the confines of international treaties and laws of war.

In this report I review bioeffects of nonionizing, nonthermal EM radiation in humans spanning several orders of magnitude in both time and space scales from a complex systems perspective. I also review theoretical frameworks for better understanding the complexity of the interactions between EM energy and human biological systems. Because of the clandestine nature of DEWs, I review the literature in other more established areas of research in bioeffects of EM energy radiation from sources such as radio/television, cell phones/towers, Wi-Fi, power lines, electrical appliances, noninvasive brain stimulation methods, and geomagnetic/atmospheric. Finally, I highlight outstanding questions and issues and provide new conceptual and analytical approaches to stimulate future research.

2. EM Frequency Spectrum

The EM spectrum ranges from 0 to 10^{25} Hz. Human sensory systems are able to consciously perceive energy transductions within just a small fragment of this frequency spectrum (380–750 nm; 400–790 × 10^{12} Hz [THz]). However, exposure to EM and sound energy outside human-detectable ranges may have a variety of biological, cognitive, emotional, motivational, behavioral, and sociological effects. For example, natural and artificial EM fields on earth span a wide spectrum of frequencies, ranging from static to extremely high microwave frequencies (0 Hz to 300 GHz) (Hunting et al. 2021).

EM waves can be classified as either ionizing radiation (IR) or nonionizing radiation (NIR) (Ozdemir and Kargi 2010). IRs are extremely high-frequency EM waves (gamma rays [10^{-12} m] and X-rays [10^{-12} to 10^{-8} m]). Gamma rays and X-rays transmit high levels of photon energy that can ionize, or break, atomic bonds that hold together molecules in cells. NIRs consist of the range of EM spectra having lower photon energies too weak to break atomic bonds. They include ultraviolet (10^{-8} to 10^{-7} m), infrared (10^{-6} to 10^{-3} m), microwave (10^{-3} to 10^{-1} m), and radio waves (>10^{-1} m) (Ozdemir and Kargi 2010).

A major challenge to understanding the biophysical mechanisms of EM energy is "the complexity and diversity of the physical processes operating simultaneously over wide spatio-temporal scales . . . their dynamics can be related to multiple levels of biological organization ranging from molecular dynamics to the functioning of ecosystems" (Hunting et al. 2021, p. 45). Thus, it is evident that a complex systems approach is required to significantly advance our understanding of the bioeffects of DE systems on the structure and function of human biological systems across multiple bandwidths and spatiotemporal scales under diverse environmental conditions.

3. Complex Systems and Complexity

As seen in this literature review, the bioeffects of DE are highly variable and inconsistent across many spatiotemporal scales of measurement. In part, this is due to the diverse range of conceptual, methodological, and analytical approaches for studying bioeffects of DE. However, it is also due in part to the complex nature of biological systems from atomic, molecular, cellular, tissue, organ, and holistic human and environmental system levels. Therefore, it is important here to define the terms complex systems and complexity for context in this review. A complex system (artificial or natural) may be defined as one comprising multiple 1) inputs and outputs; 2) structural nodes, units, or elements; 3) connections, links, or pathways connecting system components to each other and to inputs of the system; 4) mechanisms and means of sharing and coordinating information within and among components and inputs; and 5) feedback and feed-forward functional connections that interact with system inputs and produce various outputs (Paraschiv-Ionescu and Aminian 2009). Complex dynamical systems can be either linear or nonlinear, depending on how the system's components interact to produce outputs; however, most systems in nature are nonlinear. Paraschiv-Ionescu and Aminian (2009, p. 307–309) state:

> Nonlinear systems contravene the principle of superposition and proportionality involving components/variables that interact in a complex manner: small changes can have striking and unanticipated effects, and strong stimuli will not always lead to drastic changes in the behavior of the system . . . to understand the behavior of a nonlinear system, it is obligatory to perceive not only the behavior of its components, using the reductionist approach, but also the logic of the interconnections between components [i.e., holistic approach] . . . The properties of the system are distinct from the properties of the parts, and they depend on the properties of the whole.

To better understand the effects of DE on human biological and psychological functions, it is beneficial to adopt conceptual models and analytical approaches of complex nonlinear dynamic networked systems as previously defined (i.e., holistic approaches to biology).

Regarding an operational definition of complexity in this context, I cite the recent work of West et al. (2019, p. 11):

> Given the multiple definitions of complexity and the variety of phenomena that have been described as being complex . . . We argue that complex (non-simple) phenomena, by virtue of being non-simple, entail paradox and in so doing, violates the two thousand year Western tradition of Aristotelian logic; the tradition being

> that a statement A and its negation A (not A) cannot be simultaneously true. Said the other way around, a simple system cannot contain contradictions, by definition, and is therefore free of paradox.

This implies that the mathematical models, designed around a hypothesized mechanism within a particular discipline, are often not generalizable to phenomena outside that particular discipline. Even within a particular discipline, inconsistencies in research findings suggest empirical paradox. Simplification of complex phenomena to make them orderly and predictable often leads to paradoxes in science and this appears to clearly be the case in the study of the bioeffects of EM. Therefore, it becomes necessary to transcend the limitations of linear logic to resolve empirical paradoxes in science. West et al. (2019) suggest to transition from the "either/or" way of resolving paradox to the "both/and" way, and this may be accomplished using network theory. I will return to this notion later under the section "Conceptual and Analytical Approaches", but first I consider the complexity of DE systems, human biological systems, and environmental systems and how their complex interactions might give rise to emergent bioenergetical effects. As stated by Chiel and Beer (1997, p. 554), "The nervous system is embedded within a body, which in turn is embedded within the environment. The nervous system, the body, and the environment are each rich, complicated, highly structured dynamical systems, which are coupled to one another, and adaptive [or maladaptive] behavior emerges from the interactions of all three systems." Also, consistent with Quantum Field Theory (Bischof and Del Giudice 2013), the emergent collective dynamics and correlated biocommunication of the organism is enabled not by the ensemble of molecules but by the ensemble of their correlations. That is, "The dynamics of each component depends on the simultaneous dynamics of the other components, so that the ensemble of components behaves in unison in a correlated way" (p. 1) (see also Brizhik et al. 2009).

4. DE Systems Complexity

DEW systems may be considered complex human-engineered systems designed to transmit EM energy to complex biological human systems to achieve various outcomes. More specifically, DEWs damage targets using highly focused energy systems, including laser, acoustic, microwaves, and particle beams (Bloembergen et al. 1987; Park 2007; Schneider 2007; Sanyal et al. 2016; Obering 2019; Lockheed Martin*). Geis (2003) defined four types of DE technologies: continuous wave (CW) lasers, pulsed lasers, CW high-power microwaves, and pulsed microwaves. In high-power microwave systems, the EM frequency spectrum ranges from low

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*https://www.lockheedmartin.com/en-us/capabilities/directed-energy.html megahertz (10^6 Hz; wavelength 300 m) to high gigahertz (10^{11} Hz; wavelength 3 mm) (Kushwaha and Sharma 2008) and rely on electrical power to generate beams of energy in short pulses (nanoseconds to microseconds) at megawatt to gigawatt output levels (Gunzinger and Dougherty 2012). Others have reported that DEW systems span the EM spectrum, including gamma rays, X-rays, ultraviolet, visible spectrum, infrared, terahertz radiation, microwave, and radio waves—and include lasers, microwave, millimeter wave, visible lights, and pulse energy systems (Park 2007). Since the 1930s, power and energy output levels continue to increase, while weapons platforms, delivery systems, and applications continue to expand. However, because specific details on the parameters of DEWs are highly classified, parameters such as operational range, beam size, antenna gain, power density, range, time to achieve an effect, and unconventional countermeasures are not publically known (Kenny et al. 2008). Further, an important consideration that has not received much attention in the publically available literature with respect to DE exposures is how DE is facilitated or interfered with as it propagates through the atmosphere under diverse environmental conditions (McGonegal 2020).

Beyond research on DEWs, investigation of the effects of EM energy on biological functions has taken many different forms and test modalities including direct and indirect exposure, engineered and natural sources, observational, experimental and epidemiological designs, electrical and magnetic fields, and so forth. Further, many parameters must be taken into consideration to understand the mechanisms of the effects of DE on human biological systems, whether the intended purpose is to investigate the disruptive or facilitative effects. Considering the large parameter space and the multiplicative possible combinations of interacting parameters, and considering the complexity of human biological systems at which DE systems are targeted, it is necessary to understand how the various parameters interact in complex, dynamic ways to induce various complex, dynamic bioeffects. As summarized by Belyaev (2010, p. 188):

> Exposures to non-ionizing electromagnetic fields vary in many parameters: power (specific absorption rate, incident power density), wavelength/frequency, near field/far field, polarization (linear, circular), continuous wave (CW) and pulsed fields (that include variables such as pulse repetition rate, pulse width or duty cycle, pulse shape, pulse to average power, etc.), modulation (amplitude, frequency, phase, complex), static magnetic field (SMF) and electromagnetic stray fields at the place of exposure, overall duration and intermittence of exposure (continuous, interrupted), acute and chronic exposures.

Further, the EM environment; one's genetic background; cell type; size-, gender-, and age-related differences; medical history and medications; individual differences; and physiological variables all function to interact in complex and nonlinear ways to produce various bioeffects (Belyaev 2010; 2015). Whether researching bioeffects of engineered DE systems such as DEWs, noninvasive direct or indirect near-field brain stimulation, or natural atmospheric and geomagnetic systems, "Dose ought to be defined by all parameters of the stimulation device [or system] that affect the electromagnetic field generated in the body" (Peterchev et al. 2012, p. 436). In the following I review some basic waveform parameters: frequency, intensity/amplitude, pulse shape, width, and repetition frequency, polarity, incident angle, duration and interval between trains of pulses; total number of pulses; and interval between stimulation exposures and total number of exposures.

4.1 Frequency

NIR EM waves range from ultralow-frequency (ULF; 1–3000 mHz), extremely low-frequency (ELF; 3–3000 Hz), very low-frequency (VLF; 3–30 kHz), low-frequency (LF; 30–300 kHz), medium-frequency (MF; 300–3000 kHz), high-frequency (HF; 3–30 MHz), very high-frequency (VHF; 30–300 MHz), ultrahigh-frequency (UHF; 300–3000 MHz), super high-frequency (SHF; 3–30 GHz), and extremely high-frequency (EHF; 30–300 GHz) (Bianchi and Meloni 2007).

Radio frequency (RF) electromagnetic fields (EMFs) emitted from human-engineered technologies (e.g., power lines, television and radio broadcast stations, mobile telecommunications infrastructure and mobile phones, Wi-Fi, Bluetooth) range from 60 Hz to 300 GHz (International Commission on Non-Ionizing Radiation Protection [ICNIRP] 1998; 2020; D'Andrea et al. 2003). DEWs emit beams of EM energy from 10 MHz to 100 GHz frequency range (Obering 2019) and can operate in pulsed or continuous modes. High-power microwaves (HPMs) can be transmitted through narrowband, wideband, and ultrawideband transmissions. Narrowband transmissions focus higher microwave energy on a target; whereas, ultrawideband transmissions disperse lower energy across a wider area. Also, narrowband transmissions have a lower probability of coupling with the target than ultrawideband transmissions (McGonegal 2020). The ADS emits EM energy in a narrowband from 94 to 95 GHz and causes increasing thermal effects with increasing doses (Kenny et al. 2008).

The natural EMFs emitted by the earth (i.e., Schumann's resonance) range from about 7.83 to 50 Hz (Nickolaenko and Hayakawa 2014). EM activity recorded from the human brain using electroencephalogram (EEG), electrocorticogram (ECoG), magnetoencephalogram (MEG), and functional magnetic resonance imaging (fMRI) range from DC to about 100 Hz (ULF-ELF; although higher frequencies of 1 kHz have also been investigated; Freyer et al. 2009). EM activity recorded from the human heart using electrocardiogram (ECG) and magnetocardiogram (MCG) for derivation of heart rate variability range from ULF (≤0.003 Hz) to HF (0.15–0.4 Hz) (Shafer and Ginsberg 2017). It is not well understood how indirect DE exposure at much higher frequencies interact with and affect lower frequency rhythms of brain and cardiovascular systems. In the following I review literature on direct and indirect electrical and magnetic brain stimulation and geomagnetic influences on brain and heart rhythms (see Sections 7 and 8, Direct and Indirect Brain Stimulation).

4.2 Intensity (Power Density)

Intensity is the rate at which energy passes through a unit area, measured in J/cm², and is proportional to the square of the amplitude. Power is the rate at which energy is transferred, measured in watts (J/s) or megawatts (MW; 10^6 W). A magnetic field can be specified as either magnetic flux density, B, expressed in tesla (T), or as magnetic field strength, H, expressed in amperes/m (ICNIRP 2010). As vectors, EMFs have both magnitude and direction.

RF EMF affects the body through induced electric fields (measured in volts per meter; V/m), which alter electrochemical properties of atoms and molecules in biological systems. When exposed to EMF energy, some of the energy is deflected and some of it is absorbed by the body, depending on characteristics of the EMF and the physical properties and dimensions of the body (ICNIRP 2020). When absorbed, the EMF energy can be converted to kinetic or heat energy, depending on the dosimetric quantity, measured as the specific energy absorption rate (SAR; W/kg), or absorbed power density (S_{ab}; W/m^2). Below 6 GHz, EMFs penetrate deep into tissue; whereas, above 6 GHz, the effects are more superficial. Two primary biological effects of EMF radiation are changes in membrane permeability (nonthermal) and heating (thermal; ICNIRP 2020). The ICNIRP set safety guidelines in the LF range from 1 Hz to 100 kHz. Above 100 Hz, heating effects need to be considered (ICNIRP 2010). Whole-body averaged SARs between 1 and 4 W/Kg is the threshold range at which significant core temperature rise occurs (Food and Drug Administration [FDA] 1999). However, the FDA states that "the existing exposure guidelines are based on protection from acute injury from thermal effects of RFR exposure, and may not be protective against any non-thermal effects of chronic exposures" (FDA 1999, p. 2). For magnetic flux density, the safety threshold is 400 mT (ICNIRP 2009).

Neuroelectric signals from the brain recorded by scalp EEG range in the tens of microvolts (μV; 10^{-6} V). Neuromagnetic signals from the brain recorded by MEG are typically in the range of 50 femtoTesla (fT; 10^{-15} T) to 500 fT (De Assis et al.

2019). These fields are in the range of 10^9 to 10^8 smaller than the earth's background magnetic field. On the earth's surface, the field varies more in intensity than in direction, ranging from 25 nanoTesla (nT; 10^{-9} T) to 42,000 nT on the equator, and up to 60,000 nT at the magnetic poles (De Assis et al. 2019). Neuroelectric signals in the heart and skeletal muscles range in the millivolts (mV; 10^{-3}), and the magnetic field of the heart is in the picoTesla range (pT; 10^{-12} T) (Lim et al. 2009; Zheng et al. 2020).

4.3 Pulse Repetition Frequency (PRF)/Interval

The PRF is measured in pulses/second or hertz. PRFs range from microseconds to several seconds in DE systems (see Eureka Aerospace 2006; Peterchev et al. 2012; Goetz and Deng 2017; Sorkhabi et al. 2020). The pulse repetition interval (PRI) is the time interval between pulses and is the inverse of the PRF (PRF = 1/PRI).

4.4 Pulse Width/Duration

Pulse width or duration controls both pulse energy and average energy of a DE system. Increases (decreases) in pulse width increase (decrease) both pulse energy and average power. Pulse energy does not depend on period, but average energy does. Pulse widths vary from nanoseconds to several seconds in DEWs (Eureka Aerospace 2006). The rate (power; W/cm^2) and density (fluence; J/cm^2) of energy on the target must be considered in the determination of damage to the target; energy must be delivered over a small region in a short time to inflict significant damage (Nielsen 1994). Power and fluence vary as a function of time or pulse width. Also, the rate at which energy is dissipated from the target via conduction, convection, and radiation must be considered (Nielsen 1994). Thus, the specific mechanisms by which energy interacts with matter is crucial for understanding the bioeffects of DE.

4.5 Polarity

As mentioned above, EMFs have both magnitude and direction. They also consist of a rotational polarization field that is perpendicular to the direction of the wave, which can be either right- or left-hand circular polarization, or linear (along a plane in the direction of energy propagation). The direction of circular polarity is relevant with respect to bioeffects, but depends on other parameters. For example, Belyaev's (2010) review of nonthermal microwave energy revealed that, within certain frequency ranges (51.76 GHz), right-hand (but not left-hand) circular polarity inhibited repair of DNA damages in E. coli cells. However, within other frequency ranges (41.32 GHz), the converse was found (Belyaev et al. 1994). In both direct

(Stagg and Nitsche 2011; Woods et al. 2016; Truong and Bikson 2018) and indirect (Wang et al. 2019) brain stimulation studies, cortical excitability is also polarity-specific.

4.6 Incident Angle between Potential Source and Subject

The incident angle is the angle between the direction of impact of a DE source and the target surface. The coupling between DE source and target surface is complicated by the complexity of the human body and also depends on the frequency and other parameters of the DE field (Foster 2015; ICNIRP 2020).

4.7 Duration of Exposure and Number of Repeated Exposures

The duration of exposure to DE must be considered on time scales from milliseconds to a lifetime depending on the source. According to Levine (2009, p. 5), "At 95 GHz, the ADS energy is non-ionizing, meaning that the millimeter waves do not have enough photonic energy to affect cellular structure. The energy reaches a skin depth of 1/64th inch, raising the skin's temperature in a manner similar to the infrared energy from the sun." However, the exposure duration of the ADS has not been disclosed, to our knowledge, so it is not known what the safety levels are for various exposure durations or repeated exposures. As explained by Nielsen (1994), short pulses can cause more damage than long pulses or continuous exposure if the energy cannot be dissipated from the target.

Regarding chronic or repeated exposure to environmental sources of EMF, Lai (2019) suggests that free-radical responses likely undergo alarm, resistance, and exhaustion phases depending on how long one has been exposed, and that the effects would also depend on the different cell types and organs, as well as exposure conditions. Complex patterns are often observed and effects are not always in the same direction. The duration of exposure may be as important as power density and specific absorption rate (Belyaev 2010). However, as discussed, carrier frequency and modulation, polarization, intermittence and coherence time of exposure, static magnetic field, EM stray fields, genotype, gender, physiological and individual traits, and cell density during exposure all interact in complex and dynamic ways (Belyaev 2010).

5. Environmental Complexity

EM activity in the environment from both natural and human-engineered sources is significant to the study of bioeffects of EMF (Belyaev 2010; Apollonio et al. 2013; Hunting et al. 2021). Many interdependent physical parameters in the electrical environment (e.g., current, conductivity, electric field, charge location, number, and mobility) vary over several orders of magnitude in both spatial and temporal scales (Hunting et al. 2021). In laboratory experiments, it is an ongoing challenge and an extremely onerous process to properly shield subjects from a wide range of frequencies, isolate stimuli, document wave forms and incident magnitudes of exposures, establish symmetry, implement appropriate sham controls, and quantify dose-response relations (Foster 2015; Hunting et al. 2021). Further, individual differences in physical and biogenic variables of subjects add to the complexity of experiments on the bioeffects of EMF. Hunting et al. (2021, p. 51) nicely summarized:

> The exploration of the entire parameter space, from DC to GHz frequencies, is desirable yet challenging logistically and financially . . . Hence, to date, difficulties remain in designing meaningful and interpretable empirical investigations involving biological systems and their responses to EM fields, which in turn, can be expressed at multiple levels of biological complexity, e.g., behaviour, physiological, molecular, and atomic . . . the reproducibility of methodologies, and hence repeatability of experiments, has been an issue in the vast majority of studies published to date, casting uncertainty on our capacity to formulate a solid phenomenology on the effects of atmospheric electricity on biological organisms, including humans.

To enable investigations of the key parameters and interaction mechanisms across greater time and space scales, multiple different types of easily deployable and robust sensors would need to be miniaturized, integrated, and synchronized within and among human and environmental systems affording more complete and continuous data acquisition (Hunting et al. 2021).

6. Human Systems Complexity

Most systems in nature (environmental, chemical, biological, psychological, sociological), as well as those synthesized by humans (DEWs, electric power grids, communications and information systems, wireless networks) are highly complex and dynamic, both structurally and functionally. Although each of these areas of science and engineering (among many others) have applied conceptual and analytical frameworks of complex networks and dynamic systems within each domain independently, programmatic integrative or holistic investigation into the interdependence of multiple complex systems across domains interacting through multiple temporal and spatial scales is mostly lacking. As large an undertaking as this may appear, many principles, features, and characteristics of complex systems are generalizable across diverse systems and over many temporal and spatial scales (self-organization, emergence, criticality, recurrence, stochastic/deterministic processes, scale-free structure/dynamics, small-worldliness, fractal dimension, etc.) (Mandelbrot 1983; Newman 2003; Marwan et al. 2007; Werner 2009; Rubinov and Sporns 2010; Strogatz 2014). Research in bioeffects of DE stands to benefit from complex networks and dynamic system approaches conceptually, analytically, and practically.

Sturmberg et al. (2019, p. 1) suggest that "health is an emergent state that arises from hierarchical network interactions between a person's external environment and internal physiology . . . Understanding health as a state that is both individualized and that emerges from multi-scale interdependencies between microlevel physiological mechanisms of health and disease and macrolevel societal domains may provide the basis for a new public discourse for health service and health system redesign." Similarly, Apollonio et al. (2013, p. 2037) contend that "all biological systems may be considered as a stratification of different levels of biological organization, each with its own complexity, size, timing, structure, and function. Each level is characterized by the so-called emergent properties . . . its functions are related to all those of the lower levels, but are not completely determined by them." Yet, the majority of research published in biology, neuroscience, cognition and emotion, and behavior applies linear approaches based on questionable statistical assumptions of data normality, stationarity, and independence and tests hypotheses seeking cause–effect relations. However, much evidence exists to challenge such assumptions and to support the notion that nonlinear dynamic system interactions are reciprocal, recursive, multiple causal processes giving rise to emergent states from self-organization of complex interactions among system components (Lewis 2005). Self-organization refers to the spontaneous emergence of order (i.e., novel patterns or structures) from nonlinear interactions among constituent components of a complex dynamic system, giving rise to new levels of integration, organization, and spontaneous transitions from states of low order to states of higher order (Lewis 2005). In a complex system, the whole is greater than the sum of its parts.

Key to understanding emergence and self-organization is the concept that segregation and integration are complementary or cooperative functions. For example, two fundamental principles of brain organization are functional segregation (anatomical segregation of functionally specialized subsystems) and functional integration (the coordination and coupling of functionally segregated subsystems; Friston 1997). "The patterns of activity that obtain, under these conditions [complex dynamics among sparse brain regions], show a rich form of intermittency with the recurrent and self-limiting expression of stereotyped transient-like dynamics" (Friston 1997, p. 171). Further, Fingelkurts et al. (2010)

suggested that interactions between local (segregated) and global (integrated) system dynamics constitutes the metastable regime of brain functioning that coexist as a complementary pair, not as conflicting principles. Similarly, the theory of coordination dynamics (Werner 2009; Tognoli and Kelso 2014) posits that metastability is a subtle blend of integration and segregation, complementary in nature from the standpoint of theory, neural dynamics, and function, which "embraces both spontaneous self-organizing tendencies and the need to guide or direct such tendencies in specific ways . . . In Coordination Dynamics, the system's parts and processes communicate via mutual information exchange, and information is meaningful and specific to the forms coordination takes" (Tognoli and Kelso 2014, p. 35). These ideas could be extended to all physiological systems spanning multiple time and space scales and how they are integrated and coordinated within the body, as well as how these systems are, in turn, integrated and coordinated with the EM environment.

Apollonio et al. (2013) reviewed several models of interaction mechanisms between EMF and biological systems but revealed that few (if any) have been able to explain the discrepant and inconsistent results. Achieving a better understanding of the interaction mechanisms has become increasingly important in the study of specific bioeffects of EMF. Dosimetric and biophysical models have been classified at different complexity levels, including 1) atoms and molecules, 2) macromolecules, 3) cell compartments, 4) cells and aggregates of cells, 5) organ systems, and 6) whole organisms. However, a major limitation is that, at the level of organ systems and whole organisms, models of such complexity have largely not been attempted in bioelectromagnetic studies (Apollonio et al. 2013). They claim that "the main limit of the models described is that they try to represent the effect at the same level of the biological scale of complexity where it has been observed" (Apollonio et al. 2013, p. 2037). This is understandable given that the effects of EMF on organisms are difficult to evaluate due to the complex, heterogeneous structures of biological systems (Yalcin and Erdem 2012; Foster 2015) that can all be affected differently by EM fields. A multiscale model taken from Apollonio et al. (2013) is illustrated in Fig. 1. Following, I summarize bioeffects across different complexity levels.

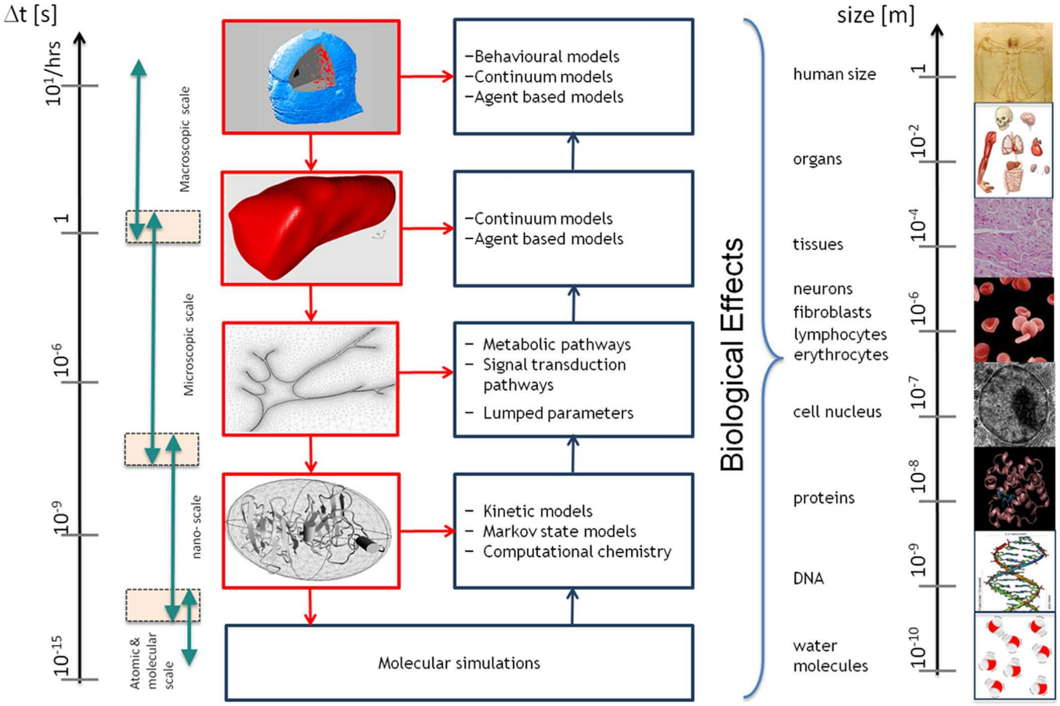

Fig. 1 **Multiscale model illustrating multiple temporal and spatial scales for modelling EMF-bioeffect interactions**[*]

6.1 Molecular (Subcellular)/Cellular Level

As current passes through biological systems, positively and negatively charged molecules in the cell environment change polarity, which leads to alterations in the concentrations of various ions in different parts of the cell (Yalcin and Erdem 2012; Pall 2013; 2016; 2018). Electrical fields alter lipid and protein configurations of cell membranes and change how ions and molecules interact with membranes. Consequently, such alterations affect a sequelae of the functioning of cells, tissues, and organs. NIR from low-intensity ELF- and RF-EMFs alter epigenetic mechanisms of gene expression by generating reactive oxygen species (ROS), inducing oxidative stress, and changing calcium metabolism, which in turn may lead to DNA damage, inhibition of DNA repair, apoptosis, and the development of cancer and other diseases (Yakymenko et al. 2016; Belpomme et al. 2018; Russell 2018; Lai 2019;; see also Bioinitiative Report 2012[†]). Two types of reactive free radicals include ROS and reactive nitrogen species (RNS), which are produced in the mitochondria as a result of cellular metabolism (Lai 2019). Russell (2018, p. 487) states that "ROS are a normal part of cellular processes and cell signaling. Overproduction of ROS that is not balanced with either endogenous antioxidants

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[*] From Apollonio et al. 2013; Fig. 1
[†] www.bioinitiative.org

(superoxide dismutase (SOD), catalase (CAT), glutathione peroxidase (GPx), glutathione (GSH), melatonin), or exogenous antioxidants (Vitamin C, Vitamin E, carotenoids, polyphenols) allows the formation of free radicals that oxidize and damage DNA, proteins, membrane lipids and mitochondria." These processes can lead to dysfunction of cells, cancer, and cell death (Yakymenko et al. 2016; Lai 2019).

Mechanisms underlying nonthermal molecular and bioeffects of nonthermal EMF radiation are likely explained by the physics of nonequilibrium and nonlinear systems and quantum mechanics (Belyaev 2005; 2015; Belpomme et al. 2018). Georgiou (2010) proposed that magnetic fields generated by low-level EMF radiation causes overproduction of free radicals via electron spin flipping in confined free-radical pairs of living cells (see also Yakymenko et al. 2016), an effect which is amplified by the biochemistry of nonlinear dynamic processes. Georgiou (2010, p. 63) states that "this synergistic mechanism is supported by experimental evidence from vast EMF exposure studies on various biological systems (human/animal cell cultures, whole animals, and even plants) covering static magnetic, extra LF and RF fields (SMF, ELF, and RF, respectively); SMF (as low as 0.05 W/m^2), ELF 3–195 Hz (as low as 10 μT) and RF 400 MHz–300 GHz (as low as 0.2 W/m^2 and SAR 0.016 W/kg)."

In addition, radio frequency radiation (RFR) is thought to activate intracellular calcium ion spiking and initiate multiple calcium-dependent signaling cascades, which function to alter the regulation of cellular metabolism (Pall 2013; 2016; 2018; Yakymenko et al. 2016). According to Pall (2013; 2016; 2018), downstream effects of spiking of calcium ions through voltage-gated calcium channels (VGCC) results in excessive calcium and nitric-oxide signaling, leading to excessive peroxynitrite and the generation of free radicals and oxidative stress, a pathophysiological response. However, a therapeutic response may also be observed by which increased nitric-oxide levels leads to increased synthesis of cyclic guanosine monophosphate (cGMP) and subsequent activation of protein kinase G (PKG), as for example in therapeutic osteoblast and bone growth stimulation (Pall 2018; see Fig. 2).

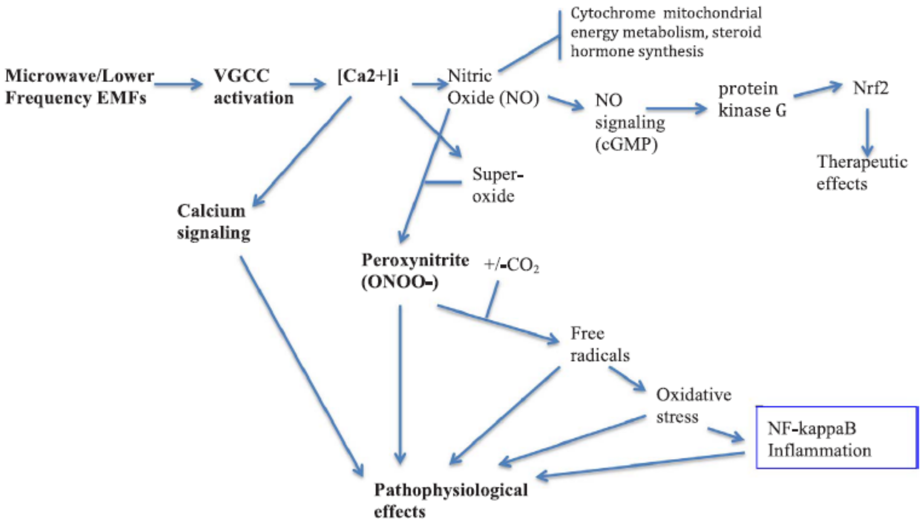

Fig. 2 Pathways of activation of VGCC[*]

At the cellular level, EM effects have been shown to influence ionic currents affecting potential energy between internal and external cell environments and thus cell firing rates. Specifically, RF radiation, low-intensity microwave energy, and lower frequency EMFs activate VGCCs in the plasma membrane, increasing intracellular calcium in the cell and activating multiple calcium-dependent signaling cascades (Pall 2018; Yakymenko et al. 2016). Yakymenko et al. (2016) found that 93 of 100 experimental studies in biological models that investigated oxidative stress due to low-intensity RFR exposures demonstrated significant oxidative effects induced by low-intensity RFR exposure. Lai (2019) cited over 200 studies showing the effects of static and ELF–EMF on cellular free-radical processes, suggesting they are the most consistent bioeffects of nonionizing EMFs. Static electrical and magnetic fields, ELF (including 50/60 Hz) EMFs, and microwave frequency range EMFs all have been shown to influence activity of VGCC (Pall 2013). Further, the effects of polarized nanosecond pulsed EMFs result in greater effects than continuous nonpolarized EMF (Pangopoulos et al. 2013; Belyaev 2015; Pall 2016; 2018) and the effects are dependent on frequency windows and nonlinear coupled oscillators (Belyaev 2005). Calcium channel blockers (L-, N-, P/Q-, and T-type) have been shown to mitigate responses to EMF exposure, suggesting a causal role of VGCC activation in the response to EMF exposure (Pall 2013).

Further evidence of molecular/cellular level bioeffects of induced magnetic fields comes from research in magnetoreception (Johnsen and Lohmann 2005) and magnetofection (Bao 2021). Three of the most likely mechanisms underlying

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[*] Fig. 1 from Pall 2018

magnetoreception in animals are EM induction, magnetic field-dependent chemical reactions (radical pair), and biogenic magnetite (Johnsen and Lohmann 2005). In humans, magnetofection involves injection of magnetic nanparticulates to regulate drug delivery. As nanoparticulate design and engineering becomes more prominent in individualized medicine (Moghimi et al. 2005; Plank et al. 2011; Bao 2021), cellular and intracelluar delivery, targeting, and controlling of the kinetics of drug delivery with nanoscale delivery technologies also has potential implications for better understanding bioeffects of EM energy fields. In 2000, Plank and colleagues defined the term magnetofection as "nucleic acid delivery under the influence of a magnetic field acting on nucleic acid vectors that are associated with magnetic (nano)particles" (Plank et al. 2011, p. 1301). Benefits of magnetofection are thought to occur via "an improvement of the dose–response relationship in nucleic acid delivery, a strong improvement of the kinetics of the delivery process and the possibility to localize nucleic acid delivery to an area which is under magnetic field influence" (Plank et al. 2011, p. 1301). Once nanoparticulates are injected, they can be controlled remotely by targeting EM energy fields to influence specific cells and locations within the body (Moghimi et al. 2005; Plank et al. 2011). Injected nanoparticulates can be engineered to activate changes in the environmental pH by rapidly oscillating external magnetic fields or heat sources. Further, they can be engineered with multifunctional capabilities to include target cell reception and embedded biological sensors (Moghimi et al. 2005). The behavior of nanoparticles within the biological microenvironment are highly variable with respect to their stability and distribution in extracellular and cellular spaces, depending on their chemical makeup, morphology, and size (Moghimi et al. 2005). Thus, future studies on bioeffects of EM energy exposure should document medical records of subjects or patients, as such interactions may differentially affect magnetofection processes (enhanced nucleic acid delivery) in those who have been injected with nanoparticulates.

6.2 Tissue/Organ Level

According to Apollonio et al. (2013, p. 2032), "The organization levels of organs and organisms have been neglected since no model of such complexity has been used in bioelectromagnetic studies." However, quantum field theory and theories based in complexity science and nonlinear dynamic systems provide some insights into this issue. Cell ensembles comprising tissues and organ systems may be the level at which EM energy is more responsible for generating bioeffects than atomic/subcellular levels (Belyaev 2015). "The absorption of EMF energy is inefficient when the receiving antenna (molecules, cells, and their ensembles) is considerably smaller than the EMF wavelength. However, coupling and energy transfer to subcellular structures may become greater if there is resonance interaction of NT MW with vibration modes of the cellular structures" (Belyaev 2015, p. 54). According to Fröhlich's theory, coupling and energy transfer between cellular structures and EMF in the MW range is facilitated when vibrations of cellular structures occur at resonant frequencies (Fröhlich 1970; 1980). Energy in biological systems may be stored through excitation of coherent electrical vibrations or polarization waves among assemblies of cells interacting in a nonlinear way to produce metastable states.

Consistent with Fröhlich's model, quantum field theory posits that the dynamics of each component of a complex system (e.g., cells and cell structures) depend on the simultaneous dynamics of all other components of the system, such that the ensemble of components behaves in a unified and correlated way (Bischof and Del Giudice 2013). Through such collective dynamics, the emergence of biocommunication is made possible, and the whole is greater than the sum of the individual components (quantum phase correlations over macroscopic scales produce coherent states). In fact, Bischof and Del Giudice (2013) claim that it is not the ensemble of molecules but the ensemble of their correlations that explain the time evolution of organisms (also see Brizhik et al. 2009). Given the fractal nature of living organisms, Bischof and Del Giudice (2013) emphasize the importance of understanding nested coherent dynamics. This will be discussed further in Section 10, "Conceptual and Analytical Approaches".

6.3 Organismic Level

At the organismic level, physiological, cognitive-affective, and behavioral effects of EMF may be observed. Perhaps most notably, electromagnetic hypersensitivity (EHS) phenomena have been on the rise over the last decade (Kaszuba-Zwoinska et al 2015; Saliev et al. 2019). EHS refers to "a broad spectrum of non-specific multiple organ symptoms including both acute and chronic inflammatory processes located mainly in the skin and nervous systems, as well as in respiratory, cardiovascular systems, and musculoskeletal system" (Kaszuba-Zwoinska et al. 2015, p. 636).

However, at present, evidence is inconsistent and there is a lack of reproducibility of reported effects. Improved methodology and standardized protocols and multiscale modelling approaches are needed to integrate analyses across molecular, cellular, tissue, and whole organism levels (Apollonio et al. 2013; Cifra et al. 2021; Hunting et al. 2021). In addition, because real EMF emissions from mobile phones, Wi-Fi, and other environmental sources include significant variations in their intensity, frequency, pulse characteristics, and other parameters, future research should incorporate variable parameters in the investigation of bioeffects; the preponderance of research to this point has been limited to studies employing simulated emissions with fixed parameters produced by generators or test systems (Panagopoulos et al. 2015). Consistent with this notion, the National Academies of Sciences, Engineering, and Medicine (2020, p. 20) states that "specific experiments would be needed with RF exposure and dosage characteristics (frequency, pulse repetition frequency, pulse width, incident angle between potential source and subject, duration of exposure, number of repeated exposures, etc.) to quantify the biological effects, but would be ethically difficult to justify." Given such ethical concerns, more multiscale modeling studies are needed.

7. Direct Brain Stimulation

Noninvasive brain stimulation (NIBS) for neuroenhancement and neurorehabilitation has evolved into an extensive and active area of research in recent decades; however, it has been a subject of interest since the discovery of electrical phenomena (Guleyupoglu et al. 2013). Our understanding of the neurophysiological mechanisms underlying direct EM brain stimulation are still limited at present. Two general categories of NIBS are transcranial magnetic stimulation (TMS) and transcranial electrical stimulation (tES). TMS generates a strong current in the brain by EM induction that can depolarize neurons; whereas, tES generates relatively weaker current that induces subthreshold polarization affecting ion channels, resting membrane potentials, and the postsynaptic activity of neurons (Miniussi et al. 2013; Yang et al. 2021). However, both TMS and tES modulate the excitation or inhibition of glial cells and interneurons (Yang et al. 2021). Such modulation may lead to brain alterations spanning multiple temporal (milliseconds to hours) and spatial scales (single neurons to widespread networks; Peterchev et al. 2012). Further, bioeffects of EM stimulation have also been shown to include changes in activation of blood-brain barrier permeability, vasodilation, electroporation, joule heating, electrophoresis, inorganic ion transport, second messengers, neurotransmitter activity, neuronal metabolism, protein signaling and transcription, and cell division (Peterchev et al. 2012).

Although the mechanisms underlying NIBS on brain function are not fully understood, outcomes of stimulation are affected by EM dose manipulation. Dose manipulation is defined by many parameters that must be clearly specified and experimentally controlled, including "the stimulation electrode or coil configuration parameters: shape, size, position, and electrical properties, as well as the electrode or coil current (or voltage) waveform parameters: pulse shape, amplitude, width, polarity, and repetition frequency; duration of and interval between bursts or trains of pulses; total number of pulses; and interval between stimulation sessions and total number of sessions" (Peterchev et al. 2012, p. 436). Further, uncontrolled variables must be considered with respect to individual differences within and among human subjects including "the underlying brain state including age, sex, hormone levels, attention/cognitive state, chronic and acute physical exercise, pharmacologic interventions including medications and anesthesia, neurotransmitter concentration, genetics, time of day, and state of endogenous neural oscillations" (Peterchev et al. 2012, p. 441).

Beyond TMS and tES, many techniques in transcranial EM stimulation have emerged over the last couple of decades including (but not limited to) transcranial DC stimulation (Nitsche et al. 2008), transcranial AC stimulation (Antal and Paulus 2013), transcranial random noise stimulation (Antal and Hermann 2016), high-definition transcranial DC stimulation (Roy et al. 2014), cortico–cortical paired associative stimulation (Sabel et al. 2020), theta-burst stimulation (Huang et al. 2005; Wischnewski and Schutter 2015), single-pulse TMS (Huerta and Volpe 2009), repetitive TMS (Rossi et al. 2009), and low-field magnetic stimulation (Fava et al. 2018). Due to space constraints and the limited scope of this review, I will not elaborate beyond TMS and tES. However, all transcranial EM stimulation devices consist of a waveform generator and electrodes (tES; V/m) or EM coil (TMS; A/m^2 or mA) (Peterchev et al. 2012). Safety levels for EM stimulation is currently less than 4 mA between frequencies 0–10,000 Hz for up to 60 min/day (Antal et al. 2017). However, given the multiple possible combinations of all discussed parameters, as well as continuously evolving technologies and protocols, safety continues to be an ongoing area of research (Bikson et al. 2016; Rossi et al. 2009; 2021). As stated by Rossi et al. (2009, p. 2012), "There are an infinite variety of combinations of such protocols, and it is important to emphasize that the effects and safety of the different protocols may differ, and that small changes, may have profound impact."

As reported by Peterchev et al. (2012), EM stimulation dose is defined by all parameters of the stimulation device. However, a major limitation of the EM stimulation literature is that a general definition and reporting framework for EM stimulation dose, as well as quantitative assessment techniques, are largely lacking, which limits interpretability and replicability of brain stimulation research (Peterchev et al. 2012; Yang et al. 2021). Further, EM stimulation effects are not limited to the stimulation frequency and local brain region underlying the electrodes or coil. EM stimulation may also affect neural activity across a larger spatial network and broader frequency range, including cross-frequency coupling and harmonics of the stimulation frequency (Huerta and Volpe 2009; Woods et al. 2016; Truong and Bikson 2018). Not surprisingly, "the outcomes of transcranial EM brain stimulation are arguably as diverse and complex as the range of brain functions"

(Peterchev et al. 2012, p. 441). Our current lack of understanding of NIBS is captured by Thut and Pascual-Leon (2010): “There is limited knowledge on the mechanisms of TMS action, including what is stimulated by TMS from the level of the cell to neuronal assemblies or networks, what is changed by TMS in terms of markers of brain activity or neuronal operations, when these TMS changes occur and how long they last. Another unresolved question is why the outcome of TMS is so variable, for instance why the effects of the same TMS design can change from being detrimental to beneficial when put into another experimental setting/task context” (p. 216). Regarding meta-analyses on the effects of EM stimulation, “There is very little direct replication in the literature” (Horvath et al. 2015, p. 539; see also Dedonker et al. 2016). Given such empirical paradox, it would seem fruitful to employ complex systems, conceptual models, and analytical approaches in future EM stimulation research.

8. Indirect Brain Stimulation

8.1 RFR

RFR comprises the EM spectrum from about 3 kHz to 300 GHz (D’Andrea et al. 2003; Russell 2018). Existing RFR exposure guidelines are based on protection from acute thermal effects above 100 kHz (FDA 1999; ICNIRP 2010). However, these guidelines do not consider the potential harmful effects of chronic nonthermal exposures in static or LF EMF from 0 Hz to 100 kHz (ICNIRP 2010). These guidelines also do not consider nonthermal exposures above 100 kHz from nonionizing wireless radiation used in modern telecommunications (e.g., 30–300 GHz fifth generation [5G] technologies to enable the Internet of things; Russell 2018). With the proliferation of mobile phones, 5G networks, smart meters, and electric vehicles over the last couple of decades, there is growing scientific evidence of nonthermal cellular damage from EMF used in telecommunications (Starkey 2016; Yakymeno 2016; Russell 2018; Driessen et al. 2020). According to Prasad et al. (2017), 63% (~4.7 billion) of the global population is subscribed to mobile phone service, which was projected to reach 75% (~5.7 billion) by 2020. Their meta-analysis from 12 case-control studies on the carcinogenic effects of 10 or more years of regular mobile phone use (1640 h) revealed a statistically significant 2.58 times increase in the odds of having a brain tumor. Further, a review by Russell (2018, p. 487) reported that “RF EMR has been shown to cause an array of adverse effects on DNA integrity, cellular membranes, gene expression, protein synthesis, neuronal function, the blood brain barrier, melatonin production, sperm damage and immune dysfunction . . . An increasing number of people are reporting a variety of symptoms with exposure to wireless devices and infrastructure, including headaches, insomnia, dizziness, nausea, lack of concentration, heart palpitations and depression. These are now recognized as signs of electrosensitivity or electromagnetic hypersensitivity." Yet, industry and Government policy strongly advocates advertising, manufacturing, and legislation in support of the adoption of these new technologies (Russell 2018). Thus, more than ever before in history, all life on earth (humans, plants, animals) is bathed in a sea of EM energy (McCraty 2015) with increasing evidence of its harmful effects with chronic exposure.

However, Prasad et al. (2017) also reviewed many studies that have failed to find an association between mobile phone use and tumors and concluded that overall the research is conflicting. Foster and Vijayalaxmi (2021) suggest that due to technical weaknesses in study designs and data analyses in many of the studies in conflict, better quality studies are needed to resolve the inconsistencies. Specifically, recommendations for improvement include 1) blind collection and analysis of data to remove investigator bias; 2) adequate description of dosimetry to facilitate independent replication and confirmation; 3) inclusion of positive controls to confirm the functioning of assays; and 4) incorporation of adequate sham control groups for comparison with exposure groups (Vijayalaxmi and Prihoda 2018; Foster and Vijayalaxmi 2021).

8.2 Atmospheric and Geomagnetic Field Stimulation

The earth's dipolar magnetic field ranges from 25 to 70 μT on the surface and fluctuates on time scales spanning milliseconds to millions of years (Nickolaenko and Hayakawa 2014; Cifra et al. 2021; Zenchenko and Breus 2021). As stated by Bianchi and Meloni (2007, p. 444): "Natural electromagnetic noise constitutes a background radio noise in which living systems are immersed and have consequently evolved since the origin of life on earth." The extent to which coupling between atmospheric and biological systems is affected by anthropogenic pollution, from ionic transport to entire ecological systems, is also a concern in need of further research (Hunting et al. 2021). I review literature on geomagnetic field stimulation from the earth and its atmosphere and RFR from human-engineered technological systems in the following.

Geomagnetic activity, or Schumann resonances, are thought to emerge inside the earth-ionospheric cavity from energy radiated from lightning strokes (Cherry 2002; Bianchi and Meloni 2007; Nickolaenko and Hayakawa 2014). Each day, several million lightning strokes occur from approximately 2000 storms worldwide at a rate of about 100 strokes/s (Bianchi and Meloni 2007). Each stoke is typically less than 1-s duration and discharges can reach 10,000 A, releasing gigajoules of energy generating between 1 and 10 GW of power (Bianchi and Meloni 2007). The diffusion of energy radiated by lightning strokes consists of a wide spectrum EM energy signal composed of damped waves from ELF to VHF bands. A spherical natural wave guide is formed between the earth and the ionosphere which, through subionospheric propagation, results in a fundamental resonance frequency at 7.8 Hz with upper harmonics at about 15.6, 23.4, and 31.2 Hz called the Schumann resonances (Bianchi and Meloni 2007; Nickolaenko and Hayakawa 2014). Signal amplitudes vary as a function of various propagation modes and wave guide parameters. Energy from these Schumann resonances is capable of entraining and phase locking with human cardiovascular and brain rhythms (Miller and Miller 2003; McCraty 2015; Alabdulgader et al. 2018; Wang et al. 2019; Zenchenko and Breus 2021). Further, the earth's ionosphere is strongly coupled to the sun, which is highly variable and exerts a wide array of EMF effects through atmospheric propagation (Bloemberger et al. 1987; Aschwanden et al. 2016; Streltsov et al. 2018). According to Panagopoulos and Balmori (2017), average intensities of static electric and magnetic fields are approximately 130 V/m and 0.5 G, respectively. They further report that polarized ELF EMFs as low as 0.1–1.0 mV/m may disrupt electrochemical balance and the function of any living cell via VGCC mechanisms, and thus create a potential cascade of health issues, while VLF EMFs need to be thousands of times stronger to initiate such effects.

The High-frequency Active Auroral Research Program (HAARP) facility in Gakona, Alaska, "is the world's most powerful and sophisticated facility for active experimentation in the upper atmosphere and ionosphere. HAARP uses powerful HF waves to heat small (~30–100 km) regions of the upper atmosphere to stimulate particular geophysical processes that can be disentangled by ground-based diagnostic instruments from complex and coupled natural phenomena in the thermosphere and ionosphere" (Streltsov et al. 2018, p. 118[*]). Streltsov et al. (2018) showed that heating the ionosphere using HAARP facilities excited large-amplitude, LF EM waves affecting the Schumann resonance in the 7.8–8.0 Hz range using HF radiation in the range of 3.20–4.57 MHz when the electric field in the ionosphere is greater than 5 mV/m. Streltsov et al. (2018, p. 118) concluded that "results from this experiment confirm that the ionospheric heating modulated with frequencies of the Schumann resonance can indeed stimulate relatively large-amplitude electromagnetic response under some particular combination of the heater frequency, modulation frequency, and geomagnetic conditions." Such experiments are designed to study plasma processes in the ionosphere and magnetosphere but have not taken into consideration the potential implications for public health and ecological systems. For example, research reviews have shown that both extremely high and extremely low intensity geomagnetic activity are

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[*] See also https://haarp.gi.alaska.edu/.

detrimental to health via disruptions in calcium ion channel dynamics and melatonin secretion from the pineal gland thought to be caused by resonant absorption mechanisms (Palmer et al. 2006). Accordingly, future atmospheric manipulation research should take into consideration the potential effects on public health and ecological systems.

Various areas of study of EM field effects on biological systems have emerged including biofield physiology (McCraty and Deyhle 2014; Hammerschlag et al. 2015; Kafatos et al. 2015; Rubik et al. 2015), magnetobiology (Makinistian et al. 2018; Zenchenko and Breus 2021), biomagnetism (De Assis et al. 2019; Bao 2021), chronobiology or biorhythmology (Zenchenko and Breus 2021), heliobiology (Zenchenko and Breus 2021), and biometeorology (Hunting et al. 2021). Hammerschlag et al. (2015) reviewed evidence contesting conventional physics doctrine suggesting that living systems could only be affected by EM fields strong enough to cause ionization or heating of tissues and supporting biofield physiology research suggesting that very weak, nonionizing EM fields may also exert biological effects (see also Bioinitiative 2012). They outlined three overlapping categories of biofield receptors that may underlie human-environmental EM interaction mechanisms: molecular-level receptors, charge flux sites, and endogenously generated electric or EM fields.

In their research program, Global Coherence Initiative (GCI), McCraty and Deyhle (2014) suggest that “every cell in our bodies is bathed in an external and internal environment of fluctuating invisible magnetic forces. Because fluctuations in magnetic fields can affect virtually every circuit in biological systems, human physiological rhythms and global behaviors are not only synchronized with solar and geomagnetic activity, but disruptions in these fields can create adverse effects on human health and behavior” (McCraty and Deyhle 2014, p. 414). They have employed a Global Coherence Monitoring System “to measure and explore fluctuations and resonances in the Earth’s magnetic field and in the Earth-ionosphere resonant cavity in order to conduct research on the mechanisms of how the Earth’s fields affect human mental and emotional processes, health, and collective behavior” (McCraty et al. 2012; McCraty and Deyhle 2014, p. 412; see also Hammerschlag et al. 2015; Rubik et al. 2015).

9. Issues and Outstanding Research Questions

A large literature investigating the effects of EM energy on biology, cognition, and behavior or health reveals mostly irreproducible and contradictory results (Apollonio et al. 2013; Buchachenko 2016; Zhi et al. 2017). A major issue in bioeffects research concerns the longstanding problem of inadequate characterization of dosimetry and standardized reporting (frequency, intensity, pulse repetition frequency, pulse width, incident angle between potential source and subject, duration of exposure, number of repeated exposures, etc.) (D'Andrea et al. 2003; Peterchev et al. 2012; Foster 2015; National Academies of Sciences, Engineering, and Medicine 2020). The coupling between external and internal EM fields in humans depends on numerous exposure parameters in the external EM environment, which may vary greatly across diverse exposure scenarios, as well on the diverse geometrical and electrical characteristics of biological structures across various hierarchical levels of complexity in humans (Foster 2015). Relatedly, proper experimental designs and adequate statistical evaluations are needed (D'Andrea et al. 2003). Because EM stimulation dose is defined by all parameters of the stimulation device or EM environment, it is crucial that all parameters are accurately described and reported to facilitate replicability and interpretability of the research (Peterchev et al. 2012). Further, individual differences within and between human subjects over time and recording conditions need to be better characterized, measured, and incorporated into analyses in future research (D'Andrea et al. 2003; Peterchev et al. 2012).

Bioeffects of EM should also be examined over longer time scales and repeated exposures to better understand cumulative or chronic effects, especially with respect to low-intensity, LF EM exposure. For example, Starkey (2016) and the Bioinitiative (2012) consortium of scientists, physicians, and engineers, among others (Panagopoulos et al. 2015; Miller et al. 2019; Panagopoulos and Chrousos 2019), have shown strong evidence of the harmful effects of RFR from smart phones, tablet computers, body-worn devices, Wi-Fi and Bluetooth transmitters, cordless phones, base stations, wireless utility meters, and other transmitters absorbed by the global population on a daily basis over years of exposure that have been overlooked or suppressed by governing bodies such as the UK Advisory Group on Non-Ionising Radiation (AGNIR), ICNIRP, the International Agency for Research on Cancer (IARC), and the FDA. Conflicts of interest between governing bodies and authors of scientific reports must be avoided. For example, Starkey (2016) disclosed that 43% of members of AGNIR were also members of other health agencies who prepared reports that the advisory group supported, while omitting and minimizing major findings in the literature that contradict the guidelines established. She states: "To protect public health, we need accurate official assessments of whether there are adverse effects of RF signals below current international ICNIRP guidelines, independent of the group who set the guidelines" (Starkey 2016, p. 499). Repeated-measure studies incorporating long-term monitoring using wearable sensor technologies (Tricoli et al. 2017; Zou et al. 2020), Schumann resonance data from magnetometers, use of electronics such as Wi-Fi and mobile phone usage could be incorporated into study designs to address the lack of long-term data and provide sufficient data for analyses of interactions among complex biological-environmental systems.

Another major issue in research on the bioeffects of EM energy is how to better understand and model complexity. Complexity often leads to paradoxes in science (West et al. 2019). Therefore, new models, theories, and analytical approaches are needed to account for the complexity of interactions of EM phenomena in engineered, natural environmental, and human biological systems. Holistic macroscale approaches are needed to go beyond reductionist approaches focused at microscale levels. A multiscale modeling approach that integrates molecular, cellular, tissue, and whole-organism levels spanning the multiple time and space scales necessary to advance our understanding of EM field bioeffects is needed (Apollonio et al. 2013; Sturmberg et al. 2019; Cifra et al. 2021; Hunting et al. 2021).

10. Conceptual and Analytical Approaches

In complex systems, nonlinear dynamic interactions occur across multiple hierarchical levels of the system among a number of interacting variables, many of which are unavailable for experimental measurement (Webber and Zbilut 1994). Conte et al. (2012) refers to such interactions as complexity, emergence, and the micro–macro link problem. Two complementary approaches for addressing this problem are bottom-up and top-down approaches. Bottom-up approaches start with analyses of microscale processes (e.g., voltage-gated ion channel dynamics) and then hypotheses are generated upwards about the macroscale processes (e.g., injury, pathology, or disease sates). By contrast, top-down approaches start with analyses of the macroscale processes and infer downwards to the properties of its constituent microscale processes (Hesse and Gross 2014). Central concepts to making the micro–macro link are self-organization, criticality, multifractal structure and dynamics, and coordination dynamics. In most systems in nature (biological, environmental), fractals (self-similar structures and dynamics) emerge from self-organized critical dynamic processes (Bak 1996).

One such approach to better understanding complexity is to test models of self-organized criticality based on scaling laws that have been ubiquitously observed in natural phenomena transcending from geo- and astrophysics (avalanches, earthquakes, solar flares, cosmic rays; Bak 1996; Aschwanden et al. 2014; 2016; Markovic and Gros 2014) to brain and heart rhythms (Allegrini et al. 2010; Bohara et al. 2017; 2018; Tuladhar et al. 2018) to social networks (Conte et al. 2012; Mahmoodi et al. 2017). The scale-free probability conjecture predicts the functional form of power laws and power law slopes (i.e., scaling exponents) for most observable parameters of self-organized critical systems (Aschwanden et al. 2016).

For example, the complexity matching hypothesis predicts that maximal information transfer occurs among complex systems when the complexity (power law scaling indices) of interacting systems are similar (Allegrini et al. 2002; West et al. 2008; Delignieres et al. 2016; Culbreth et al. 2019). Time-series data from ion channels to single-cell recordings to brain networks could be subjected to multifractal analysis (Ivanov et al. 1999; Ihlen and Vereijken 2010; Bohara et al. 2017) and diffusion entropy analysis (DEA) before, during, and following EM stimulation to test the parameter space and best determine which combinations of parameters either disrupt or facilitate complexity matching among levels of complex biological systems or between different complex systems (e.g., brain–heart coupling; Culbreth et al. 2019). This approach could be extended to environmental–biological interactions to investigate relations among EM energy, neural, physiological, and behavioral signals across multiple time and space scales and various experimental contexts. Further, nonlinear coupling among time-series data spanning diverse hierarchical levels of a complex system could also be analyzed using recurrence quantification analysis (Webber and Zbilut 1994; Marwan et al. 2007). Network analysis based on graph theoretical approaches (Newman 2003; Rubinov and Sporns 2010) could then be employed to study local and global interactions across different levels of complex biological systems based on complexity matching or nonlinear coupling among nodes of the system. Direct or indirect energy systems could then be configured to achieve the desired complex network dynamics that may optimize behavioral performance and health. In summary, analysis and modelling of large-scale systems should simultaneously integrate and coordinate the collection and analysis of empirical data, computer simulations, and analytical modelling (Conte et al. 2012).

11. Conclusion

I have provided a broad overview of the complexity of both engineered and natural EM energy systems and the complexity of human biological systems. Because as humans we are EM energy systems embedded in a sea of EM energy fields, it is important for advancing future research that we move towards multifaceted system approaches to better understand the complex, dynamic, nonlinear interactions among human and environmental EM energy systems from more integrative and holistic perspectives rather than reductionist and linear perspectives.

12. References

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List of Symbols, Abbreviations, and Acronyms

5G	fifth generation
AC	alternating current
ADS	active denial system
AFRL	Air Force Research Laboratory
AGNIR	Advisory Group on Non-Ionising Radiation (UK)
CAT	catalase
CED	conducted energy device
cGMP	cyclic guanosine monophosphate
CW	continuous wave
DC	direct current
DE	directed energy
DEA	diffusion entropy analysis
DEW	directed energy weapon
DNA	deoxyribonucleic acid
ECG	electrocardiogram
ECoG	electrocorticogram
EEG	electroencephalogram
EHF	extremely high-frequency
EHS	electromagnetic hypersensitivity
ELF	extremely low-frequency
EM	electromagnetic
EMF	electromagnetic field
FDA	Food and Drug Administration
fMRI	functional magnetic resonance imaging
fT	femtoTesla
GCI	Global Coherence Initiative
GPx	glutathione peroxidase

GSH	glutathione
HAARP	High-frequency Active Auroral Research Program
HF	high-frequency
HPM	high-power microwave
IARC	International Agency for Research on Cancer
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IR	ionizing radiation
J	joules
LF	low-frequency
MCG	magnetocardiogram
MEG	magnetoencephalogram
MF	medium-frequency
MW	megawatts
NIBS	noninvasive brain stimulation
NIR	nonionizing radiation
nT	nanoTesla
PKG	protein kinase G
PRF	pulse repetition frequency
PRI	pulse repetition interval
pT	picoTesla
RF	radio frequency
RFR	radio frequency radiation
RNS	reactive nitrogen species
ROS	reactive oxygen species
SAR	specific energy absorption rate
SHF	super high-frequency
SMF	static magnetic field
SOD	superoxide dismutase

T	tesla
tES	transcranial electrical stimulation
TMS	transcranial magnetic stimulation
UHF	ultrahigh-frequency
ULF	ultralow-frequency
VGCC	voltage-gated calcium channels
VHF	very high-frequency
VLF	very low-frequency
V/m	volts per meter

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