BEHAVIORAL AND PSYCHOLOGICAL EFFECTS OF MICROWAVE RADIATION*

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MY title may appear redundant, but I separate the subjective human psyche from the more objective goings on associated with behavior. Microwaves and other radiofrequency radiations of the electromagnetic spectrum can have highly predictable effects on behavior at modest and even low levels of irradiation. Introduction of weak fields into sensitive tissues promotes *bona fide* physiological reactions that give rise to changes in behavior. A more subjective and indeterminate class of behavioral reactions is also discussed, with emphasis on *neurasthenia,* a reversible syndrome akin to mild depression. The syndrome has been attributed to weak microwave fields, but an etiological connection has yet to be demonstrated or refuted. A third class of reactions, afflictions provoked in the human psyche by microwave radiation as a semantic agent, are not borne of physical forces in the usual sense of the word but are *imagined* effects of radiofrequency radiation, which certainly have consequences for human behavior, but their origin is in the workings of the scientifically untutored or overly suggestible mind.

Any discussion of imagined effects will inevitably focus on distortions and unsupportable speculations that have received much play in the popular media. A good case in point is the statement that microwave ovens emit ionizing radiations, which appeared in *Time* (April 9, 1979) and *U.S.*

*Presented as part of a *Symposium on Health Aspects of Nonionizing Radiation* sponsored by the Subcommittee on Public Health Aspects of Energy of the Committee on Public Health of the New York Academy of Medicine and held at the Academy April 9 and 10, 1979.

This study was supported by the Research Service of the U.S. Veterans Administration and by grant FD 00650 from the Food and Drug Administration.

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News and World Report (April 16, 1979) shortly after the accident at the Three Mile Island nuclear facility in Pennsylvania. The reader should not draw the conclusion that mine is a *lèse majesté* or condemnation of those members of the Fourth Estate who have fostered the public's belief in nonexistent ills and insults of radiofrequency radiation. If the proximal stimulus of public unrest largely lies in the press and television, the ultimate cause is the failure of radiobiological scientists and technologists to communicate adequately their knowledge to the purveyors of public information. The lines of communication between expert and expositor are indeed poor.

VERIDICAL BEHAVIORAL REACTIONS

Experimental studies. More than 5,000 reports of biological effects have appeared in the literature of radiofrequency radiations,[1,2] most based on experimental exposures of small animals to fields in the microwave spectrum (300 MHz.-300 GHz.) or at lower radio frequencies, and a substantial number relate in whole or in part to behavioral reactions. Most of the scientific reports from the United States are based on studies in which exposures were of short (minutes to hours) duration to highly intense fields well in excess of 10 mW/cm.^{2} The "hard" behavioral data that have emerged are therefore associated with acute effects and include (in approximate order of decreasing strength of fields) convulsive activity, work stoppage, work decrement, decreased endurance, perception of the field, and aversive behavior.

Electrical units and concepts. I shall characterize the data on acute behavioral effects in terms of electrical units such as mW/cm.^{2}, J/g., and mW/g. Appendix A and its associated tables define and illustrate the more commonly used electrical conventions and summarizes some basic physical concepts relevant to the quantitation of radiofrequency fields in biological systems. The reader is urged to review the appendix before proceeding further if he finds himself in unfamiliar territory.

Convulsions. *Grand-mal* seizures are induced by intense irradiation by radiofrequency energy and probably result from high body temperatures; they have been observed within 30 minutes in mice and rats under standard environmental conditions at power-density thresholds that cover a considerable range—from less than 5 to more than 500 mW/cm.^{2}—depending on the geometrical and electrical factors that determine the efficiency with which such radiation is coupled to the body.[3] While the power densities associated with convulsive activity are highly variable, the whole-body averaged dose of energy is not.[4] Under standard environmental conditions, the threshold convulsive dose lies between 22 and 35 J/g. of body mass and holds for exposures ranging from less than a millisecond[5] to 15 minutes.[6] While energy-dose thresholds of convulsions are highly stable, they are quite sensitive to basal body temperature at initiation of irradiation and to environmental variables, especially those of ambient temperature and air velocity.[4,6,7] The critical factor is core temperature; when elevated to a level near 43°C. the probability of a febrile convulsion within a few minutes approaches unity—an observation true for nearly all mammals tested. Convulsions induced by radiofrequency radiation indicate a dangerously intense field because morbidity and death frequently follow.[7,8]

Work stoppage. A hungry animal can be trained to work steadily to obtain food. Introduction of an agent that renders the animal ill or anoretic, or otherwise disables it, stops work. Several studies have shown that 918-and 2450-MHz. microwave fields stop work by rats after five to 20 minutes of irradiation when whole-body energy-dose rates have respectively ranged from ~20 to ~5 mW/g.[9,10,11] The energy dose associated with these time-intensity values—when the animal is not subjected to the additional stress of corporal restraint—is approximately 9 J/g. The power densities of irradiation that result in the cited dose rates would range upward from 10 to 150 mW/cm.^{2} or more, depending on the efficiency of energy absorption. Unlike convulsions, death has not been observed at threshold doses for work stoppage during brief exposures (<30 min.). Indeed, tests of behavioral competency performed 24 hours after irradiation have revealed full recovery of an animal's ability to perform light work.[9,11]

Work perturbation. Closely related to measures of work stoppage are those of work perturbation, i.e., where the rate or efficiency of performance is altered, perhaps even facilitated, but is not disrupted. Recent studies of the squirrel monkey by de Lorge[12] not only exemplify the case of behavioral perturbation, but illustrate how animals larger than mice and rats have much higher tolerance for microwave fields of a given frequency and intensity. De Lorge's monkeys worked at a two-lever task that required adroitness in discrimination and timing to achieve rewards of small pellets of food. After the monkeys had been partially deprived of food until body mass was reduced by 10%, which insured strong motivation to perform the two-lever task, they were exposed to 2,450 MHz. fields that ranged in power density from 0 to 75 $mW/cm.^2$ and were concentrated on the upper torso and head. Performance was not reliably affected until rectal temperatures were elevated by 1°C. or more. The irradiation required to produce a 1°C. change in temperature was near 50 $mW/cm.^2$ for a 30-minute duration of exposure. Disruption of performance did not occur in the monkeys until power density was increased above 60 $mW/cm.^2$ Even after exposures at 70 to 75 $mW/cm.^2$, which were strongly disruptive, the impairment of performance was only temporary. Dosimetric measurements were not made by de Lorge, but I estimate that the wholebody energy dose associated with the monkeys' thresholds of perturbation—slowed or increased rates or responding—ranges from 5 to 7 J/g.

Endurance. The work-stoppage and work-decrement experiments described above were all based on tasks, such as the pressing of a lever, that do not require sustained, strenuous effort. When forced expenditure of effort at a task is required over a long period of time, one measures endurance if an agent is introduced that interferes with performance of the task. In an elegant study by Hunt and his colleagues,[13] rats were required to swim almost continuously in an automated, water-filled alley immediately after being subjected during a 30-minute period to sham radiation, or to radiation by 2.45-GHz. energy that resulted in a dose rate of 6.3 or of 11 mW/g. Rats absorbing energy at the higher dose rate, which resulted in an energy dose near 20 J/g., were markedly impaired during the initial period of swimming, then recovered and swam about 600 meters at a normal rate before again showing impaired performance. When tested 24 hours after irradiation at the 11-mW/g. dose rate, the rats' swimming speeds were normal for about 1,200 meters before their performance worsened relative to controls. Some of the controls could swim a distance of 9 km. during a 24-hour period.

The rats that had been absorbing energy at the rate of 6.3 mW/g. for 30 minutes, when tested immediately after irradiation, swam as well as controls for about 1,200 meters, then performed poorly over the next 600 meters before again swimming at speeds that fell within control values. The dose of energy imparted to these rats, about 11 J/g., was associated with a modest degradation of endurance when the animals were tested immediately after exposure to 2,450-MHz. RF fields that could range in intensity from just above 35 $mW/cm.^2$ to 65 $mW/cm.^2$

Perception of RF fields. The perceptibility of radiofrequency fields is the most thoroughly established datum in the behavioral literature on such radiations, but a datum that must be qualified. The qualification relates to modulation of the radiofrequency field. When a radiofrequency field is sharply pulsed so as to produce a burst of electromagnetic waves of short rise time and high peak intensity, most individuals on whom the burst of waves is incident hear a popping or clicking sound. This effect was first systematically studied by Allan Frey,[14,15,16] and is now believed by most scientists who have studied it to result from thermoelastic expansion of tissues in the head. Sudden if extremely slight heating of tissues, because of their thermally-dependent change of density, is believed to launch a minuscule pressure wave detected (as are ordinary sound waves) at the cochlea.[17-20] The threshold of radiofrequency hearing per pulse of detected energy is the smallest consensually validated dose of microwave radiation that results in a biological effect, about 10 to 20 μJ/g., animals of smaller mass being more sensitive. These doses of energy are so small that, near threshold levels, the resulting increases in brain temperature per pulse average less than one-hundred-thousandth of a degree ($<10^{-5}$°C.).[19]

The threshold of detection of unmodulated or of softly (sinusoidally) modulated radiofrequency waves is much higher than that of pulsed waves. King and her colleagues[21] utilized the most sensitive assay known to experimental psychologists to determine sensory thresholds and found that the threshold dose rate lies near 600 μW/g. in rats subjected for 60 seconds to sinusoidally modulated 2,450-MHz. microwaves. The corresponding energy dose is near a maximal value of 35 mJ/g. The range of averaged power densities of incident 2,450-MHz. energy that would result in a dose rate of 600 μW/g. in mature rats is about 3.5 to 6.0 mW/cm.^{2} Since the radiofrequency hearing effect depends on an energy dose three orders of magnitude below the threshold of detectable warming, to which the rats of King *et al.* presumably were responding, it follows that the (1-second) time-averaged power density at which threshold responding occurs to a single audible pulse of radiofrequency waves is near 2 to 3 μW/cm.^{2}

Aversive behavior. When pulsed 1.2-GHz. microwaves of a character associated with radiofrequency hearing are continuously presented to rats that are given a choice—they can stay in the field or leave it for an area shielded from the radiation—they tend to remain in the shielded area.[22,23] One gathers that the continuously pulsed field, which averages about 200 μW/cm.^{2} in power density, is not too aversive, because rats given the choice will repeatedly "probe" and enter the radiated area even though they develop a general preference for the shielded site. At 200 μW/cm.^{2} a

1.2 GHz. field would result in dose rates between 30 and 80 μW/g.

A seeming paradox to the relative ease with which a rodent can detect a pulsed or nonpulsed microwave field of moderate intensity (~20 mW/cm.^{2}) lies in the extreme difficulty rats encounter in learning to escape from highly intense radiation, at least when the field is not pulse modulated and is not heralded or accompanied by salient sensory stimuli.[24] At power densities near lethal levels for a 4- to 8-min. exposure, i.e., in an unpulsed 918-MHz. field that results in a dose rate of 60 mW/g., rats simply do not quickly learn a simple locomotor response that would immediately attenuate or extinguish the field.[24] The datum of detectibility of fields of low to moderate intensity but failure of escape learning in a nearly lethal field, is really not a paradox but demonstrates that the continuous presence of a field and its sudden cessation have quite different psychological properties. Several minutes of irradiation at 10 to 25 mW/cm.^{2} or more can produce detectible warming.[25] However, sudden cessation of the intense radiofrequency field evades sensory witness, probably because of the large thermal time constant of the mammal's well-hydrated tissues. In effect, the field extinguishes, but the elevated temperature of tissues in which thermal nociceptors are situated declines too slowly to provide a discernible thermal cue to reinforce an escape response. Because of the poor detectability of the source of an attenuating or rapidly extinguished radiofrequency field, it is not surprising that human beings who work near unshielded or imperfectly shielded radiofrequency heaters in industrial settings have received intense irradiation, have developed symptoms of malaise, but have failed to discriminate the cause of their symptoms.[40]

General comment on experimental studies. A general rule is evident with respect to findings of behavioral reactivity during or shortly after acute exposures to radiofrequency radiation: The effects at high power densities above 100 mW/cm.^{2} are pronounced, easily recognized by the informed observer (if not by the uninformed recipient), and obviously thermally dangerous. At lower levels of such radiation, behavioral evidence of damage decreases rapidly; dose rates an order of magnitude below the rat's LD-50, which in a standard environment is near 35 mW/g. for a 20-minute exposure,[8] do not generate gross behavioral signs of harmful effects. It is true that effects per se are seen at much lower doses and dose rates (e.g., the radiofrequency hearing phenomenon), but no behavioral data implicate hazards for the animal acutely subjected to fields at aver-

TABLE I. REPRESENTATIVE DATA ON PROMPT BEHAVIORAL RESPONSES OF MAMMALS TO IRRADIATION BY RADIOFREQUENCY ELECTROMAGNETIC ENERGY

Class of behavior	*Citation No.*	*Species (mass)*	*Frequency and mode of irradiation**	*Duration of exposure†*	*Average power density*	*Energy dose rate‡*	*Energy dose*	*Mode of irradiation*
Aversion (Unpulsed fields)	24	Rat (300 g.)	918-MHz. sine	10 min. total	*125-375 mW/cm.²*	60 mW/g.	**5x7 J/g.**	Multimode cavity
Convulsions	7	Mouse (30 g.)	2,450-MHz. Sine	300 s.	*70-325 mW/cm.²*	80 mW/g.	**24 J/g.**	Multimode cavity
	7, 8	Rat (400 g.)	2,450-MHz. sine	380 s.	*440-800 mW/cm.²*	65 mW/g.	**25 J/g.**	Multimode cavity
Endurance	13	Rat (250 g.)	2,450-MHz. sine	30 min.	*30-80 mW/cm.²*	6 mW/g.	**11 J/g.**	Multimode cavity
	13	Rat (250 g.)	2,450-MHz. sine	30 min.	*55-140 mW/cm.²*	11 mW/g.	**20 J/g.**	Multimode cavity
Work stoppage	10	Rat (200 g.)	918-MHz. CW	6 min. (Avg.)	*8 mW/cm.²*	8 mW/g.	**3 J/g.**	Plane wave near field
	11	Rat (435 g.)	600-MHz. CW	22 min. (Avg.)	**20 mW/cm.²**	*2 to 14 mW/g.*	*3 to 18 J/g.*	Plane wave far field
Work perturbation	12	Squirrel monkey (900 g.)	2,450-MHz. CW	15 min.	**50 mW/cm.²**	*7 mW/g.*	*6 J/g.*	Plane wave far field
Aversion (pulsed fields)	22	Rat (250 g.)	1,200-MHz. pulsed	27 min. (cumul.)	**200 mW/cm.²**	*100 μW/g.*	*10 μJ/g. per pulse*	Plane wave far field
Perception (unpulsed fields)	21	Rat (425 g.)	2,450-MHz. Sine	<60 s	*3-6 mW/cm.²*	600 μW/g.	**≤36 mJ/g.**	Multimode cavity

TABLE I. (Continued)

Class of behavior	*Citation No.*	*Species (mass)*	*Frequency and mode of irradiation**	*Duration of exposure†*	*Average power density*	*Energy dose rate‡*	*Energy dose*	*Mode of irradiation*
Perception (pulsed fields)	19	Human (head only)	2,450-MHz. pulsed	5 μs. (repeated)	(Not applicable since single pulses are the variables of interest)		16 μJ/g. per pulse	Plane wave near field
	20	Guinea pig (head only)	918-MHz. pulsed	10 μs. (repeated)			6 μJ/g. per pulse	Wave-guide

The quantities shown for intensities of the incident field (power density) and for absorbed energy (dose rate and dose) are based on direct measurement (bold type), on calculations based on direct measurement (regular type), or on estimates (in Italics) via the *Radiofrequency Radiation Dosimetry Handbook* (see Durney et al., *Radio Science 14:* 1979). As is evident, unless animals in a plane-wave field of constant intensity are immobilized, quantities of absorbed energy are usually highly variable. Irradiation in a cavity or waveguide can result in a constant rate of energy absorption, even by freely moving animals; the associated range of power densities is an estimate of limits, the minimal and maximal quantities that, depending on an animals's orientation in a plane-wave field, would be required to produce a given dose rate. As a rule of thumb—for brief exposures during which loss of thermal energy by the irradiated animal is minimal—the mean body temperature will rise by ~0.25°C. for each J/g. of absorbed radiation.

*Sine = sinusoidal modulation, CW = continuous (unmodulated) waves, Pulsed = pulse-modulated waves

†Duration generally refers to minimal period of time to production of a given behavioral response

‡Whole-body average

Comment
Escape behavior *not* demonstrated during 5 2-min. exposures at 2-min. intervals.
Temperature, humidity, and velocity of air flow in the environment are critical as is the animal's core temperature at initiation of irradiation. Convulsion occurs at a rectal temperature near 43°C.
Immed. after irradiation endurance was moderately less than that of controls.
Immed. after irradiation endurance was markedly less; 24 hours later endurance was moderately less than controls'.
Rats were under bodily restraint to maintain constant exposure geometry.
Rats were free to move about in a field of highly varying coupling characteristics.
Monkeys worked while restrained in a chair; work stoppage was not observed but quality of performance was impaired.
Marked behavioral aversion was not observed; rats exhibited a preference (70%) for the shielded side of a shuttle box.
Values for duration and energy dose are upper limits since animals demonstrated detection of field during 60-s. presentations.
Normal human volunteers were subjected to fields under several conditions of pulse width and peaks of power density; 16 μJ/g. was lowest threshold observed. The guinea pigs were irradiated with their heads in a special waveguide.

aged power densities below 1 mW/cm.[2] A summary of acute (prompt) effects is given in Table I.

EPIDEMIOLOGICAL STUDIES

Lying in an indeterminate grey area between verifiable and imaginary behavioral effects of radiofrequency radiation are those cited in epidemiological reports. While epidemiological studies do not yield "hard" data, they have generated findings that command worldwide interest. Illustrative of the interest-provoking content is a study recently performed by Abraham Lilienfeld and his colleagues on former American employees of the United States Embassy in Moscow.[26] This study confirmed many earlier Eastern European reports with respect to neurasthenic symptoms among individuals working in stressful environments.[27-32]

The symptoms of neurasthenia are relatively persistent and include irritability, headache, lethargy, insomnia, irascibleness, impotence, and loss of libido—or what Western psychiatrists currently label the chronic depressive reaction.[33] While the syndrome doubtlessly exists, the specific attribution of microwaves and other radiofrequency fields as causative agents[27] was not supported by the Lilienfeld findings or, indeed, by many more recent Eastern European reports cited above. There is, however, the problem of interpreting the epidemiologist's necessarily uncontrolled observations. In the first place, the quantitation of strength of ambient fields has often been little more than guesswork. The industrial and military environments in which the typical epidemiological study has been performed contain so many variables that isolation and quantitation of specific sources of biological variation are extremely difficult.

Lilienfeld's group found that the incidence of neurasthenic symptoms among employees of the American embassy in Moscow is not positively correlated—and, indeed, is slightly negatively correlated—with levels of radiation measured inside and outside the Embassy with—for epidemiological studies—uncharacteristically great precision; however, even this negative finding will be challenged. Granted that levels of irradiation ranged from immeasurably low at the embassy's ground floor to maxima between 3 and 18 μW/cm.[2] near the top floor, the assumption that personnel remained effectively invariant with respect to vertical location in the building will be argued: Some upward and (especially) downward mobility has to be assumed—or did personnel billeted in the upper stories arrive at their posts without entering the embassy at the ground level? Another challenge will come from those who confuse the effects of ionizing with those of nonionizing radiations and argue for a "hit" theory, i.e., they will argue that just the *presence* of the field, however low or high its strength, triggers the neurasthenic reaction.

I do not subscribe to the hit theory for radiofrequency waves, and, for that matter, consider Lilienfeld's correlative analysis of field strength versus neurasthenic incidence as useful and valid as any reported in the epidemiological literature. What I stress is that some individuals with the will to believe that extremely weak radiofrequency fields induce neurasthenia—and other, much graver ills—will conjure arguments to support their beliefs. I also stress that I do not succumb to the fallacy of an argument *ad ignorantiam:* While I can argue on unimpeachable grounds that a good case for a microwave etiology for neurasthenia has not been made, I cannot argue that the evidence nullifies a possible connection.

The question of a role of microwave fields in the etiology of neurasthenia is amenable to experimental resolution with animal models. A key feature of the neurasthenic syndrome—sexual incompetence—could easily be tested in rats and, of course, rabbits. Edward Hunt and I have argued during the past year for studies in which chronically irradiated animals are tested for sexual competency. Our arguments have fallen on ears scientifically sympathetic but deaf to sponsorship. As one colleague put it, "If we start counting the frequency with which an irradiated rabbit mounts its mate and then report the numbers in the open literature, we're certain to incur the wrath of Senator Proxmire and secure the ignominy of the Golden Fleece award."

Imaginary Psychological Reactions

For many years American biologists who worked with radiofrequency radiations looked askance at Eastern European reports of neurasthenia among personnel occupationally exposed to microwave fields well below the U.S. guide number of 10 $mW/cm.^2$ It is now realized that the studies giving rise to Eastern European reports of positive findings and the singularly negative American studies had little in common. Our Eastern confrerès performed many relatively long-term experimental studies of animals at low levels of irradiation; we typically performed acute studies at relatively much higher levels. In retrospect, one must admit more than a little Yankee arrogance and a failure of scientific perspective to assume that the negative American findings cast doubt on positive reports from the East.

The failure of many American scientists to realize that the essence of confirmation or rebuttal lies in systematic replication does not, of course, validate Eastern claims of subtle, microwave-induced neuropathies and behavioral disorders. These claims still await laboratory confirmation or rebuttal because so many of the earlier studies—in the United States as well as abroad—were based on dosimetrically unanchored experiments in which the accuracy of measurement of field strengths of incident radiations is also suspect. Yet both irony and poetic justice attend claims by American authors that microwaves at very low levels"...can blind you, alter your behavior, [induce cancer], and even kill you,"[34] and are responsible for a high incidence of sudden death from heart attacks in Finland.[35] Because of the implication that fields at power densities well below 1 $\mu W/cm.^2$ are involved in this alleged morbidity and mortality, even the most accepting of Eastern European scientists would find this litany of Yankee horror stories incredible.

I shall turn now to specific examples of imaginary effects of microwave radiation. Examples are illustrative but hardly exhaustive because constraints on imagination are far less limiting than those on the time and space required for rebuttal.

Mongoloid offspring of airline pilots. Paul Brodeur, in his book, *The Zapping of America,*[34] recounted the travails of Dr. Irvin Emanuel, now director of the Child Development and Mental Retardation Center in Seattle, Wash. When highly informal observations indicated that Down's syndrome might be correlated with paternal status as airline pilot, Dr. Emanuel sought support for a formal study from the national office of the Airline Pilot's Association. This was not forthcoming. The determined Dr. Emanual next screened nearly 200 birth certificates of mongoloid children born in the Seattle area. Examination of the certificates revealed that no such child had been sired by an airline pilot. Dr. Emanuel did find that the average age of the mothers of the mongoloid children was advanced, which agrees with the well-established correlation between maternal age and incidence of mongolism. When interviewed subsequently by Mr. Brodeur, Dr. Emanuel gave a full account of the informal observations *and* of the subsequent study. Only the informal observations were reported by Mr. Brodeur, which prompted Dr. Emanuel to write in a letter sent to me that "What [Mr. Brodeur] did not do was include my description of our maternal age findings as I have recounted them to you. I regard this as an important omission which slants my conversation more in his direction than I am willing to see in the light of the information which I have."

Others have studied the incidence of mongolism among populations in which fathers have had protracted, occupationally or service-connected exposures to radiofrequency radiation. Except for one report based on a statistical artifact, no relation has been found between Down's syndrome and paternal exposure to radiofrequency radiation. The "mongoloid connection," then, is largely in Mr. Brodeur's imagination, as is his assumption that airline pilots are exposed to dangerous levels of microwave radiation. Perhaps the source of radiation is the cockpit cathode-ray tube, my second example.

Video-display terminals. A notable case of cataracts in two young editors with the *New York Times* was reported in 1977 and 1978 in a succession of newspaper stories. The blame was placed on cathode-ray tubes inside video-display terminals used by the editors. (One gathers that these unfortunate gentlemen saw Mr. Brodeur in his appearance on Tom Snyder's televised show *Tomorrow,* during which Mr. Brodeur informed Mr. Snyder and millions of viewers that the cathode-ray tube of the video camera's monitor might be emitting microwave radiation at dangerous levels.)

Other stories appeared in which birth defects and abortions were also blamed on microwaves radiated by video-display terminals. Finally, the management of the *Times* arranged for a series of surveys by engineers of radiations emitted by these terminals. The only measurable levels of nonionizing radiation emitted by these instruments were those of visible light. These surveys were independently confirmed by scientists and engineers of the National Institute for Occupational Safety and Health.[36]

Who is radiating whom? Measurement of radiofrequency fields generated by electronic devices is necessarily referred to background levels. By definition, an immeasurably small level of radiation is one near or below the level of background radiation. Mr. Brodeur is quite correct in assuming that video-display terminals and other thermionic devices generate microwaves, but he seems to be unaware that all matter in the universe above a temperature of absolute zero emits "black-body" (including microwave and infrared) radiation. Within limits, the quantity of microwave energy emitted by a body increases with increasing temperature, in keeping with Planck's law. Indeed, the operator of a video-display terminal with a higher average temperature than the device he is looking at radiates more microwave energy at the device than he gets from it!

Standards Versus Ambient Levels of Microwaves

One last figment of the microwave-inflamed imagination is a presumed association between standards of microwave radiation and their ambient levels. One of the more frequently discussed riddles of microwave radiation is the highly restrictive Eastern European limits on continuous exposure three to four orders of magnitude below the voluntary guide number in the United States of 10 mW/cm.^{2} Closely linked to this riddle is the supposition that environmental levels of microwave irradiation are much higher in the United States than in, say, the Soviet Union.

Recent surveys of densely populated areas of the United States by the Environmental Protection Agency reveal that in all but a tiny proportion of areas, levels of radiofrequency radiation are below the most stringent Eastern European limit.[37] While survey data do not indicate whether levels of such radiation are significantly lower in Moscow, say, than in New York City, they do indicate that *de facto* observance of a stringent civil standard is and has been the rule in the United States.

In some areas the stringent level is exceeded. Tall buildings in the vicinity of television and FM broadcast antennas are sometimes the recipients of signals that exceed 10 μW/cm.^{2}, but one assumes with some warrant that these excesses are as likely in some areas of Moscow—especially near the roof of the U.S. Embassy—as in New York City. Whatever the case, it does not follow that a statutory limit is commensurate with ambient levels of radiofrequency radiation.

With respect to the current United States guide number, I share with most contemporary radiobiologists the conviction that continuous, ultralong-term exposure of a biological system to radiofrequency radiation at 10 mW/cm.^{2} could augur for problems, particularly for emanations of VHF television and commercial FM transmitters. The twin factors of resonant absorption and relatively high fluxes of radiation deliberately and of necessity aimed at human populations could lead to hazards if field strengths of TV and FM signals approached the 10 mW/cm.^{2} level. While the scientific jury is out on the potential for irreversible harmful effects at much lower power densities, I doubt on intuitive grounds that there is any justification for the most stringent Eastern European standard, the 1 μW/cm.^{2} limit of Czechoslovakia. By establishing such a standard, our confreres in Czechoslovakia have effectively outlawed the bearing of children! The emission of "natural" microwave energy from a mother's body—from, specificially, the amniotic fluid that surrounds the fetus—

results in an incident whole-body flux of microwaves that effectively exceeds the statutory limit.*

One should not overlook some important implications of black-body radiation for scientists and physicians. First, a counterargument might be offered that radioactive elements are part of the fabric of biology. We are born with such elements, and we constantly absorb decaying isotopes from the external environment. Would one then argue that additional exposure to x or gamma-rays is therefore permissible or desirable? While answering strongly in the negative, I note an absence of parallelism between ionizing and "vital" (which is to say, infrared and microwave) radiations. Decaying isotopes are present in all biological bodies, but are irrelevant to metabolism; one could live and indeed live better without them. The vital microwave and infrared radiations are part and parcel of the metabolic stuff of living matter and, indeed, of all matter in motion. They are not exotic to the human condition but are an inseparable part. The incorporation of an excessive quantity of microwave or infrared radiation is certainly not desirable, but any argument that danger attends an encounter with exogenous microwaves at levels commensurate with and well below those inherent in the body begs an imagined peril that I am at a loss to comprehend.

Much easier to comprehend is the damage that can arise from false convictions—from the psychologically inspired physiological stress that attends anticipation of insult, contributes to chronic anxiety, and results in organic upset and deterioration among susceptible individuals.[39] Indeed, I believe there is far greater danger in false prophecy than in the weak electromagnetic fields around which the gloomy prophets spin their auguries of peril.

EPILOGUE

I have not commented much on that larger and essentially untested boundary of ultralong-term exposure to radiofrequency radiations. The flux of incident radiofrequency energy near 1 μW/cm.^{2} should hold no fear for

*By international convention, the spectrum of radiofrequency (RF) electromagnetic energy extends in 12 bands from just above zero hertz (D.C. or 0 Hz.) to 3 tHz. (terahertz= 10^{12} Hz.). The microwaves occupy Bands 9, 10, and 11 (300 MHz. to 300 GHz.) and thus are overlapped by one octave of radiofrequency radiation, Band 12, which also overlaps the infrared spectrum. If the radiant emittance of the human body is integrated over all 12 bands of the radiofrequency spectrum, the power-density number increases to $\sim$5 μW/cm.^{2} Moreover, integration of the human body's radiant emittance over the entirety of the radiofrequency and infrared spectra yields minimal and maximal power densities, respectively, near 3 and 50 mW/cm.^{2}, which reflect extremes of whole-body metabolic activity of "standard" man. The basal metabolic activity of the human brain is so great that its cells emit electromagnetic energy at a rate well in excess of 30 mW/cm.^{2}

reasons already mentioned. But there is a grey line of uncertainty that becomes ever more uncertain as that flux approaches the current American guide number of 10 mW/cm.[2] Need is manifest to explore that grey line experimentally, to assess the consequences of continuous radiofrequency irradiation over the life span and over generations of mammalian species with short spans of life. The need hardly inheres in present-day environmental levels of radiofrequency waves for the great majority of persons because man as a microwave radiator is much more the giver than the receiver, but the future bids strongly for ever increasing levels, especially if microwave-mediated energy is sought from the sun through the aegis of the solar-powered satellite.[38] We can experiment now in preparation for the future, or we can wait and let the future experiment on us.

SUMMARY

The first category of behavioral reaction to microwaves and other radiofrequency electromagnetic radiations involves responses confirmed in laboratory experiments from which a dose-response picture indicates absence of damaging effects of acute exposures (typically less than 60 minutes) at whole-body energy-dose rates below 3 mW/g. To result in this dose rate, the power density of incident radiation could be as low as 2 to 3 mW/cm.[2] for a small animal but would be on the order of 15 to 20 mW/cm.[2] for a human being. The second category treats of behavioral sequelae of indeterminate origin observed during epidemiological studies of industrial and military populations. Because of the general lack of quantitative information on intensity of ambient radiofrequency fields and because of myriad uncontrolled variables in the mundane environment, the extant epidemiological findings are at best hypotheses in need of experimental verification. The third category is that of imagined effects of radiofrequency radiations at power densities so low as to fall below the human body's rate of emitting microwave energy. Examples cited are the belief that video-display terminals emit significant quantities of microwave energy and the thesis that airline pilots have a higher than normal probability of fathering mongoloid children because of excessive exposure to microwaves. Because chronic anxiety can produce systemic disruption, propagators of imaginary hazards of microwave radiation probably generate more stress and disease in suggestible populations than the low-intensity fields to which all manner of ills are attributed.

Appendix I

ENERGY QUANTITIES AND CONCEPTS USED IN BIOLOGICAL STUDIES OF RADIOFREQUENCY ELECTROMAGNETIC RADIATION

Dosimetric units. In the System Internationale (S.I.) of quantities and units, the formal unit of all forms of energy—kinetic or potential, electrical or radiant, thermal or mechanical—is the joule (J). One joule is the equivalent of 10^7 ergs and of 0.239 "small" calories. Moderately active "Standard Man," for example, requires about 12,552 J of energy a day from ingested food to maintain his body mass of 70 kg., i.e., 1/0.239 = 4.184, which, multiplied by 3,000 calories = 12,552 J or ~ 12.5 kilojoules (kJ) per day.

When the joule is normalized to body mass in kilograms (joules per kilogram = J/kg.), these S.I. units express the energy dose, the amount of energy per unit of mass imparted to an absorbing body. A working unit of joules per gram (J/g.) is often used for convenience. Standard Man's daily nutritional dose in joules is ~179 J/kg. or ~0.18 J/g.

The watt (W) is the S.I. unit of the time-averaged rate at which energy is generated, transferred, transformed, absorbed, or dissipated. Accordingly, W is defined as number of joules per second (W= J/s.). To express the mass-normalized time rate of energy generation, transformation, etc., the appropriate S.I. unit is W/kg., which is widely used as the radiofrequency energy dose rate and is also known as the Specific Absorption Rate or SAR [working units are milliwatts per gram (mW/g.), and microwatts per gram (μW/g)]. For comparison, Standard Man metabolizes energy at a whole-body averaged rate of 1 mW/g. (sleeping), 2 mW/g. (light activity), 10 mW/g. (severe exercise), or 18 mW/g. (running up a flight of stairs).

The metabolic rate is not a dose rate, which is defined as the mass-normalized rate of incorporation of external energy; the numbers given for various levels of metabolic activity are cited solely to provide the reader with a frame of reference for appreciating rates at which radiofrequency energy is incorporated into a biological body. Energy-dose and energy-dose-rate numbers carry no necessary metabolic meaning, but simply express quantities of rates of *physical* heating, latent or kinetic, by absorbed electromagnetic energy. Heat is defined physically as energy in transit from a source to an absorbing body; heating is simply the rate at which any form of energy, microscopically speaking, is coupled to an ensemble of molecules. Heat is not to be confused with temperature, which is the average kinetic energy of a system of molecules. It is an anomaly of the English language that only one adjective, "thermal," is used to modify the different constructs of heat and temperature. This anomaly has been the source of much confusion because one investigator's claim of nonthermal effects of microwaves may be intended to mean an effect not based on a measurable change of temperature, while another investigator may mean *no* effect of temperature, and yet another investigator may unwittingly intend an effect not based on heating (i.e., not based on transfer and absorption of energy). The latter meaning is a physical contradiction in terms because an effect cannot be induced in a system by an external agent unless energy is imparted. The only valid meaning of nonthermal radiofrequency radiation (in the sense of a nonheating field) is that which is completely scattered (zero absorption) by the body on which it is incident. It is important to note that veridical thermal effects based on heating have several theoretical categories of causation, including increase of temperature (manifest heating), change of physical state (latent heating), and rate of increase of temperature, which is believed to be critical for the phenomenon of radiofrequency hearing.

The reader is cautioned at this juncture that the term "heating"is used in the physical, molecular sense of the word. I assume without fear of physical contradiction that absorption of a quantum of RF energy by an ensemble of molecules will increase their kinetic energy (kT). But an increase of kT from heating at the molecular level is no warrant that ensuing events at levels of greater structural complexity are a simple reflection of ΔkT. In that enormous and highly ordered aggregate of molecules known as the neuron, the RF field that invests it and its millions of interconnected counterparts may theoretically ignite macromolecular physiological events that are associated with but are not linearly attributable to ΔkT. By analogy, a coil of spring steel can be viewed at one level as a repository of potential energy as it is compressed, and as an exemplar of kinetic energy upon release, yet the myriad behaviors and consequences of such springs at the macromolecular level are only remotely attributable to micromolecular ΔkT. In recognition that J and W are constructs related to energy (and, as regards RF dosimetry, to electrical energy), there is no implication whatsoever that J/g. or W/g. as independent dosimetric variables possess that surplus of meaning that forces a "thermal" interpretation on any biological response to an absorbed RF radiation.

TABLE A-I. REPRESENTATIVE QUANTITIES, DEFINITIONS AND UNITS OF ELECTROMAGNETIC RADIATION RECOMMENDED BY IEC AND IOS

Quantity and definition	*SI unit*	
	Name	*Symbol*
Electromagnetic radiation		
The *radiant energy* Q_e (or W) is the energy emitted, transferred or received as radiation.	joule	J
The *radiant energy density* ω is the radiant energy in an element of volume divided by that element: $\omega = dQ_e/dV$.	joule per cubic meter	J/m.[3]
The *radiant flux* or *radiant power* Φ_e is the time rate at which energy is emitted, transferred or received as radiation: $\Phi_e = P = dQ_e/dt$.	watt	W
The *radiant exitance* M_e at a point of a surface element is the radiant flux leaving an element of the surface divided by the area of that element: $\Phi M_e = \int_e dA$.	watts per square meter	W/m.[2]
The *irradiance* or *energy flux density* ("power density") E_e at a point of a surface is the radiant flux incident on an element of the surface divided by the area of that element: $\Phi_e = \int E_e dA$.	watts per square meter	W/m.[2]
The radiant exposure H_e is the time integral of the irradiance: $H_e = \int_e t$.	joule per square meter	J/m.[2]

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Densimetric units. Radiofrequency waves incident on a biological body are often characterized by one or more of three sets of S.I. units, volts per meter (V/m. = electric-field strength), amperes per meter (A/m. = magnetic-field strength), and, especially in the microwave spectrum, watts per meter squared (W/m.^{2}). While V/m. and A/m. relate to the strengths of two field components of an RF wave, the W/m.^{2} (which is referred to formally as irradiance or energy flux density and informally as power density) relates to the average or peak quantities of energy that flow each second of time through a measured area of space. Watts or milliwatts per centimeter squared (W/cm.^{2} or mW/cm.^{2}) are commonly used derivations and have the relation of 10 W/m.^{2} = 1 mW/cm.^{2} = 1,000 μW/cm.^{2}

Power density is the cross-product of the two components of field

TABLE A-II. PROPOSED QUANTITIES, DEFINITIONS, AND UNITS FOR DOSING OF BIOLOGICAL BODIES WITH NONIONIZING ELECTROMAGNETIC RADIATION

Quantity and definition	*SI unit*	
	Name	*Symbol*
Absorbed electromagnetic energy		
The *energy dosage* Q_{ab} is the energy imparted to a biological body from irradiation by electromagnetic energy.	joule	J
The *energy dosage-rate* $\dot{Q}_{ab}$ is the time rate at which energy is imparted to a biological body from irradiation by electromagnetic energy.	watt	W
The *energy dose* D_{ab} is the energy imparted to an element of mass of a biological body from irradiation by electromagnetic energy. $D_{ab} = Q_{ab} M^1$	joule per kilogram	J/kg.[1]
The *energy dose-rate* $\dot{D}_{ab}$ is the time rate at which energy is imparted to an element of mass of a biological body from irradiation by electromagnetic energy. $\dot{D}_{ab}=dD_{ab}/dt$	watt per kilogram	W/kg.[1]

Reproduced by permission from Justesen, D.R.: Toward a prescriptive grammar for the radiobiology of nonionising radiations: Quantities, definitions, and units of absorbed electromagnetic energy. *J. Microwave Power 10:*343, 56, 1975.

strength and, as an expression of propagating radiofrequency energy, is not a dosimetric measure. Because of the many electrical and anatomical variables that control the quantity of energy absorbed by a body in a field of a given power density (see Gandhi, p. 999, this issue), the power-density number is only a crude index of the dose rate.

Tables A-I and A-II summarize respectively formal S.I. quantities, units, and nomenclatures for radio densitometry, and related conventions, and formal S.I. units and quantities for radio dosimetry (nomenclatures have been proposed but have yet to be resolved by the S.I. arbiters).

ACKNOWLEDGEMENT

I thank O.P. Gandhi, A.W. Guy, Habib Massoudi, and R.D. Phillips for critical comments on an earlier draft of the manuscript.

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