Biological Effects of Radiofrequency Electromagnetic Field

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INTRODUCTION

Radiofrequency electromagnetic field/radiation (RFR) covers a large segment of the electromagnetic spectrum and falls within the nonionizing bands. Its frequency ranges between 3 KHz and 300 GHz. Cellular phones, wireless transmission towers for radio, TV, and telecommunication, radar and many other applications emit RFR. Different frequencies of RFR are used in different applications. For example, the frequency range of 540–1600 KHz is used in AM radio transmission, while 76–108 MHz is used for FM radio. Cell phone technology uses frequencies mainly between 800 MHz and 3 GHz, and RFR of 2450 MHz is used in microwave cooking.

Because of the proliferation of wireless communication in recent years, a large population of people is exposed to RFR constantly. There are two major concerns on the possible biological/health effects of RFR: the effect of RFR absorbed during cell phone use and the exposure to RFR emitted from transmission towers. These two situations represent very different exposure conditions. The close proximity of a cell telephone antenna to the user's head leads to the deposition of a relatively large amount of radiofrequency energy in the head. The relatively fixed position of the antenna relative to the head causes a repeated irradiation of a more or less fixed amount of body tissue. Exposure to RFR from cell phones is of a short-term, repeated nature at a relatively high intensity, whereas exposure to RFR emitted from transmission towers is of long duration but at a very low intensity and, in general, the whole body of a person is exposed.

Biological effects of RFR depend on how energy is deposited in the exposed organism. There are three major physical parameters: frequency, intensity, and duration of exposure. To understand the possible health effects of exposure to RFR, one needs first to understand the effects of these different parameters and how they interact with each other. These are discussed in this entry.

FREQUENCY, INTENSITY, AND PATTERN OF ENERGY ABSORPTION

The frequency of RFR is analogous to the color of a light bulb, and intensity is its wattage. There is a question of whether the effects of RFR of one frequency are different from those of another frequency. In this case, one is basically asking the question, "Are the effects of red light different from those of green light?" The answer to this is that it depends on the situation. They are different: if one is looking at a traffic light, "red" means "stop" and "green" means "go." But, if one is going to send some information by Morse Code using a light (on and off, etc), it will not matter whether one uses a red or green light, as long as the receiver can see and decode it. We do not know which of these two cases applies to the biological effects of RFR regarding frequency.

It must be pointed out that data are sparse showing either different frequencies producing different effects or an effect observed at one frequency but not at another. An example is the study by Sanders, Joines, and Allis, who observed that RFR at frequencies of 200 and 591 MHz, but not at 2450 MHz, produced effects on energy metabolism in neural tissues.[1] There are also several studies that showed that different frequencies of RFR produced different effects.[2–5] However, it is not certain whether these differences were actually due to differences in the pattern of energy absorption in the body of the exposed animal at the various frequencies. In addition, some studies showed frequency-window effects, i.e., effect is only observed at a certain range of frequencies and not at higher or lower ranges.[6–17] These results may suggest that the frequency of an RFR can be a factor in determining the biological outcome of exposure.

On the other hand, there are more studies showing that different frequencies can produce the same effect. For example, changes in blood–brain barrier have been reported after exposure to RFRs of 915, 1200, 1300, 2450, and 2800 MHz, and effects on calcium metabolism have been reported at 50, 147, 450, and 915 MHz.[6,8,9,12,13,16–20] If there is any difference in effects among different frequencies, it is a difference in quantity and not in quality.

The intensity of RFR in the environment is the power density measured in units such as milliwatts per square centimeter. However, power density provides little information on the biological consequence unless the amount of energy absorbed by the irradiated object is known. This is generally given as the specific absorption rate (SAR), which is the rate of energy

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absorbed by a unit mass of tissue of the object, and usually expressed as watts per kilogram. Thus, to understand the biological effect of RFR, one should know the SAR. It is a more reliable determinant and index of RFR biological effects than power density. Specific absorption rate is used in the setting of exposure standards for RFR.

Biological effects can occur after exposure to high intensity of RFR (high SAR) that can cause general or local heating. In some RFR exposure guidelines, the limits of 0.4 W/kg for occupational exposure and 0.08 W/kg for general public exposure are used based on the experimental results that ''disruption of behavior'' in animals occurs at 4 W/kg. However, there are many studies that show biological effects at SARs less than 4 W/kg after short-term exposure to RFR. For example, behavioral effects have been observed at SARs less than 4 W/kg: D'Andrea et al., 0.14–0.7 W/kg; DeWitt et al., 0.14 W/kg; Gage, 3 W/kg; King, Justesen, and Clarke, 2.4 W/kg; Lai et al., 0.6 W/kg; Mitchell, Switzer, and Bronaugh, 2.3 W/kg; Navakatikian and Tomashevskaya, 0.027 W/kg; Schrot, Thomas, and Banvard, 0.7 W/kg; Thomas et al., 1.5–2.7 W/kg; Wang and Lai, 1.2 W/kg.[21–31] There are also many reports of other biological functions affected by RFR at a SAR less than 4 W/kg. Most of the energy from a cellular telephone antenna is deposited in the skin and the outer portion of the brain. The peak energy output of cell telephones can range from 0.3 to 1 W, although the average output could be much smaller. Relatively high SARs have been determined in various dosimetry studies: Dimbylow and Mann, 2.3 and 4.8 W/kg per watt output at 900 MHz and 1.8 GHz; Anderson and Joyner, 0.12−0.83 W/kg; Gandhi et al., 0.13–5.41 W/kg at 0.6 W output (835 and 1900 MHz); and Van de Kamer and Lagendijk, 1.72–2.55 W/kg at 0.25 W output (915 MHz).[32–35]

Surprisingly, effects have also been reported in cells and animals after exposure to very low-intensity RFR that apparently cannot cause a physiologically significant change in temperature. Some 40 studies can be listed as low-intensity effects. The following are examples of some of these studies (some studies only give the power density, in mW/cm^2, of the radiation, whereas others give the SAR, in W/kg, in the exposed objects). Lebedeva et al. showed changes in brain wave activation in human subjects exposed to cellular phone RFR at 0.06 mW/cm^2.[36] Magras and Xenos reported a decrease in reproductive function in mice exposed to RFR at power densities of 0.000168–0.001053 mW/cm^2.[37] Phillips et al. reported DNA damage in cells exposed to RFR at SAR of 0.0024–0.024 W/kg.[38] Salford et al. reported nerve cell damage in brain of rats exposed for 2 hr to cell phone signal at 0.02 W/kg.[39] Tattersall et al. showed that low-intensity RFR (0.0016–0.0044 W/kg) modulated the function of a part of the brain called the hippocampus, in the absence of gross thermal effects.[40]

In addition, there are some indications that biological effects may also depend on how energy is deposited in the body. The rate of absorption and the distribution of RFR energy in an organism depend on many factors. These include the dielectric composition of the irradiated tissue, e.g., bones with a lower water content absorb less of the energy than muscles; the size of the object relative to the wavelength of the RFR (thus, the frequency); the shape, geometry, and orientation of the object; and the configuration of the radiation, e.g., how close is the object from the RFR source? These factors make the distribution of energy absorbed in an irradiated organism extremely complex and nonuniform, and also lead to the formation of so called ''hot spots'' of concentrated energy in the tissue. For example, an experiment reported by Chou et al., measuring local energy absorption rates (SARs) in different areas of the brain in a rat exposed to RFR, has shown that two brain regions less than a millimeter apart can have more than a twofold difference in SAR.[41] The rat was stationary when it was exposed. The situation is more complicated if an animal is moving in an RF field. Depending on the amount of movement of the animal, the energy absorption pattern in its body could become either more complex and unpredictable or more uniform. Thus, the pattern of energy absorption inside an irradiated body is nonuniform, and biological responses are dependent on distribution of energy and the body part that is affected.[42,43] Related to this is that we have found that different areas of the brain of the rat have different sensitivities to RFR.[44] This further indicates that the pattern of energy absorption could be an important determining factor of the nature of the response.

Different propagation characteristics such as ''modulation,'' or different waveforms and shapes may have different effects on a living system. For example, the same amount of energy can be delivered to tissue ''continuously'' or ''in short pulses.''

Another interesting observation of the research is that modulated and pulsed RFR seem to be more effective in producing an effect. They can also elicit a different effect when compared with continuous-wave radiation of the same frequency.[16,19,43,45–47] This observation is important because cell phone radiation is modulated at low frequencies. This also raises the question of how much do low-frequency electric and magnetic field components contribute to the biological effects. Biological effects of extremely low-frequency (<100 Hz) electric and magnetic fields are quite well established.

REPEATED EXPOSURE AND DURATION OF EXPOSURE

The majority of the biological studies on RFR have been conducted with short-term exposures, i.e., a few minutes to several hours. Little is known about the effects of long-term exposure. However, in actual human exposure situations, RFR exposure tends to be repetitive and long term. What are the effects of long-term exposure? Does long-term exposure produce different effects from short-term exposure? Do effects accumulate over time?

An important question regarding the biological effects of RFR is whether the effects are cumulative, i.e., after repeated exposure, will a biological system adapt to the perturbation and, with continued exposure, when will homeostasis break down leading to irreparable damage? The question of whether an effect will cumulate over time with repeated exposure is particularly important in considering the possible health effects of cell phone usage, because it involves repeated exposure of short duration over a long period (years) of time. Existing results indicate changes in the response characteristics of a biological system with repeated exposure, suggesting that the effects are not ''forgotten'' after each episode of exposure. Various biological outcomes have been reported after long-term/repeated exposure to RFR:

1. Effects were observed after prolonged, repeated exposure but not after short-term exposure.[48,49]
2. Effects that were observed after short-term exposure, disappeared after prolonged, repeated exposure (i.e., habituation) (e.g., Refs.[50–52]).
3. Different effects were observed after different durations of exposure (e.g., Refs.[26,53,54]).
4. There is also an indication that an animal becomes more sensitive to the radiation after long-term exposure (e.g., Refs.[4,21–23]). For example, the conclusion from a series of experiments on disruption of behavior in animals after one-time exposure to RFR is that ''disruption of behavior occurred when an animal was exposed at a SAR of approximately 4 W/kg.''[55] However, after long-term exposure (7 hr/day, 7 days/week for 90 days to 14 weeks), the threshold for behavioral and physiological effects of RFR was found to occur between 0.14 and 0.7 W/kg.[21,22] Thus, RFR can produce an effect at much lower intensities after an animal is repeatedly exposed. This can have very significant implications for people exposed to RFR in the environment.

The conclusion from this body of research is that effects of long-term exposure can be quite different from those of short-term exposure. There is also some evidence that effects of RFR accumulate over time. Here are some examples: Phillips et al. reported DNA damage in cells after 24 hr of exposure to low-intensity RFR. DNA damage can lead to gene mutation, which accumulates over time.[38] Magras and Xenos reported that mice exposed to low-intensity RFR became less able to reproduce.[37] After five generations of exposure, the mice were not able to produce offspring. This shows that the effect of RFR can pass from one generation to another. Persson, Salford, and Brun reported an increase in permeability of the blood–brain barrier in mice when the total energy deposited in the body exceeded 1.5 J/kg, i.e., the effect depends on the amount of energy deposited and not the rate of deposition.[56] This suggests that, under similar exposure conditions, a short-term/high-intensity exposure can produce the same effect as a long-term/low-intensity exposure. This is an indication that RFR effects can accumulate over time.

Related to this is that various lines of evidence suggest that responses to RFR could be a stress response.[57,58] Stress effects are well known to cumulate over time and involve first adaptation and then an eventual breakdown of homeostatic processes when the stress persists.

The possibility that effects cumulate over time and that acute effects change with repeated exposure have important implications on the setting of standards of RFR exposure. This suggests that the total amount of energy absorbed, the specific absorption (SA) (SA = SAR $\times$ time) rather than SAR, should be used as the index.

THERMAL AND NONTHERMAL EFFECTS

When RFR energy is absorbed, it is converted into heat. A readily understandable mechanism of effect of RFR is tissue heating (thermal effect). Biological systems alter their functions as a result of change in temperature. However, there is also a question as to whether ''nonthermal'' effects can occur from RF exposure. There can be two meanings to the term nonthermal effect. It could mean that an effect occurs under the condition of no apparent change in temperature in the exposed animal or tissue, suggesting that physiological or exogenous mechanisms maintain the exposed object at a constant temperature. The second meaning is that somehow RFR can cause biological effects without the involvement of heat energy (i.e., temperature independent). For practical reasons, it may be futile to make these distinctions simply because it is very difficult to rule out thermal effects in biological responses to RFR, and because heat energy is inevitably dissipated when RFR is absorbed.

In some experiments, thermal controls (i.e., samples subjected to direct heating) have been studied. Indeed, there are reports showing that ''heating controls'' do not produce the same effect of RFR.[59–62] These were taken as an indication of nonthermal effects. However, as we have discussed earlier, it is difficult to reproduce the same pattern of internal heating of RFR by external heating, as we know that a conventional oven cooks food differently from a microwave oven. And the pattern of energy distribution in the body is important in determining the effect of RFR (e.g., Refs.[19,42,43]). Thus, ''heating controls do not produce the same effect of RFR,'' does not really support the existence of nonthermal effects.

Furthermore, even though no apparent change in body temperature during RFR exposure occurs, it cannot really rule out a ''thermal effect.'' In one of our experiments, we have shown that animals exposed to a low SAR of 0.6 W/kg are actively dissipating the energy absorbed, thus, no significant increase in body temperature was observed in these animals.[42] This suggests that the nervous system involved in body temperature regulation is activated. The physiology of body temperature regulation is complicated and can involve many organ systems. Thus, changes in thermoregulatory activity can indirectly affect biological responses to RFR.

Another difficulty in eliminating the contribution of thermal effects is that it can be ''microthermal.'' An example of this is the auditory effect of pulsed RFR. We can hear RFR delivered in pulses. One of the explanations for this ''hearing'' effect is that it is caused by thermoelastic expansion of the head of the ''listener.'' In a paper by Chou et al., it was stated that ''... one hears sound because a miniscule wave of pressure is set up within the head and is detected at the cochlea when the absorbed microwave pulse is converted to thermal energy.''[63] The threshold of hearing was determined to be approximately 10 μJ/g/pulse, which causes an increment of temperature in the head of one millionth of a degree centigrade. Lebovitz gives another example of the microthermal effect of RFR on the vestibulocochlear apparatus, an organ in the inner ear responsible for keeping the body balance and sense of movement.[64] He proposed that an uneven distribution of RFR absorption in the head can set up a temperature gradient in the semicircular canals of the vestibulocochlear apparatus, which in turn affects the function of the vestibular system. The semicircular canals are very minute organs in our body.

What about in vitro experiments in which isolated organs or cells are exposed to RFR? Generally, these experiments are conducted with the temperature controlled by various regulatory mechanisms. However, it turns out that the energy distribution in culture disks, test tubes, and flasks used in these studies are often very uneven.[65] Hotspots are formed. There is a question of whether the temperature within the exposed samples can be efficiently controlled.

However, the existence of intensity windows, reports of modulated fields producing stronger or different effects than continuous-wave fields, and the presence of effects when exposed to RFR at very low intensity described in the sections above could be indications of nonthermal effects. My argument is that, in the setting of exposure standards, it may not be practical to differentiate these effects owing to the difficulty of eliminating the thermal effects.

OTHER CONSIDERATIONS

It has been repeatedly pointed out that the results reported in RFR research are difficult to replicate or reproduce. Problems in data reproducibility are not uncommon in science. In RFR research, it is further complicated by the complexity of interaction among the various exposure parameters as discussed above. This may make the response more sensitive to experimental procedures. Moderate variations in procedures could lead to different results. Examples are recent attempts to study RFR-induced DNA damage and spatial learning deficit.[38,66–71] Different results were observed when different experimental procedures were used. However, by comparing them carefully, these differences in results may actually help to reveal the mechanisms of interaction between RFR and biological systems.

An area of research that requires more study is the role played by the physiological conditions of an organism on its response to RFR. For example, The British Stewart Report on ''Mobile Phone and Health'' recommends caution in the use of cellular phones by young children because of their ''developing nervous system.''[72] Yet, little is known on whether developing biological systems are actually more vulnerable to the effects of RFR. On the other hand, people under certain drug therapies may be more susceptible to RFR. This is suggested by a study by Kues et al. in the early 1990s showing that the ophthalmic drug timolol significantly enhanced corneal endothelial lesion induced by RFR in the monkey.[73] Little research has been carried out to further investigate this type of interactions.

Another consideration is that the genetics of an organism may affect its response to electromagnetic fields. For example, two groups of researchers reported different effects of magnetic field on 7,12-dimethylbenz [*a*]anthracene (DMBA)-induced breast tumors in Sprague–Dawley rats.[74] One team, led by Wolfgang Löscher, later found that two substrains of Sprague–Dawley rats responded differently to the carcinogen and the magnetic field and that this could account

for the different results found by the two research groups.[75]

CONCLUSIONS

1. It is quite certain that RFR exposure can cause biological effects even at low intensity. However, the potential hazardous health effects of such exposure to humans are not clear. We do not know if these effects occur in humans exposed to RFR, or whether the reported effects are health hazards. Biological effects do not automatically mean adverse health effects. Many biological effects are reversible. However, it is very clear that low-intensity RFR is not biologically inert. Much more needs to be learned, however, before a presumption of safety can be made.
2. Frequency, intensity, exposure duration, and the number of exposure episodes can affect the response to RFR, and these factors can interact with each other and produce different effects. To understand the biological consequence of RFR exposure, one must know whether the effect is cumulative, whether compensatory responses result, and when homeostasis will break down. The response is not likely to be linear with respect to the intensity of the radiation. Other parameters of RFR exposure, such as waveform, frequency and amplitude modulation, etc., are also important determinants of biological responses and affect the shape of the dose–response relationship.
3. Not much is known about the biological effects of long-term exposure. The effects of long-term exposure can be quite different from those of short-term exposure. The effects may accumulate. In that case, the total energy absorbed (i.e., specific absorption) is a more relevant index of biological effect than the rate of energy absorption (SAR).
4. In many RFR exposure guidelines, a limit of 0.4 W/kg is used based on the experimental results that disruption of behavior in animals occurs at 4 W/kg. However, there are many studies that show biological effects at SARs less than 4 W/kg after short-term exposure to RFR. Therefore, the rationale of 4 W/kg should be reconsidered. The guidelines also only consider short-term exposure effect. Effects of long-term exposure, modulation, and other propagation characteristics are not considered. Another omission is that the physiological conditions of the exposed organism are not taken into consideration. Therefore, the present guidelines are questionable in protecting the public from possible harmful effects of RFR exposure.
5. Owing to the uncertainty in science, exposure of the general population to RFR should be kept to a minimum and should follow the ALAR-principle (As Low as Reasonably Achievable).

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