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# Cell phone radiation: Evidence from ELF and RF studies supporting more inclusive risk identification and assessment☆

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**Abstract**

Many national and international exposure standards for maximum radiation exposure from the use of cell phone and other similar portable devices are ultimately based on the production of heat particularly in regions of the head, that is, thermal effects (TE). The recent elevation in some countries of the allowable exposure, that is, averaging the exposure that occurs in a 6 min period over 10 g of tissue rather than over 1 g allows for greater heating in small portions of the 10-g volume compared to the exposure that would be allowed averaged over 1-g volume. There is concern that 'hot' spots, that is, momentary higher intensities, could occur in portions of the 10-g tissue piece, might have adverse consequences, particularly in brain tissue.

There is another concern about exposure to cell phone radiation that has been virtually ignored except for the National Council of Radiation Protection and Measurements (NCRP) advice given in a publication in 1986 [National Council for Radiation Protection and Measurements, Biological Effects and Exposure Criteria for Radiofrequency Electromagnetic Fields, National Council for Radiation Protection and Measurements, 1986, 400 pp.]. This NCRP review and guidance explicitly acknowledge the existence of non-thermal effects (NTE), and included provisions for reduced maximum-allowable limits should certain radiation characteristics occur during the exposure.

If we are to take most current national and international exposure standards as completely protective of thermal injury for acute exposure only (6 min time period) then the recent evidence from epidemiological studies associating increases in brain and head cancers with increased cell phone use per day and per year over 8–12 years, raises concerns about the possible health consequences on NTE first acknowledged in the NCRP 1986 report [National Council for Radiation Protection and Measurements, Biological Effects and Exposure Criteria for Radiofrequency Electromagnetic Fields, National Council for Radiation Protection and Measurements, 1986, 400 pp.].

This paper will review some of the salient evidence that demonstrates the existence of NTE and the exposure complexities that must be considered and understood to provide appropriate, more thorough evaluation and guidance for future studies and for assessment of potential health consequences. Unfortunately, this paper is necessary because most national and international reviews of the research area since the 1986 report [National Council for Radiation Protection and Measurements, Biological Effects and Exposure Criteria for Radiofrequency Electromagnetic Fields, National Council for Radiation Protection and Measurements, 1986, 400 pp.] have not included scientists with expertise in NTE, or given appropriate attention to their requests to include NTE in the establishment of public-health-based radiation exposure standards. Thus, those standards are limited because they are not comprehensive.


*Keywords:* Non-thermal effects; Electromagnetic fields; Exposure standards

## 1. Introduction

### 1.1. The current approach to exposure limits (based on heating and electric current flow in tissues)

It is universally accepted that radiofrequency radiation (RFR) can cause tissue heating (thermal effects, TE) and that extremely low-frequency (ELF) fields, e.g., 50

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and 60 Hz, can cause electrical current flows that shock and even damage or destroy tissues. These factors alone are the underlying bases for present exposure standards. EMF exposures that cause biological effects at intensities that do not cause obvious thermal changes, that is, non-thermal effects (NTE), have been widely reported in the scientific literature since the 1970s including beneficial applications in development and repair processes. The current public safety limits do not take modulation into account and thus are no longer sufficiently protective of public health where chronic exposure to pulsed or pulse-modulated signal is involved, and where sub-populations of more susceptible individuals may be at risk from such exposures.

### *1.2. Modulation as a critical element*

Modulation signals are one important component in the delivery of EMF signals to which cells, tissues, organs and individuals can respond biologically. At the most basic level, modulation can be considered a pattern of pulses or repeating signals which have specific meaning in defining that signal apart from all others. Modulated signals have a specific 'beat' defined by how the signal varies periodically or aperiodically over time. Pulsed signals occur in an on–off pattern, which can be either smooth and rhythmic, or sharply pulsed in quick bursts. Amplitude and frequency modulation involves two very different processes where the high-frequency signal, called the carrier wave, has a lower frequency signal that is superimposed on or 'rides' on the carrier frequency. In amplitude modulation, the lower frequency signal is embedded on the carrier wave as changes in its amplitude as a function of time, whereas in frequency modulation, the lower frequency signal is embedded as slight changes in the frequency of the carrier wave. Each type of low-frequency modulation conveys specific 'information', and some modulation patterns are more effective (more bioactive) than others depending on the biological reactivity of the exposed material. This enhanced interaction can be a good thing for therapeutic purposes in medicine, but can be deleterious to health where such signals could stimulate disease-related processes, such as increased cell proliferation in precancerous lesions. Modulation signals may interfere with normal, non-linear biological functions. More recent studies of modulated RF signals report changes in human cognition, reaction time, brainwave activity, sleep disruption and immune function. These studies have tested the RF and ELF-modulated RF signals from emerging wireless technologies (cell phones) that rely on pulse-modulated RF to transmit signals. Thus modulation can be considered as information content embedded in the higher frequency carrier wave that may have biological consequences beyond any effect from the carrier wave directly.

In mobile telephony, for example, modulation is one of the underlying ways to categorize the radiofrequency signal of one telecom carrier from another (TDMA from CDMA from GSM). Modulation is likely a key factor in determining whether and when biological reactivity might be occurring, for example in the new technologies which make use of modulated signals, some modulation (the packaging for delivery for an EMF 'message') may be bioactive, for example, when frequencies are similar to those found in brain wave patterns. If a new technology happens to use brain wave frequencies, the chances are higher that it will have effects, in comparison, for example, to choosing some lower or higher modulation frequency to carry the same EMF information to its target.

This chapter will show that other EMF factors may also be involved in determining if a given low-frequency signal directly, or as a modulation of a radiofrequency wave, can be bioactive. Such is the evolving nature of information about modulation. It argues for great care in defining standards that are intended to be protective of public health and well-being. This chapter will also describe some features of exposure and physiological conditions that are required in general for non-thermal effects to be produced, and specifically *to illustrate how modulation is a fundamental factor which should be taken into account in public safety standards*.

## 2. Laboratory evidence

Published laboratory studies have provided evidence for more than 40 years on bioeffects at much lower intensities than cited in the various widely publicized guidelines for limits to prevent harmful effects. Many of these reports show EMF-caused changes in processes associated with cell growth control, differentiation and proliferation, that are biological processes of considerable interest to physicians for potential therapeutic applications and for scientists who study the molecular and cellular basis of cancer. EMF effects have been reported in gene induction, transmembrane signaling cascades, gap junction communication, immune system action, rates of cell transformation, breast cancer cell growth, regeneration of damaged nerves and recalcitrant bone-fracture healing. These reports have cell growth control as a common theme. Other more recent studies on brainwave activity, cognition and human reaction time lend credence to modulation (pulsed RF and ELF-modulated RF) as a concern for wireless technologies, most prominently from cell phone use.

In the process of studying non-thermal biological effects, various exposure parameters have been shown to influence whether or not a specific EMF can cause a biological effect, including intensity, frequency, the co-incidence of the static magnetic field (both the natural earth's magnetic field and anthropogenic fields), the presence of the electrical field, the magnetic field, or their combination, and whether EMF is sinusoidal, pulsed or in more com-

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plex wave forms. These parameters will be discussed below.

Experimental results will be used to illustrate the influence of each EMF parameter, while also demonstrating that it is highly unlikely the effects are due to EMF-caused current flow or heating.

### 2.1. Initial studies that drew attention to NTE

Several papers in the 1960s and early 1970s reported that ELF fields could alter circadian rhythms in laboratory animals and humans. In the latter 1960s, a paper by Hamer [2] reported that the EMF environment in planned space capsules could cause human response time changes, i.e., the interval between a signal and the human response. Subsequent experiments by a research group led by Adey were conducted with monkeys, and showed similar response time changes and also EEG pattern changes [3,4]. The investigators shifted the research subject to cats and decided they needed to use a radiofrequency field to carry the ELF signal into the cat brain, and observed EEG pattern changes, ability to sense and behaviorally respond to the ELF component of RFR, and the ability of minor electric current to stimulate the release of an inhibitory neurotransmitter, GABA, and simultaneous release of a surrogate measure, calcium ions, from the cortex [5,6]. At this time Bawin, a member of the research group, adopted newly hatch chickens as sources of brain tissue and observed changes in the release of calcium ions from in vitro specimens as a function of ELF frequency directly or as amplitude modulation ('am') of RFR (RFRam) [7–11]. Tests of both EMF frequency and intensity dependences demonstrated a single sensitive region (termed 'window') over the range of frequency and intensity examined. This series of papers showed that EMF-induced changes could occur in several species (human, monkey, cat and chicken), that calcium ions could be used as surrogate measures for a neurotransmitter, that ELF fields could produce effects similar to RFRam (note: without the 'am', there was no effect although the RFR intensity was the same), and that the dose and frequency response consisted of a single sensitivity window.

Subsequent, independent research groups published a series of papers replicating and extending this earlier work. Initial studies by Blackman, Joines and colleagues [12–25] used the same chick brain assay system as Bawin and colleagues. These papers reported multiple windows in intensity and in frequency within which calcium changes were observed in the chick brain experimental systems under EMF exposure. Three other independent groups offered confirmation of these results by reporting intensity and frequency windows for calcium, neurotransmitter or enolase release under EMF exposure of human and animal nervous system-derived cells in vitro by Dutta et al. [26–29], of rat pancreatic tissue slices by Albert et al. [30], and of frog heart by Schwartz et al. [31] but not frog-heart atrial strips in vitro [32]. This series of papers showed that multiple frequency and intensity windows were a common phenomenon that required the development of new theoretical concepts to provide a mechanism of action paradigm.

### 2.2. Refined laboratory studies reveal more details

Additional aspects of the EMF experiments with the chick brain described by Blackman and colleagues, above, also revealed critical co-factors that influenced the action of EMF to cause changes in calcium release, including the influence of the local static magnetic field, and the influence of physico-chemical parameters, such as pH, temperature and the ionic strength of the bathing solution surrounding the brain tissue during exposure. This information provides clues for and constraints on any theoretical mechanism that is to be developed to explain the phenomenon. Most current theories ignore these parameters that need to be monitored and controlled for EMF exposure to produce NTE. These factors demonstrate that the current risk assessment paradigms, which ignore them, are incomplete and thus may not provide the level of protection currently assumed.

### 2.3. Sensitivity of developing organisms

An additional study was also conducted to determine if EMF exposure of chicken eggs while the embryo was developing could influence the response of brain tissue from the newly hatched chickens. The detailed set of frequency and intensity combinations under which effects were observed, were all obtained from hatched chickens whose eggs were incubated for 21 days in an electrically heated chamber containing 60-Hz fields. Thus tests were performed to determine if the 60-Hz frequency of ELF fields (10 V/m in air) during incubation, i.e., during embryogenesis and organogenesis, would alter the subsequent calcium release responses of the brain tissue to EMF exposure. The reports of Blackman et al. [19] and Joines et al. [25] showed that the brain tissue response was changed when the field during the incubation period was 50 Hz rather than 60 Hz. This result is consistent with an anecdotal report of adult humans, institutionalized because of chemical sensitivities, who were also responsive to the frequency of power-line EM fields that were present in the countries where they were born and raised [33]. This information indicates there may be animal and human exposure situations where EMF imprinting during development could be an important factor in laboratory and epidemiological situations. EMF imprinting, which may only become manifest when a human is subjected to chemical or biological stresses, could reduce ability to fight disease and toxic insult from environmental pollution, resulting in a population in need of more medical services, with resulting lost days at work.

## 3. Fundamental exposure parameters—to be considered when establishing a mode (or mechanism) of action for non-thermal EMF-induced biological effects

### *3.1. Intensity*

There are numerous reports of biological effects that show intensity "windows", that is, regions of intensity that cause changes surrounded by higher and lower intensities that show no effects from exposure. One very clear effect by Blackman and colleagues is 16-Hz, sine wave-induced changes in calcium efflux from brain tissue in a test tube because it shows two very distinct and clearly separated intensity windows of effects surrounded by regions of intensities that caused no effects [17]. There are other reports for similar multiple windows of intensity in the radiofrequency range [22,26,29,31]. Note that calcium ions are a secondary signal transduction agent active in many cellular pathways. These results show that intensity windows exist, they display an unusual and unanticipated "non-linear" (non-linear and non-monotonic) phenomenon that has been ignored in all risk assessment and standard setting exercises, save the NCRP 1986 publication [1]. Protection from multiple intensity windows has never been incorporated into any risk assessment; to do so would call for a major change in thinking. These results mean that lower intensity is not necessarily less bioactive, or less harmful.

Multiple intensity windows appeared as an unexpected phenomenon in the late 1970s and 1980s. There has been one limited attempt to specifically model this phenomenon by Thompson et al. [34], which was reasonably successful. This modeling effort should be extended because there are publications from two independent research groups showing multiple intensity windows for 50, 147, and 450 MHz fields when amplitude modulated at 16 Hz using the calcium ion release endpoint in chicken brains, in vitro. The incident intensities (measured in air) for the windows at the different carrier frequencies do not align at the same values. However, Joines et al. [23,24] and Blackman et al. [20] noted the windows of intensity align across different carrier frequencies if one converts the incident intensity to the intensity expected within the sample at the brain surface. This conversion was accomplished by correcting for the different dielectric constants of the sample materials due to the different carrier frequencies. The uniqueness of this response provides a substantial clue to theoreticians but it is interesting and disappointing that no publications have appeared attempting to address this relationship. It is obvious that this phenomenon is one that needs further study.

### *3.2. Frequency*

Frequency-dependent phenomena are common occurrences in nature. For example, the human ear only hears a portion of the sound that is in the environment, typically from 20 to 20,000 Hz, which is a frequency "window". Another biological frequency window can be observed for plants grown indoors. Given normal indoor lighting the plants may grow to produce lush vegetation but not produce flowers unless illuminated with a lamp that emits a different spectrum of light partially mimicking the light from the sun. Thus, frequency windows of response to various agents exist in biological systems from plants to homo sapiens.

In a similar manner, there are examples of EMF-caused biological effects that occur in a frequency-dependent manner that cannot be explained by current flow or heating. The examples include reports of calcium ion efflux from brain tissue in vitro by Blackman and Joines and colleagues at low frequency [15,19] and at high frequency modulated at low frequency [20,35,24]. An additional example of an unexpected result is by Liboff [36].

In addition, two apparently contradictory multiple-frequency exposure results provide examples of the unique and varied non-thermal interactions of EMF with biological systems. Litovitz and colleagues showed that an ELF sinusoidal signal could induce a biological response in a cell culture preparation, and that the addition of a noise signal of equal average intensity could block the effect caused by the sinusoidal signal, thereby negating the influence of the sinusoidal signal [37]. Similar noise canceling effects were observed using chick embryo preparations [38,39]. It was also shown that the biological effects caused by microwave exposures imitating cell phone signals could be mitigated by ELF noise [40]. However, this observation should not be generalized; a noise signal is not always benign. Milham and Morgan [41] showed that a sinusoidal ELF (60-Hz) signal was not associated with the induction of cancer in humans, but when that sinusoidal signal was augmented by a noise signal, basically transients that added higher frequencies, an increase in cancer was noted in humans exposed over the long-term. Thus, the addition of noise in this case was associated with the appearance of a health issue. Havas [42–44] has described other potential health problems associated with these higher frequency transients, termed "dirty power." The bioactive frequency regions observed in these studies have never been explicitly considered for use in any EMF risk assessments, thus demonstrating the incomplete nature of current exposure guideline limits.

There are also EMF frequency-dependent alterations in the action of nerve growth factor (NGF) to stimulate neurite outgrowth (growth of primitive axons or dendrites) from a peripheral-nerve-derived cell (PC-12) in culture shown by Blackman et al. [45,46] and by Trillo et al. [47]. The combined effect of frequency and intensity is also a common occurrence in both the analogous sound and the light examples given above. Too much or too little of either frequency or intensity show either no or undesirable effects. Similarly, Blackman et al. [15] has reported EMF responses composed of effect "islands" of intensity and frequency combinations, surrounded by a "sea" of intensity and frequency combinations of null effects. Although the mechanisms responsible for these effects have not been established, the effects represent a here-to-fore unknown phenomenon that may have complex ramifications for risk assessment and standard setting. Nerve growth and neurotransmitter release that can be altered by different combinations of EMF frequencies and intensities, especially in developing organisms like children, could conceivably produce over time a subsequent altered ability to successfully or fully respond behaviorally to natural stressors in the adult environment; research is urgently needed to test this possibility in animal systems.

Nevertheless, this phenomenon of frequency dependence is ignored in the development of present exposure standards. These standards rely primarily on biological responses to intensities within an arbitrarily defined engineering-based frequency bands, not biologically based response bands, and are solely based on an energy deposition determinations.

## 4. Static magnetic field—a completely unexpected complexity

The magnetic field of the earth at any given location has a relatively constant intensity as a function of time. However, the intensity value, and the inclination of the field with respect to the gravity vector, varies considerable over the face of the earth. More locally, these features of the earth's magnetic field can also vary by more than 20% inside manufactured structures, particularly those with steel support structures.

At the Bioelectromagnetics Society annual meeting in 1984 [48], Blackman revealed his group's discovery that the intensity of the static magnetic field could establish and define those oscillatory frequencies that would cause changes in calcium ion release in his chick brain preparation. This result was further discussed at a NATO Advanced Research workshop in Erice, Italy in the fall of 1984 and by publications from that meeting and subsequent research: Blackman et al. [14,18] and Liboff et al. [36,49,50]. Substantial additional research on this feature was reported by Liboff and colleagues [51,52,50]. Blackman et al. also reported on the importance of the relative orientation of the static magnetic field vector to the oscillating magnetic field vector [21] and demonstrated a reverse biological response could occur depending on parallel or perpendicular orientations of the static and oscillating magnetic fields [53].

There have been many attempts to explain this phenomenon by a number of research teams led by Smith [49], Blackman [15], Liboff [36,54], Lednev [55], Blanchard [56], Zhadin [57], del Giudice [58], Binhi [59–62], and Matronchik [63] but none has been universally accepted. Nevertheless, experimental results continued to report static and oscillating field dependencies for non-thermally induced biological effects in studies led by Zhadin [64,65], Vorobyov [66], Baureus Koch [67], Sarimov [68], Prato [69,70], Comisso [71], and Novikov [72].

With this accumulation of reports from independent, international researchers, it is now clear that if a biological response depends on the static magnetic field intensity, and even its orientation with respect to an oscillating field, then the conditions necessary to reproduce the phenomenon are very specific and might easily escape detection (see for example, Blackman and Most [73]. The consequences of these results are that there may be exposure situations that are truly detrimental (or beneficial) to organisms, but that are insufficiently common on a large scale that they would not be observed in epidemiological studies; they need to be studied under controlled laboratory conditions to determine impact on health and wellbeing.

## 5. Electric and magnetic components—both biological active with different consequences

Both the electric and the magnetic components have been shown to directly and independently cause biological changes. There is one report that clearly distinguishes the distinct biological responses caused by the electric field and by the magnetic field. Marron et al. [74] show that electric field exposure can increase the negative surface charge density of an amoeba, Physarum polycephalum, and that magnetic field exposure of the same organism causes changes in the surface of the organism to reduce its hydrophobic character. Other scientists have used concentric growth surfaces of different radii and vertical magnetic fields perpendicular to the growth surface to determine if the magnetic or the induced electric component is the agent causing biological change. Liburdy et al. [75], examining calcium influx in lymphocytes, and Greene et al. [76], monitoring ornithine decarboxylase (ODC) activity in cell culture, showed that the induced electric component was responsible for their results. In contrast, Blackman et al. [77,78] monitoring neurite outgrowth from two different clones of PC-12 cells and using the same exposure technique used by Liburdy and by Greene showed the magnetic component was the critical agent in their experiments. EMF-induced changes on the cell surface, where it interacts with its environment, can dramatically alter the homeostatic mechanisms in tissues, whereas changes in ODC activity are associated with the induction of cell proliferation, a desirable outcome if one is concerned about wound healing, but undesirable if the concern is tumor cell growth. This information demonstrates the multiple, different ways that EMF can affect biological systems. Present analyses for risk assessment and standard setting have ignored this information, thus making their conclusions of limited value.

## 6. Sine and pulsed waves—like different programs on a radio broadcast station

Important characteristics of pulsed waves that have been reported to influence biological processes include the following: (1) frequency, (2) pulse width, (3) intensity, (4) rise and fall time, and (5) the frequency, if any, within the pulse ON time. Chiabrera et al. [79] showed that pulsed fields caused de-differentiation of amphibian red blood cells. Scarfi et al. [80] showed enhanced micronuclei formation in lymphocytes of patients with Turner's syndrome (only one X chromosome) but no change in micronuclei formation when the lymphocytes were exposed to sine waves (Scarfi et al. [81]). Takahashi et al. [82] monitored thymidine incorporation in Chinese hamster cells and explored the influence of pulse frequency (two windows of enhancement reported), pulse width (one window of enhancement reported) and intensity (two windows of enhancement reported followed by a reduction in incorporation). Ubeda et al. [83] showed the influence of difference rise and fall times of pulsed waves on chick embryo development.

### 6.1. Importance for risk assessment

It is important to note that the frequency spectrum of pulsed waves can be represented by a sum of sine waves which, to borrow a chemical analogy, would represent a mixture of chemicals, anyone of which could be biologically active. Risk assessment and exposure limits have been established for specific chemicals or chemical classes of compounds that have been shown to cause undesirable biological effects. Risk assessors and the general public are sophisticated enough to recognize that it is impossible to declare all chemicals safe or hazardous; consider the difference between food and poisons, both of which are chemicals. A similar situation occurs for EMF; it is critical to determine which combinations of EMF conditions have the potential to cause biological harm and which do not.

Obviously, pulse wave exposures represent an entire genre of exposure conditions, with additional difficulty for exact independent replication of exposures, and thus of results, but with increased opportunities for the production of biological effects. Current standards were not developed with explicit knowledge of these additional consequences for biological responses.

## 7. Mechanisms

Two papers have the possibility of advancing understanding in this research area. Chiabrera et al. [84] created a theoretical model for EMF effects on an ion's interaction with protein that includes the influence of thermal energy and of metabolism. Before this publication, theoreticians assumed that biological effects in living systems could not occur if the electric signal is below the signal caused by thermal noise, in spite of experimental evidence to the contrary. In this paper, the authors show that this limitation is not absolute, and that different amounts of metabolic energy can influence the amount and parametric response of biological systems to EMF. The second paper, by Marino et al. [85], presents a new analytical approach to examine endpoints in systems exposed to EMF. The authors, focusing on exposure-induced lymphoid phenotypes, report that EMF may not cause changes in the mean values of endpoints, but by using recurrence analysis, they capture exposure-induced, statistically significant, non-linear movements of the endpoints to either side of the mean endpoint value. They provide further evidence using immunological endpoints from exposed and sham treated mice [86–88]. Additional research has emerged from this laboratory on EMF-induced animal and human brain activity changes that provides more evidence for the value of their research approach (Marino et al. [89–92], Kolomytkin et al. [93] and Carrubba et al. [94–98]). Further advanced theoretical and experimental studies of relevance to non-thermal biological effects are emerging; see for example reports by Binhi et al. [59–62], Zhadin et al. [64,99,65], and Novikov et al. [72]. *It is apparent that much remains to be examined and explained in EMF biological effects research through more creative methods of analysis than have been used before. The models described above need to be incorporated into risk assessment determinations.*

## 8. Problems with current risk assessments—observations of effects are segregated by artificial frequency bands that ignore modulation

One fundamental limitation of most reviews of EMF biological effects is that exposures are segregated by the physical (engineering/technical) concept of frequency bands favored by the engineering community. This is a default approach that follows the historical context established by the incremental addition of newer technologies that generate increasingly higher frequencies. However, this approach fails to consider unique responses from biological systems that are widely reported at various combinations of frequencies, modulations and intensities.

When common biological responses are observed without regard for the particular, engineering-defined EMF frequency band in which the effects occur, this reorganization of the results can highlight the commonalities in biological responses caused by exposures to EMF across the different engineering-defined frequency bands. An attempt to introduce this concept to escape the limitations of the engineering-defined structure occurred with the development of the 1986 NCRP radiofrequency exposure guidelines because published papers from the early 1970s to the mid 1980s (to be discussed below) demonstrated the need to include amplitude modulation as a factor in setting of maximum exposure limits. The 1986 NCRP guideline [1] was the one and only risk evaluation that included an exception for modulated fields.

The current research and risk assessment attempts are no longer tenable. The 3-year delay in the expected report of the 7-year Interphone study results has made this epidemiological approach a 10-year long effort, and the specific exposure conditions, due to improved technology, have changed so that the results may no longer be applicable to the current exposure situation. It is unproductive to continue to fund epidemiological studies of people who are exposed to a wide variety of diversified, uncontrolled, and poorly characterized EMF in their natural and work environments. In place of the funding of more epidemiological studies should be funding to support controlled laboratory studies to focus on the underlying processes responsible for the NTE described above, so that mechanisms or modes of action can be developed to provide a theoretical framework to further identify, characterize and unify the action of the heretofore ignored exposure parameters shown to be important.

### *8.1. Potential explanation for the failure to optimize research in EMF biological effects*

Unfortunately, risk evaluations following the 1986 NCRP example [1], returned to the former engineering-defined analysis conditions, in part because scientists who reported non-thermal effects were not placed on the review committees, and in the terms of Slovic [100] "Risk assessment is inherently subjective and represent a blend of science and judgment with important psychological, social, cultural, and political factors. . . . Whoever controls the definition of risk controls the rational solution to the problem at hand. . . . Defining risk is thus an exercise in power." It appears that by excluding scientists experienced with producing non-thermal biological effects, the usually sound judgment by the selected committees was severely limited in its breadth-of-experience, thereby causing the members to retreat to their own limited areas of expertise when forced to make judgments, as described by Slovic [100], "Public views are also influenced by worldviews, ideologies, and values; so are scientists' views, particularly when they are working at limits of their expertise." The current practice of segregating scientific investigations (and resulting public health limits) by artificial divisions of frequency dramatically dilutes the impact of the basic science results, thereby reducing and distorting the weight of evidence in any evaluation process (see evaluations of bias by Havas [101], referring to NRC 1997 [102] compared to NIEHS 1998 [103] and NIEHS 1999 [104]).

## 9. Suggested research

Are there substitute approaches that would improve on the health-effects evaluation situation? As mentioned above, it may be useful in certain cases to develop a biologically based clustering of the data to focus on and enrich understanding of certain aspects of biological responses. Some examples to consider for biological clustering include: (1) EMF features, such as frequency and intensity inter-dependencies, (2) common co-factors, such as the earth's magnetic field or co-incident application of chemical agents to perturb and perhaps sensitize the biological system to EMF, or (3) physiological state of the biological specimen, such as age or sensitive sub-populations, including genetic predisposition as described by Fedrowitz et al. [105,106], and for human populations, recently reported by Yang et al. [107].

To determine if this approach has merit, one could combine reports of biological effects found in the ELF (including sub-ELF) band with effects found in the RF band when the RF exposures are amplitude modulated (AM) using frequencies in the ELF band. The following data should be used: (a) human response time changes under ELF exposure [2], (b) monkey response time and EEG changes under ELF exposure [3,4], (c) cat brain EEG, GABA and calcium ion changes induced by ELF and AM-RF [8,9,7,10,6,11,108,5], (d) calcium ion changes in chick brain tissue under ELF and AM-RF [8,9,7,10,13–15,21,16–18,12,19,20,22,35,23–25,11], and (e) calcium changes under AM-RF in brain cells in culture [26–28] and in frog heart under AM-RF [31]. The potential usefulness of applying biological clustering in the example given above even though AM is used, is that the results may have relevance to assist in the examination of some of the effects reportedly caused by cellular phone exposures which include more complex types of modulation of RF. This suggestion is reasonable because three groups later reported human responses to cell phone emissions that include changes in reaction times – Preece et al. [109,110], Koivisto et al. [111,112] and Krause et al. [113,114] – or to brain wave potentials that may be associated with reaction time changes—Freude et al. [115,116].

Subsequently, Preece et al. [117] tested cognitive function in children and found a trend, but not a statistically significant change in simple reaction time under exposure, perhaps because he applied a Bonferroni correction to his data (alpha for significance was required to be less than 0.0023). It would appear that a change in the experimental protocol might provide a more definitive test of the influence of exposure on simple reaction time because it is known that a Bonferroni correction is a particularly severe test of statistical significance, or as the author observed, "a particularly conservative criterion."

Krause et al. [118] examined cognitive activity by observing oscillatory EEG activity in children exposed to cell phone radiation while performing an auditory memory task and reported exposure related changes in the ∼4–8 Hz EEG frequencies during memory encoding, and changes in that range and also ∼15 Hz during recognition. The investigators also examined cognitive processing, an auditory memory task or a visual working memory task, in adults exposed to CW or pulsed cell phone radiation on either the right or left side of the head, and reported modest changes in brain EEG activity in the ∼4–8 Hz region, compared to CW exposure, but with caveats that no behavior changes were observed, and that the data were varying, unsystematic and inconsistent with previous reports (Krause et al. [119]). Haarala and colleagues conducted an extensive series of experiments, examining reaction time [120], short-term memory [121], short-term memory in children [122], and right versus left hemisphere exposure [123]. Although these studies did not

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support the positive effects from exposure reported by others, they provided possible explanations for the apparent lack of agreement.

Other research groups have also examined the effects of cell phone radiation on the central nervous system, including Borbely et al. [124], Huber et al. [125], Loughran et al. [126], and D'Costa et al. [127], who found changes in sleep EEG patterns and other measures during or after short-term exposures, while others, such as Fritzer et al. [128] exposed for longer time periods found no changes in sleep parameters, EEG power spectra, correlation dimension nor cognitive function. The work of Pritchard [129] served as the basis to examining correlation dimensions, which is opening a potentially fertile avenue for investigation. Although this approach provides more indepth information on ongoing processes and function, it has not yet been used to address potential consequences associated with long-term cell phone use.

The papers published in the 1960s through 1991, described in earlier sections of this paper, foreshadowed the more recent publications in 1999 through 2008 showing response time changes, or associated measures, in human subjects during exposure to cell phone-generated radiation. It is unfortunate that essentially none of the earlier studies was acknowledged in these recent reports on cognition, reaction time and other measures of central nervous system processes. Without guidance from this extensive earlier work, particularly those demonstrating the variety of exposure parameter spaces that must be controlled to produce repeatable experiments, the development of the mechanistic bases for non-thermal effects from EMF exposures will be substantially delayed. The omission of the recognition of the exposure conditions that affect the biological outcomes continues as recently as the National Academy of Science 2009 publication [130] of future directions for research, which emphasizes the modest perspective in the results from committee members working at the limits of expertise, as anticipated by Slovic [100].

Let us hope that subsequent national and international committees that consider future directions for EMF research include members who have performed and reported non-thermal effects, in order to provide a broader perspective to develop programs that will more expeditiously address potential health problems as well as to provide guidance to industry on prudent procedures to establish for their technologies.

At present, we are left with a recommendation voiced in 1989 by Abelson [131] in an editorial in Science Magazine that addressed electric power-specific EMF, but is applicable to higher frequency EMF as well, to "adopt a prudent avoidance strategy" by "adopting those which look to be 'prudent' investments given their cost and our current level of scientific understanding about possible risks."

## 10. Conclusions

There is substantial scientific evidence that some modulated fields (pulsed or repeated signals) are bioactive, which increases the likelihood that they could have health impacts with chronic exposure even at very low exposure levels. Modulation signals may interfere with normal, non-linear biological processes. Modulation is a fundamental factor that should be taken into account in new public safety standards; at present it is not even a contributing factor. To properly evaluate the biological and health impacts of exposure to modulated RFR (carrier waves), it is also essential to study the impact of the modulating signal (lower frequency fields or ELF-modulated RF). Current standards have ignored modulation as a factor in human health impacts, and thus are inadequate in the protection of the public in terms of chronic exposure to some forms of ELF-modulated RF signals. The current IEEE and ICNIRP standards are not sufficiently protective of public health with respect to chronic exposure to modulated fields (particularly new technologies that are pulse-modulated and heavily used in cellular telephony). The collective papers on modulation appear to be omitted from consideration in the recent WHO and IEEE science reviews. This body of research has been ignored by current standard setting bodies that rely only on traditional energy-based (thermal) concepts. More laboratory as opposed to epidemiological research is needed to determine which modulation factors, and combinations are bioactive and deleterious at low intensities, and are likely to result in disease-related processes and/or health risks; however this should not delay preventative actions supporting public health and wellness. If signals need to be modulated in the development of new wireless technologies, for example, it makes sense to use what existing scientific information is available to avoid the most obviously deleterious exposure parameters and select others that may be less likely to interfere with normal biological processes in life. The current membership on Risk Assessment committees needs to be made more inclusive, by adding scientists experienced with producing non-thermal biological effects. The current practice of segregating scientific investigations (and resulting public health limits) by artificial, engineering-based divisions of frequency needs to be changed because this approach dramatically dilutes the impact of the basic science results and eliminates consideration of modulation signals, thereby reducing and distorting the weight of evidence in any evaluation process.

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