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RADIOPHOBIA: THE GREAT AMERICAN SYNDROME[1]

Man-made radiation, ionizing and nonionizing, is an environmental pollutant characteristic of 20th century technology. Permissible levels of exposure for both types have become a matter of increasing public concern and rancor. These two broad categories of radiation, their differences, and their biological significance are compared and discussed.

INTRODUCTION

Irrational fear of low-level radiation is a constantly increasing component of public attitudes and the political responses to them. While careless management of any perturbation to the natural environment, particularly ionizing radiation, can produce both acute and long-term hazards, the extensive body of scientific knowledge of the biological effects of ionizing and nonionizing radiation that already exists (although far from complete) has been most often perverted, confused, or ignored in the public and private decision processes.

A fundamental thesis underlying this phenomenon is perhaps best expressed by some excerpts from an earlier author, a neurologist:

> "The chief and primary cause of [the] very rapid increase of nervousness is *modern civilization*, which is distinguished from the ancient by these five characteristics: steampower, the periodical press, the telegraph, the sciences, and the mental activity of women.
>
> "The greater prevalence of nervousness in America is a complex resultant of a number of influences, the chief of which are dryness of the air, extremes of heat and cold, civil and religious liberty, and the great mental activity made necessary and possible in a new and productive country under such climatic conditions.
>
> "All this is modern, and originally American. Of all the facts of modern sociology, this rise and growth of functional nervous disease is one of the most stupendous, complex, and suggestive . . . .
>
> "Among the signs of American nervousness specially worthy of attention are the following:
>
> - susceptibility to stimulants and narcotics and various drugs
> - inebriety and neurasthenia
> - hay-fever
> - neuralgia
> - nervous dyspepsia
> - asthenopia
> - early and rapid decay of teeth
> - premature baldness
> - sensitiveness to cold and heat
> - unprecedented beauty of American women
> - the strain of dentition, puberty, and change of life
> - American oratory, humor, speech, and language
>
> "The evil of American nervousness, like all other evils, tends, within certain limits, to correct itself; increasing wealth will bring increasing calm and repose; the friction of nervousness shall be diminished by various inventions; social customs with the needs of the times, shall be modified; strength and vigor shall be developed at the same time with, and by the side of debility and nervousness."
>
> (From G. M. Beard, *American Nervousness — Its Causes and Consequences*, G.P. Putnam's Sons, New York, 1881.)

My relationship with the biological effects of radiation, and the public reaction to them, began when my Department of Defense office initiated Project Pandora in 1965 to investigate whether the microwave radiation beamed at the Moscow Embassy had any psychological or biological significance.[2,3] At the request of the Secretary of State, a team went to Moscow in 1976 to try to convince the Soviets to stop the Embassy radiation. It consisted of a physician, a physicist (myself), a biologist, and an electrical engineer. After the Embassy staff was informed of the presence of the radiation, we all found ourselves practicing medicine in earnest. In fact, the task of

Project Pandora

In May of 1965, when no other obvious purpose could be confirmed for the Soviet microwave irradiation of the U.S. Embassy in Moscow, the author suggested to the Department of State that:

> "A possible explanation of the Moscow signal may reside in an attempt to produce a relatively low level neurophysiological condition among Embassy personnel....There exists very little data in the United States or other western countries on the effect of low level microwave radiation....On the other hand, there is an extremely large amount of Soviet technical literature discussing non-thermal effects at levels below the United States accepted standard....The possible effects of low level continuous exposure are problematical and are based on the Soviet material...; very few experiments with complex waveforms or experiments on primates are ever reported....Possible hypothetical models for non-thermal interaction must consider insertion of neurophysiologically significant waveforms by non-linear absorption and consequent demodulation and mixing of various carrier frequencies and specific biochemical absorption resonances....While a sober and systematic program of research in this area should be undertaken over a long time period, the time scale of the present problem indicates that a program to specifically check the complex Moscow signal waveform on higher primates should be carried out."

In November of 1966, Eugene V. Byron prepared "the final report on the Applied Physics Laboratory's contribution to Project Pandora — specifically aid in the implementation, and the evaluation of a microwave test facility at Walter Reed Army Institute of Research." A month earlier, he had prepared the "operational procedure for Project Pandora microwave test facility....intended primarily for non-microwave oriented technical personnel to enable them to operate the facility with a minimum of training."

trying to allay individual fears and concerns continued intermittently for at least two years afterward. The actual physical results of the exposure were nonexistent, but the real psychological trauma (in this case in a group of well-educated and dedicated people) was sad and startling.

A very different event, the Three Mile Island accident, is a demonstration of how good the mechanical design of a reactor was (even with some errors) from the point of view of redundancy for safety, how poor the operator training was, and, less obviously, how poor the control room design was even for well-trained operators. For a relatively serious accident such as this and despite all the outcry, the public exposure to radiation was quite small.

The Clamshell Alliance episodes in New Hampshire, the reactions in the Michigan Upper Peninsula and in Texas to Seafarer (the proposed Navy Extra Low Frequency [ELF] Communication System), the agitation over the Air Force Pave Paws (a surveillance radar), both on Cape Cod and in California, prohibitions and restrictions on movement of radioactive materials, public objections to installation of microwave towers, and many other incidents, major and minor, are representative of the confusion between different types of radiation and different exposure levels and the underlying phobic reaction to the very word "radiation."

In the public mind, the semantics of the word "radiation" does not explicitly include the vast wavelength differences and consequent differences of interaction with biological tissue. Increasing apprehension and confusion about all kinds of radiation, whether it be ionizing (which may have a biological impact even at very low exposures) or nonionizing (which has no known irreversible effects at low levels), is imbedded in the spoken and printed word. From the late 18th century to now there is hardly a period when some fad (or less than legitimate scientific hypothesis) has not been present regarding the interaction of the electromagnetic field with the human body—the present being no exception, as is exemplified by the arcane logic applied by the press and some recent popular authors.[4]

HISTORICAL BACKGROUND

The interaction of electromagnetic phenomena with biological organisms has intrigued both the scientific community and the layman almost since the beginning of electrical science. Although the ancients may have speculated as to whether lightning and the lodestone were manifestations of some superior life force, modern electrical science really began with Gilbert[5] and Von Guericke[6] in the early 17th century (Plate 1). Systematic speculation as to whether, in fact, electricity was some manifestation of a vital force and whether, in turn, this could have either healing or inimical effects on the body, appears infrequently in the literature until about the 18th century. Electrical generators were first used for human therapy by Krueger and Kratzenstein[7,8] about 1740. By the end of the 18th century, however, many physicians had attempted to treat medical conditions with electrical forces (Plate 2). The numerous experiments on animals and executed criminals by Galvani,[9]

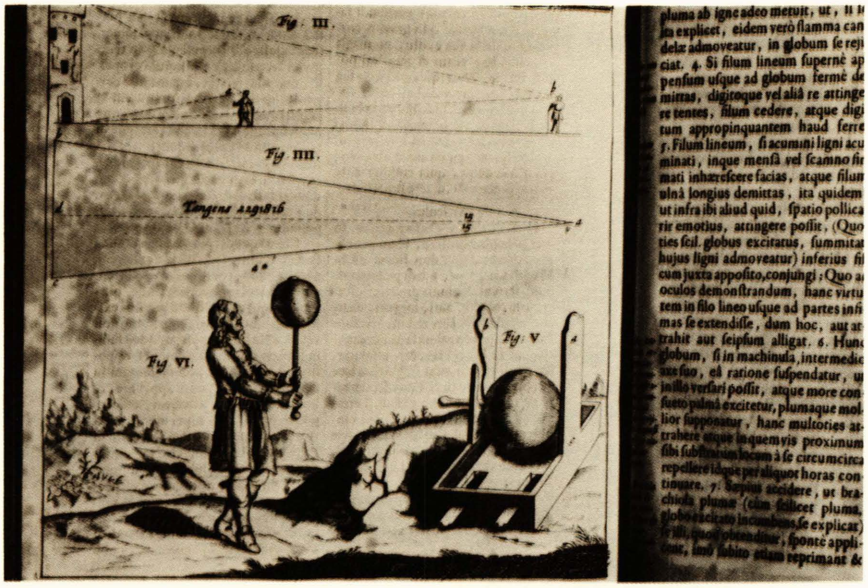


Plate 1—Von Guericke's book of 1672, *Experimenta Nova . . .*,[6] perhaps better known for its illustrations of the "Magdeburg spheres" demonstrating atmospheric pressure, also provides the first description of an electrostatic "machine."

Aldini, and Volta shortly before and after 1800, which related electricity to neural function, are well known although they unfortunately led to many incorrect conclusions.

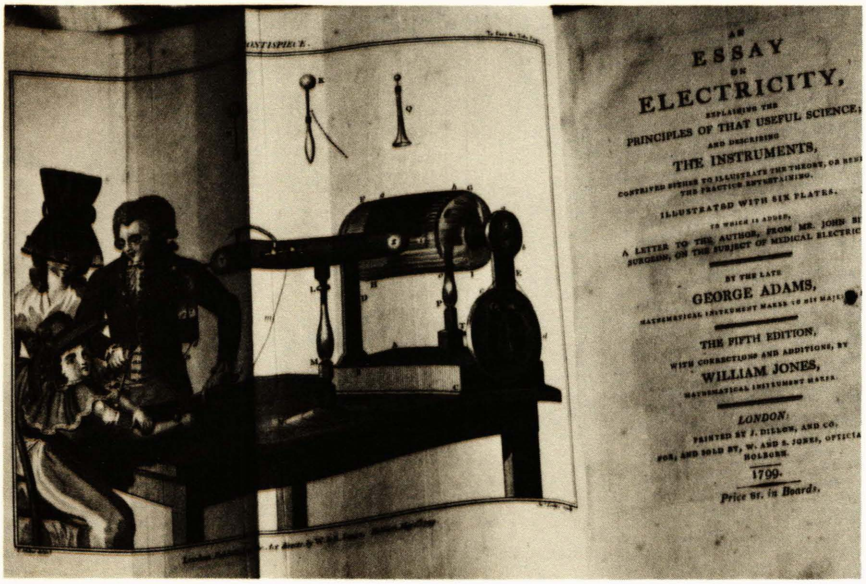
Faraday first published the principle of electromagnetic induction in 1831.[10] Within a few years, devices for "medical" self treatment using induction generators appeared on the market (Plate 3). By the 1850's, there were several serious medical treatises discussing the use of electric phenomena to relieve paralytic symptoms and for other therapeutic applications.[11] The science of modern neurophysiology began in this period.[12] Throughout the 19th century, there were both serious and "quack" attempts to apply pulsed, direct, and alternating currents to medical problems. The theoretical intertwining of the relationship of time-dependent electric and magnetic fields by James Clerk Maxwell[13] and the consequent experiments of Heinrich Hertz[14] made short-wavelength electromagnetic radiation available in the 1880's (Plate 4).

Röntgen first reported his observations of "X rays" in 1895.[15] By the following year, several manuals[16] for their practical application to imaging appeared (Plate 5), and radiation was being used for treatment of dermatological conditions. Becquerel,[17] stimulated by Röntgen's observations, looked for X rays in fluorescent materials, resulting in the classic observation of radiant energy that appeared to penetrate opaque materials (Plate 6). Thus the study of radioactivity was born. Marie Curie and her husband[18] soon after were able to isolate polonium and radium (Plate 7). In this same period, Rutherford[19] and his associates started the detailed analysis of thorium, its decay series, and the physical properties of the radiation from radioactive materials. By the early 1900's, X rays and radioactive materials were available, as was high-frequency "Hertzian" radiation. The armamentarium of the physician seeking to use radiation therapy tended to lump together X rays and all other forms of electromagnetic energy available from DC to high frequencies,[20] particularly those generated by the Tesla coil (Plate 8). The first experiments on artificially induced mutation were performed in 1927 by Muller[21] using X rays. With the availability of vacuum tube oscillators, many may remember the prevalent use of high frequency diathermy in the 1930's. Before World War II, the dangers of ionizing radiation, including X rays, were well established. "Radiation" became a prime source of public alarm with the dawn of a new age at Alamagordo in 1945. Following World War II, a new concern was directed particularly toward high-power microwave radiators with high-gain antennas derived from the war's radar and communication programs. APL's Safety Committee in 1960[22] felt it necessary to acquaint the staff members with

> "the possible hazards existing by direct exposure of personnel to microwave radiation. The subject has only recently become of concern to the Laboratory, by reason of the fact that the power of radar equipment (both service equipments and experimental models) has greatly increased during recent years, and will increase still more in the future."

Many physicians have stated that, in general practice, approximately 75% of patient visits are related to psychic discomfort rather than to a symptom that really requires physical treatment. There may be, indeed, a much higher percentage of underlying real physical problems, but the apparent operative exacerbation is usually due to emotional and mental discomfort. The practicing physician, then, has three concerns with low-level radiation, both ionizing and nonionizing:

1. The patient's fear of radiation may be the basis of a perceived ailment.
2. The local public should accept the use of the ionizing and nonionizing spectrum for thera-



AN
ESSAY
ON
ELECTRICITY,
EXPLAINING THE
PRINCIPLES OF THAT USEFUL SCIENCE;
AND DESCRIBING
THE INSTRUMENTS,
CONTRIVED EITHER TO ILLUSTRATE THE THEORY, OR REN
THE PRACTICE ENTERTAINING.
ILLUSTRATED WITH SIX PLATES.
TO WHICH IS ADDED,
A LETTER TO THE AUTHOR, FROM MR. JOHN BI
SURGEON, ON THE SUBJECT OF MEDICAL ELECTRIC
BY THE LATE
GEORGE ADAMS,
MATHEMATICAL INSTRUMENT MAKER TO HIS MAJ
THE FIFTH EDITION,
WITH CORRECTIONS AND ADDITIONS, BY
WILLIAM JONES,
MATHEMATICAL INSTRUMENT MAKER.
LONDON:
PRINTED BY J. DILLON, AND CO.
FOR, AND SOLD BY, W. AND S. JONES, OPTICIA
HOLBORN.
1799.
Price 8s. in Boards.

Plate 2—George Adams' *Essay on Electricity*, shown here in its 5th edition, 1799, emphasizes the use of electrical discharges in medicine and is typical of the thinking in the latter half of the 18th century.

peutic and diagnostic purposes in medical practice.

3. Indeed, perhaps 90% of potentially harmful ionizing radiation exposure above natural background is caused by medical and dental practice. If the estimates that 30 to 40% of this is unnecessary are correct,[23] then the physician's initial decisions can be a major controlling factor in overall radiation exposure.

We could, perhaps, define "radiophilia" in contrast to "radiophobia" as an intense desire to use an excess of radiation in medicine and dentistry. Excess use frequently has little to do with good technical practice, but rather is more a function of good legal practice in assuring adequate records because of the fear of malpractice suits.

INTERACTION OF RADIATION WITH BIOLOGICAL MATTER

If we view the totality of the electromagnetic spectrum (Fig. 1), it stretches in wavelength from about an earth radius for power line frequencies or Seafarer to a tiny fraction of an angstrom (1×10^{-8} cm) for cosmic radiation. We perceive the world in a small band of visible light and receive the benefits and sometimes painful burns of the infrared and

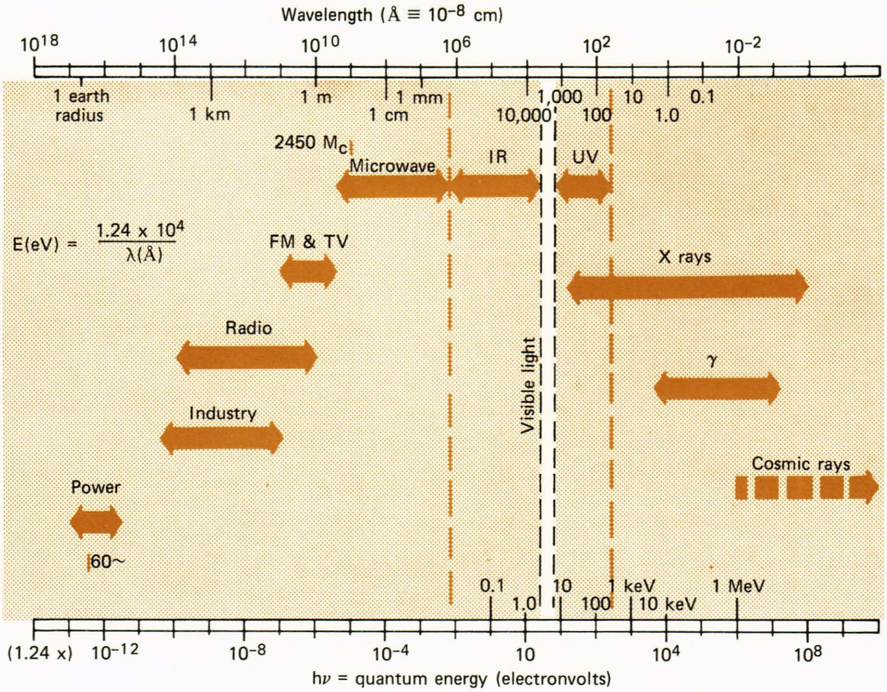


Fig. 1—The electromagnetic spectrum: wavelength and associated quantum energy.

ultraviolet. The technical information that follows is important for understanding the interrelations of the broad variation of physical factors across the electromagnetic spectrum as well as the vast differences in biological impact upon the individual.

To visualize the interaction of radiation with matter, it is useful to think of the wavelengths relative to the interatomic spacings of material, typically 5 to 10 angstroms. Invoking the duality concepts of modern physics, if the wavelength is substantially larger than the interatomic spacings, a classical wave picture of transmission and reflection is appropriate. If, on the other hand, the wavelength is smaller than the interatomic spacings, light may be considered as particulate matter with considerable penetrating power. For example, in the medical use of X rays, wavelengths range generally from a few tenths to a few angstrom units. X-ray generators usually produce a broad spectrum of X rays, with the wavelength of the peak of the energy distribution about twice the shortest wavelength.

The generic use of the term "radiation" presents an intrinsic semantic dichotomy in that radio frequency (essentially the region from 30 hertz to about 300 × 10^9 hertz, one spectral region of great public concern [Seafarer, Pave Paws, microwave relays, radars, broadcast antennas, etc.]) is nonionizing radiation. However, the word "radiation" has been much more familiar to the public in terms of ionizing radiation, thought of as a source of trauma from the early days of radium poisoning, from X-ray-induced malignancies of the early radiographers, and from the long-term horror of Nagasaki and Hiroshima.

The nonelectromagnetic particles, such as the electron or the beta ray, as well as the proton or any other charged particle, produces ionization when penetrating material. The average energy deposited by ionizing radiation is about 32.5 electronvolts (eV) per ion pair. Only about 4 eV are necessary to dissociate a single bond. A minimum energy of about 10 to 25 eV is needed to actually remove an electron from a molecule. A photon of sufficient energy to ionize will be converted to a pattern of electrons moving through the matter (Fig. 2), either by photoelectric effect or by Compton scattering. At high energies, a "pair" (consisting of an electron and a positron) may be produced. The amount of ionization produced along the particle track represents the linear energy transfer (LET) (Fig. 3) and is a function of the charge, mass, and velocity of the particle relative to the speed of light. Alpha particles have a high linear energy transfer. Neutrons, which interact primarily by producing a proton by a "billiard-ball" impact, generally have a high linear energy transfer because most of the protons are relatively slow.[24,25] Neutrons, of course, can also produce an actual transmutation of elements by a nuclear process.

Point sources of radiation, both internal and external, complicate the analysis because of the inverse square of the radius effect. Internal emitters, particularly of long-lived alpha particles, therefore represent an extremely high local density of ionization.

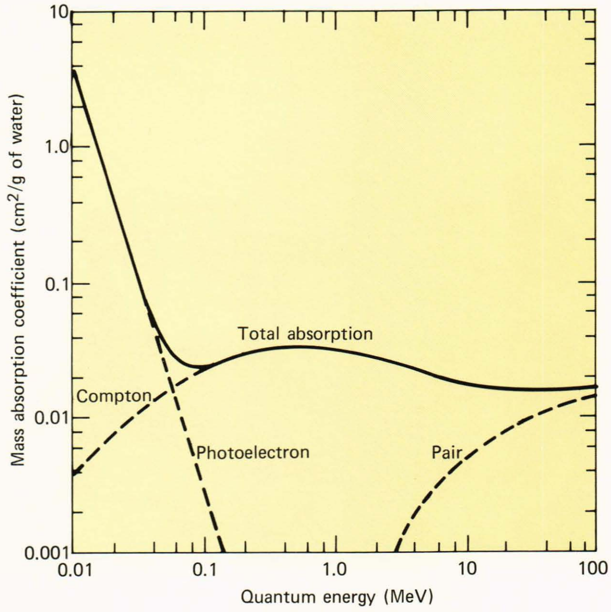


Fig. 2—Absorption of ionizing electromagnetic radiation. (Adapted from Z. M. Bacq and P. Alexander, *Fundamentals of Radiobiology*, 2nd ed. (revised), Pergamon Press, New York, 1961, p. 18.)

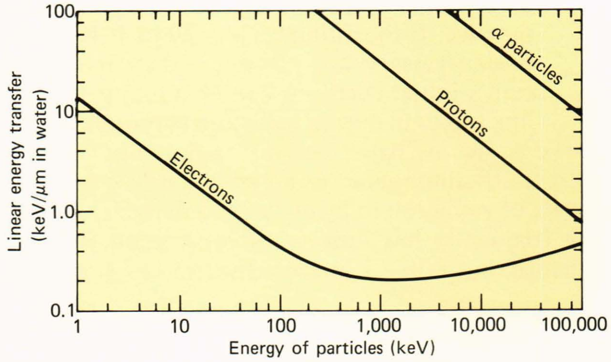


Fig. 3—Linear energy transfer. (Adapted from Z. M. Bacq and P. Alexander, *Fundamentals of Radiobiology*, 2nd ed. (revised), Pergamon Press, New York, 1961, p. 30.)

I will not attempt to discuss the possible hazards that do exist at sufficiently high intensities for ultraviolet and infrared light (particularly lasers) or ultrasonics. There has been some concern about overexposure in the visible light region, such as in the use of "blue light" for the treatment of various skin conditions.

The qualitative definitions of ionizing versus nonionizing radiation depend on the quantum energy $h\nu$ (Planck's constant × frequency) of the associated photon. Ultraviolet light at 2500 angstroms is equivalent to a quantum energy of about 5 eV. If the quantum energy is enough to separate an electron from its bound position in an atom to enter a free state, it is properly called ionizing. Radio-frequency radiation has too low a frequency to form quanta of sufficient

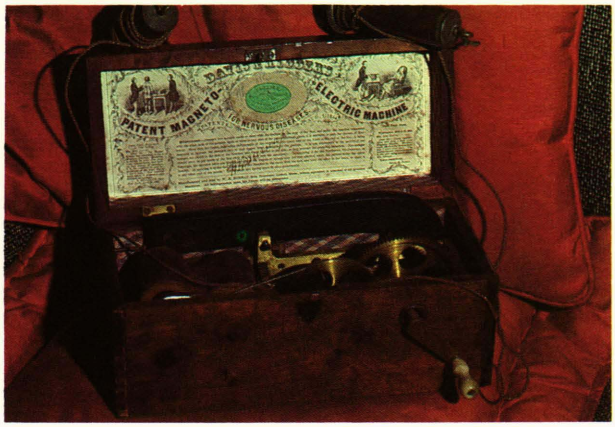


Plate 3—Made and patented (1854) in the United States, electromagnetic induction of a stimulus for treatment of "nervous disease" was provided by rotating a coil between the poles of a horseshoe magnet.

energy to produce ionization and, at first glance, contains inadequate quantum energy to affect any significant electronic states in a single molecule other than perhaps absorption in rotational levels of very large molecules.

For radiant energy in both the nonionizing and ionizing regions, our inability to fully understand or accurately predict observed effects rests upon the lack of a detailed theory of the total chain of the energy deposition mechanisms. As a vast oversimplification, we might say that for nonionizing radiation, we are comfortable in our understanding only with the end product of the energy partition. Many of the effects that we see can be explained by the thermalization (heat as the end product) of this energy. For ionizing radiation, although the microscopic processes have been much more intensively studied than for nonionizing radiation, we are completely comfortable only with the initial energy deposition process. The path is still a long and difficult one for scientists in both fields.

There is not enough space here to summarize thoroughly the various well-established and not-so-well-established concepts involved in the deposition of ionizing radiation. However, there are a few points that can be made:

1. The initial radiation interaction can be either direct or indirect.
2. Direct action involves the ejection or excitation of a molecular electron because of the passage of the ionizing particle.
3. Indirect action involves the formation of free radicals, most generally in the water of the biological system, and their subsequent interaction with the biological molecule.

The target theory[24,25] presents a simplistic, but nevertheless convenient, model to discuss interaction. The first problem, of course, is "What is the target?" The thrust of most research in the last decade, particularly for low-level, long-term effects, has been based on the assumption that the primary targets resulting in cell mutation that produces genetic or long-term somatic complications are the DNA molecules composing the chromosomes. A number of investigators have expressed increasing concern over limiting the study to the DNA.[26] Our knowledge of DNA structure is rapidly expanding, with many biological phenomena attributable to the perturbation of this structure. This, in turn, has tended to emphasize, in investigations of cellular properties, that the individual cell is in itself a very complex structure. Perhaps the area we know least about is the interactions of the various parts of this structure with each other. Thus, when we talk of the target in the cell, it may be equally important to consider, for example, the mitochondria, the cell membrane, or the nuclear membrane, all of which have their own highly complex structures subject to complex and probably cooperative quantum mechanical interactions[27] when excited by the passage of a nuclear particle or, for that matter, by an oscillating electric field.

Most simply, in the target theory we can consider

1. A single "hit" producing an effect;
2. A "multihit" being required to produce an effect; and
3. A multitarget interaction requiring more than one target to produce an effect rather than disturbance of a single target.

Presumably, if all the targets in a biological ensemble under irradiation were identical, then a precisely measured dose/response curve (Fig. 4 is an example) with adequate statistics should be able to unwind the exact modalities of the hit/target model. Unfortunately, however, biologic organisms are not identical, and the curve may be a measure of this variability as much as it is an indicator of the applicable model.

Dose, the total amount of radiant energy absorbed, must always be distinguished as a parameter

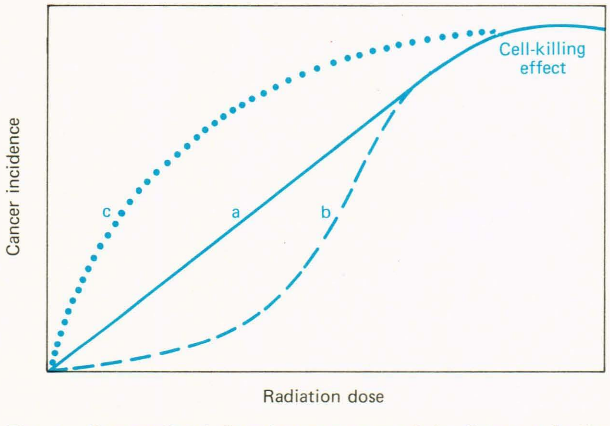


Fig. 4—Generalized dose/response models. Curve a is the nonthreshold linear extrapolation; curve b is the model representing reduction in effects at low dose or low dose rate; curve c is the model representing a possible increase in proliferation of mutated cells caused by reduction in cell-killing effect at low dose. (From "Report of the Interagency Task Force on the Health Effects of Ionizing Radiation," U.S. Dept. of Health, Education, and Welfare, Washington, DC, June 1979.)

separate from dose rate, the amount of energy absorbed per unit of time. We should also define radiation biological equivalent (RBE)[24] as the ratio of the amount of standard gamma radiation needed to give the same effect as a unit quantity of any other type of radiation. Thus, something that is biologically more potent will have a high radiation biological equivalent.

For ionizing radiation, it is becoming more and more apparent that the existence of a finite dose threshold above zero for inception of cell damage is highly improbable. In contrast to this, for nonionizing radiation, it is not clear whether low levels can, in fact, produce irreversible effects. The evidence to date is quite in the negative, although there is increasing evidence of reversible effects at surprisingly low levels.

A majority of radiation biologists believe that the nonthreshold linear extrapolation (Fig. 4, curve a) is generally conservative at low levels. This is particularly so for the accumulation of very low continuous or highly fractionated exposure (total exposure is accumulated from separate small exposures) compared to single exposures[28] because of the possible repair mechanisms within the cell. However, there is a school that believes that the linear extrapolation, particularly for low linear energy transfer, can severely underestimate the effects because of cell death phenomena. Their hypothesis is that low rates may give greater residual effects for unit dose because less cell killing occurs. The most recent National Academy of Sciences report [29] suggests a "linear quadratic" model for low linear energy transfer radiation as a best fit to available data.

We are only beginning to understand something about the mechanisms of cell repair. The dose rate for background radiation is 8 to 9 orders of magnitude less than the dose rates for most irradiated human populations who have been the basis for human extrapolation; the natural background ionizing events occur at much less than one per day in each mammalian cell nucleus, whereas at the high dose rates they may be occurring at the rate of about 2600 per second.[30] Thus, repair at the molecular level may be heavily influenced by this dose rate; one would expect that at the very low levels the probability of repair is much higher. However, any repair process can also result in distortion of the cell's characteristics. On the other hand, because the high dose rate is more likely to kill the cell, perpetuation of any distortion should be reduced. The only mechanisms of induction of radiation effects known with any precision are those for cataracts and impairment of fertility.

Few fields have required as continuous an interaction between the biological and physical scientist throughout the experimental process as has research on the effects of radio frequencies on living organisms. The incident field must be defined in detail — its amplitude, phase and frequency components, relative vector relations (near or far field), direction of incidence, polarization, and what standing waves occur in experimental devices or between one or more organisms under irradiation. For any given frequency, a biological organism must be interpreted in terms of the complex dielectric impedances that differ widely for tissues such as bone, fat, muscle, and brain. The depth of penetration into tissue varies widely with the water content and density of the tissue and the frequency of the radiation[31] (Table 1). Interference phenomena result within the body from reflections and refractions due to the differently shaped organs whose dimensions are frequently comparable to the wavelength in use. Finally, the heat-dissipation mechanisms internal to the animal and from the animal to the outside world must be accounted for.

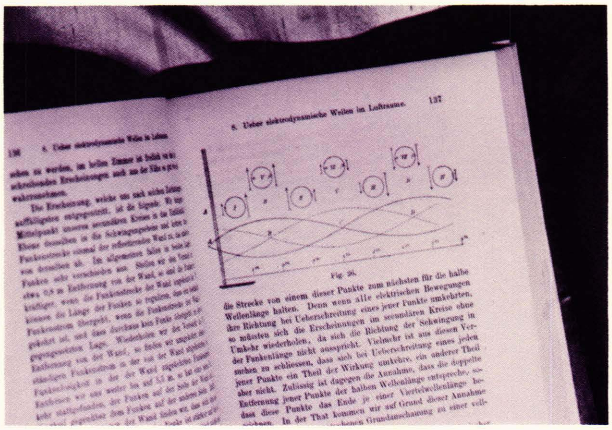


Plate 4—Hertz's 1892 compendium, *Untersuchungen über die Ausbreitung der elektrischen Kraft*,[14] compiled descriptions of his experimental generation of meter-wavelength radiation.

Even for skilled engineers, accurate measurements of external incident fields may be difficult. The problem of accurate dosimetry at specific locations within the organism (without perturbation of measurement by the probe) has evoked considerable ingenuity and is an active and difficult field of research. In addition, extrapolation to man of any measurement performed on a small laboratory animal such as a rat or mouse is fraught with difficulties and possible misinterpretations.

The real detail and sophistication of the energy absorption process becomes apparent when we consider the problem of describing the electromagnetic field within a complex biological body whose characteristic dimensions may be of the order of magnitude of the wavelength of the incident radiation. The various approximate boundary-condition solutions for tissues of finite thickness with very different complex dielectric constants and spheroidal, cylindrical, or ovoid body cavities result in widely varying calculated peak values of deposition of energy. A simple one-dimensional calculation for a single interface is illustrated in Fig. 5. In particular, the Soviets have long discussed (and we have become much more sen-

Table 1

ELECTROMAGNETIC WAVE PROPAGATION IN TISSUES*

Tissues of high water content (muscle and skin)				*Tissues of low water content (fat and bone)*			
Frequency (MHz)	*Wavelength in Air (cm)*	*Wavelength in Tissue (cm)*	*Depth of Penetration (cm)*	*Frequency (MHz)*	*Wavelength in Air (cm)*	*Wavelength in Tissue (cm)*	*Depth of Penetration (cm)*
100	300	27	6.66	100	300	106	60.4
300	100	11.0	3.89	300	100	41	31.1
915	32.8	4.46	3.04	915	32.8	13.7	17.7
2,450	12.2	1.76	1.70	2,450	12.2	5.21	11.2
3,000	10	1.45	1.61	3,000	10	4.25	9.74
10,000	3	0.464	0.343	10,000	3	1.41	3.39

*Adapted from Ref. 31, pp. 694-695. © 1972 IEEE.

sitive to) the concept of "microthermal" effects, where a temperature rise in a particular organ or organ component may be the critical initiator of a specific biological effect rather than the average deposition throughout the organism.

A useful approach to estimating the average specific absorption rate is to approximate the human or animal body by a simpler geometric shape with some degree of equivalence. A prolate spheroidal model[32] shows a resonance characteristic for an "average" man at 70 megahertz with the electric (E) vector parallel to the principal axis (Fig. 6). The dependence with frequency varies with the relative direction of the E vector, the size and conformation (e.g., sitting, standing) of the individual, and the presence of reflecting surfaces. The presentation of average specific absorption rate does not describe the actual distribution of energy as a function of frequency within the model. Spatial variation of absorption characteristics for a real body consisting of head, legs, groin, breasts, etc., are not explicitly contained in this approximation but can be estimated by thermographic measurements of body-shaped models.

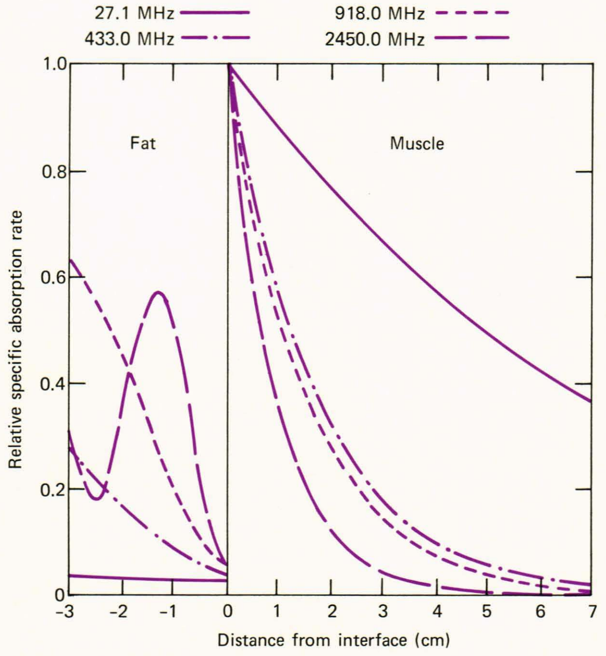


Fig. 5—Relative pattern of specific absorption rate in plane fat and muscle layers exposed to a plane wave at various frequencies. (From Ref. 31, p. 696. © 1972 IEEE.)

This leads us to a rather unfortunate choice of terms: "thermal" and "nonthermal." We generally refer to a thermal effect when some form of energy is absorbed in matter, producing increased random motion in the constituents of that matter. In particular, in the classical theory, radio-frequency radiation impinging on biological material produces, by dint of its electric field, oscillating rotary motion of the normally polar water molecules. The coherent rotation produced by the field becomes random by collision, i.e., "thermalized." A "nonthermal" interaction, on the other hand, is presumed to mean some mode of interaction more specific to the particular energy state or configuration into which the energy is deposited. Unfortunately, the precise description of thermal deposition can be quite sophisticated as discussed, and "nonthermal" as a descriptor has been so misused as to become almost useless in scientific discussion. It is generally true that the ultimate result of any nonionizing radiation absorption is a thermal deposition of energy with, presumably, an increase in local temperature unless there is some sink, such as a blood supply, to remove the deposited energy.

A large number of experiments have reported differences between pulsed and continuous wave (CW) radiation for equivalent average power.[33] The matter, however, is far from resolved, with a significant number of experiments showing no difference. We must be extremely cautious about equilibrating

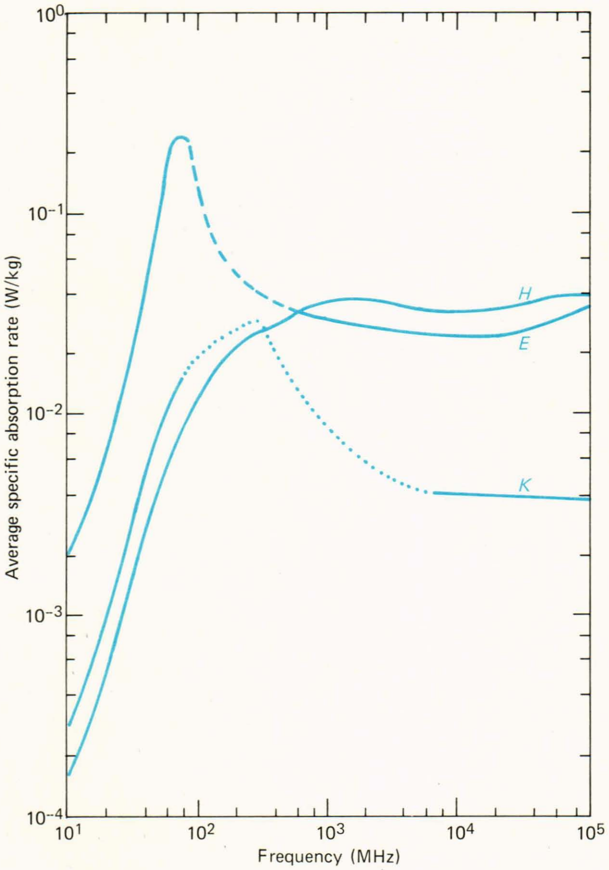
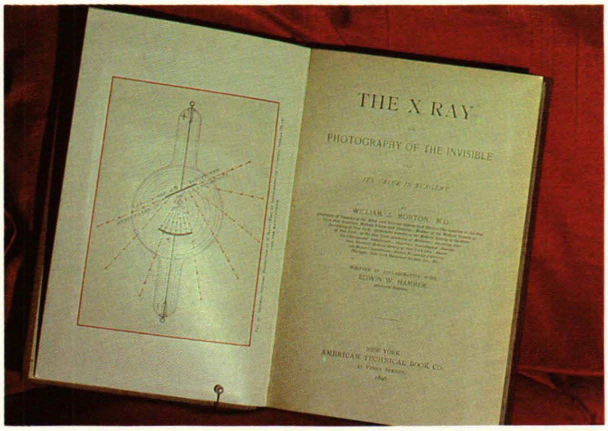


Fig. 6—Average specific absorption rate for a prolate spheroidal model of an average man for an incident power density of 1 milliwatt per square centimeter for three relative polarizations all parallel to the principal axis of the ellipse: electric vector (*E*); magnetic vector (*H*); and direction of propagation (*K*). For a plane wave, the electric and magnetic vectors are mutually perpendicular to each other and to the direction of propagation. (From Ref. 32.)

pulsed and continuous wave exposure of equal average power. Differences between the two may be related to intrinsic nonthermal phenomena as well as to the expanded frequency spectrum (i.e., Fourier expansion) of a pulsed waveform.

Generally, reliance on simplified mathematical models and thermographic observations has become a tacit acceptance of thermal phenomena, e.g., gross energy deposition, as the only effective mechanism. The main issue facing the scientific community is the lack of understanding of the detailed mechanisms for the primary deposition of energy. In particular, effects that may be nonthermal in nature could depend on:

1. Energy deposited (specific absorption rate multiplied by time), determined by frequency, shape, dimension, and dielectric properties;
2. The magnitude of the field *E* (electric) or *H* (magnetic) as a physical factor;
3. Specific frequencies, including modulation frequencies on carriers; and


THE X RAY

PHOTOGRAPHY OF THE INVISIBLE

WILLIAM J. MORTON, M.D.

EDWIN W. HAMMER

NEW YORK
AMERICAN TECHNICAL BOOK CO.

Plate 5—To the present day, no new technology has been more rapidly applied than X rays to medical practice. Morton's book,[16] along with others in many countries of the world, followed Röntgen's initial disclosure by just months.

4. Quantum characteristics of complex biomolecules, including possible cooperative modes of a specific assembly of molecules.

Recent developments in the biophysics and biochemistry of the cell indicate that our knowledge of single-molecule quantum transitions, particularly vibrational or rotational, is far from complete. For example, extremely large and complex molecules such as DNA afford the possibility of a number of oscillatory modes[34] that may have transition energies in the radio-frequency region. Most significant, however, is that cell function is being related in increasing detail to the function of its external and internal membranes. The cell membrane is an extremely complex structure consisting of various species of phospholipids and cholesterol in a double layer, with complex proteins inserted into and through the layer, supplying binding sites for monovalent and divalent cations.[35] Cooperative phenomena involving this complex, highly ordered structure are predicted theoretically to afford the possibility of a number of quantized transitions. The experiments of Adey and his colleagues,[36] confirmed now in other laboratories, have demonstrated phenomena in brain tissue that could well be related to specific cooperative phenomena occurring in the cell membrane.

Thus, there is a significant possibility that interaction in membranes can occur that transcends the impact on the organism of simply the amount of heat added by eventual thermalization of the absorbed energy. Any change in membrane structure encompassed by specific absorption of particular energies and consequent relaxation could conceivably result in changes in cell permeability, for example, with resultant biochemical triggering of vastly greater amounts of chemical energy change, as well as impacting on the informational relationships of the cell.

The situation is considerably more complex for nonionizing radiation, at least for the question of initial deposition of energy, than for ionizing radiation. Given a specific nuclear particle (be it gamma ray, neutron, electron, proton, etc.), we can make a reasonable prediction for the principal initial mode of deposition, the total amount of ionization produced as a function of that particle's charge, mass, and initial energy, and the density of the matter it traverses. However, the task of the ionizing radiation researchers in determining the sequence of biological events after the initial deposition of energy is enormous. Much of the sequence is unknown or controversial, as has been demonstrated by the continuing controversy over permissible exposure to low-level ionizing radiation.

BIOLOGICAL EFFECTS OF RADIATION

For ionizing radiation, three classes of stochastic effects may be identified:

1. Mutagenic: changes are observed in the offspring over several generations;
2. Teratogenic: the embryo or fetus is disturbed, resulting in abnormal development; and
3. Carcinogenic: changes are observed in the individual exposed.

In the somatic cell, reproduction of a damaged cell in some cases can lead to developmental anomalies or neoplasms unless counteracted by the body's immunological mechanisms (Fig. 7). In the case of damage to genetic material, mutations with a high probability of being deleterious may result.

Ionizing radiation dose is usually stated in rads, equivalent to depositing 100 ergs per gram of energy, or in roentgen equivalent, medical units (rem), the dose in rads being multiplied by the radiation biological equivalent previously defined to obtain the dose in rems. The reader is cautioned that the descriptors "high" or "low" tend to represent a subjective view of the particular case.

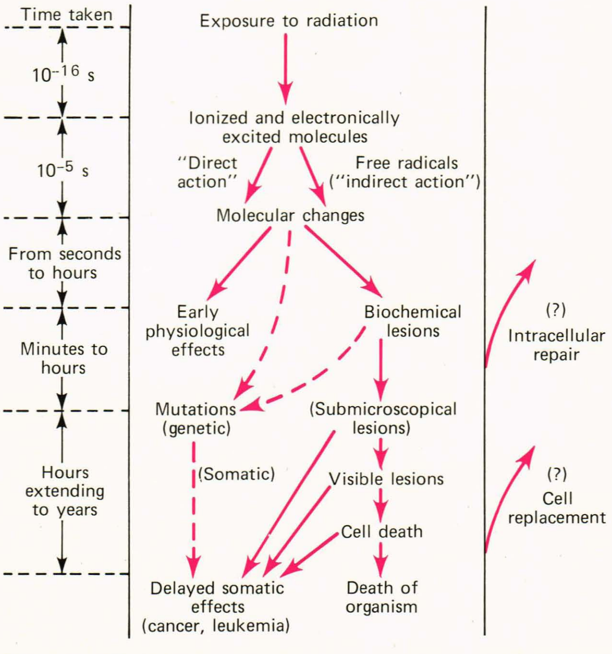


Fig. 7—Simplified diagram of possible biological processes initiated by the absorption of ionizing radiation. (Adapted from Z. M. Bacq and P. Alexander, *Fundamentals of Radiobiology*, 2nd Ed. (revised), Pergamon Press, New York, 1961, facing p. 1.)

The natural background ionizing radiation[37] (approximately 0.1 rem, or 100 millirems per year) is estimated to produce about 1% of naturally occurring genetic defects. The early (1956) Biological Effects of Atomic Radiation (BEAR) report of the National Academy of Sciences, on genetic mutations, estimated the doubling dose (the amount of radiation required to double the number of mutations in a single generation relative to those occurring spontaneously) at probably 30 to 80 rads, with 40 rads as the best guess, or 10 rads per generation for the 30-year to reproduction period.[30] The lowest possible value for the doubling dose is about 3 rems, i.e., 30 years multiplied by 0.1 rem from natural sources. This would imply that all spontaneous mutations are caused by natural irradiations, which is a highly improbable estimate. The 1972 Biological Effects of Ionizing Radiation (BEIR) report[30] estimates that 20 to 200 rems is an appropriate range for the doubling dose, which is slightly higher than the 5 to 150 rads (probably 30 to 80 rads) given in the BEAR report. This was based on mouse data, human data from the Japanese survivors, and *Drosophila* data. The 1980 BEIR[29] estimate is "not notably different," with a doubling dose of 50 to 250 rems. If we examine genetically related disease and anomalies that constitute a contribution to "ill health" assuming a 20-rem doubling rate, an exposure of 5 rems per generation would increase the amount of ill health, genetically related, by 5% of the present value.[30] With 200 rems as a doubling dose, this would be 0.5%.

Insufficient time has gone by for an accurate assessment of recessive genetic mutations produced by radiation. It might be noted, however, that in mouse experiments followed through many generations, descendents of ancestors who were subjected to very heavy radiation showed no impairment of fertility or virility generations later.

Generally, several hundred rads are necessary *in utero* to produce conditions such as microcephaly, mental retardation, growth impairment, or visual defects. Exposure of newborn or very young animals to such heavy radiation has apparently resulted in psychoses, neuroses, and reduction in growth parameters, as seen in the A-bomb survivors. Sublethal doses in laboratory experiments on mammals indicate that 100 to 400 rads give developmental abnormalities. About 10 rads in fetal and neonatal cases have some morphological, but not functional, changes.

Carcinogenesis is generally assumed to be a multievent process. Abnormal cell proliferation — initially caused by radiation damage, a virus, or chemical action — is subject to pre-existing or parallel changes in the immunological suppression capability of the body or to an increase in endocrine stimulation of growth. An increasing number of scientists today believe that the inception of abnormal growth processes in a single cell occurs as part of the normal life process, perhaps caused by natural background radiation, by chemicals absorbed by the body, or even by an intrinsic flaw in the coding of a particular DNA sequence. The immunological response of the body, which prevents further development of an abnormal cell, is also part of the normal balance process. What we have to consider, then, is the rate of inception of abnormality and the potency of the body's complex immunological reactions. Either an increase in the rate of formation of abnormalities or a decrease in the immunological response can contribute to the induction of carcinogenesis. A double-path model of carcinogenesis such as this is compatible with various hypotheses of synergistic action between ionizing radiation, various chemical irritants, and perhaps even nonionizing radiation.

The questions that have to be asked about the significance of occurrence under ionizing irradiation of various types of cancers concern the dose, the dose rate, the linear energy transfer, the age of the organism, the specific tissues involved, pre-existing conditions, and past exposure factors.

Both the BEIR[30] and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)[38] reports conclude that, in all probability, there are fewer mutagenic effects at low dose rates and that somatic problems, particularly neoplasms, are probably overestimated by the linear nonthreshold hypothesis (Table 2), particularly for low dose rate and low linear energy transfer. The radiation biological equivalent varies widely with the linear energy transfer; it may be as high as 10. The effectiveness of high linear energy transfer radiation appears to decrease little, if at all, with dose rate. However, low dose rates for low linear energy transfer have been estimated to result in as much as a fivefold reduction in leukemia induction when compared with a single large dose. In general, there is considerable evidence that low linear energy transfer radiation has substantially reduced effects at low dose rates. This view is challenged by some who believe that less cell killing and the consequent greater probability of propagating an abnormality could occur at low rates.[23]

Table 2

SUMMARY OF ESTIMATES OF WHOLE-BODY IONIZING RADIATION DOSE RATES IN THE UNITED STATES (1970)*

Source	*Average Dose Rate†* *(mrem/yr)*	*Annual Person-Rems* *(in millions)*
Environmental		
Natural	102	20.91
Global fallout	4	0.82
Nuclear power	0.003	0.0007
Subtotal	106	21.73
Medical		
Diagnostic	72‡	14.8
Radiopharmaceuticals	1	0.2
Subtotal	73	15.0
Occupational	0.8	0.16
Miscellaneous	2	0.5
Total	182	37.4

*From Ref. 30.

†Note: The numbers shown are average values only. For given segments of the population, dose rates considerably greater than these may be experienced.

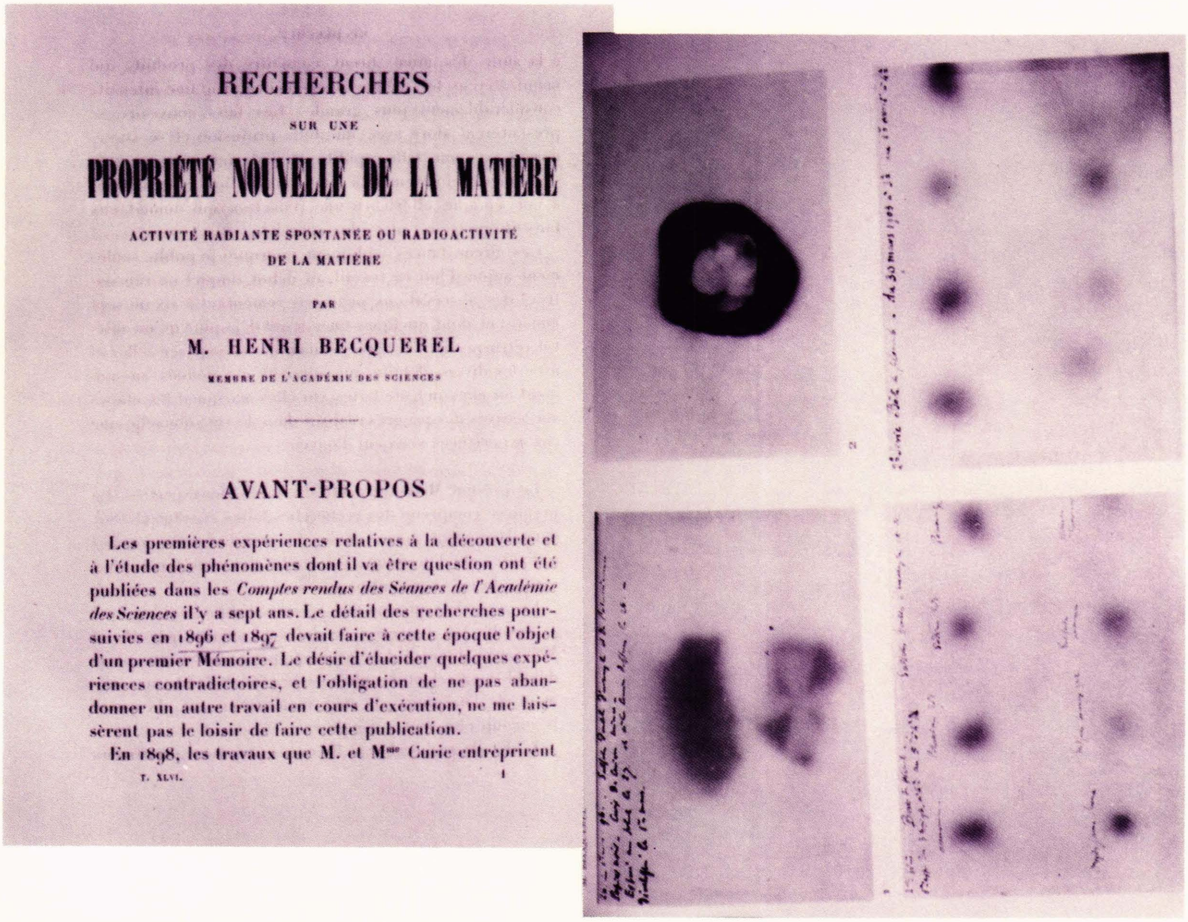
‡Based on the abdominal dose.

For irradiation-induced cancers in controlled experiments, there is generally an increase in induction and a decrease in latent period with increasing dose. As the dose is increased above a certain point, the probability of cancer induction tends to decrease. This is caused by cell killing, tissue destruction, and reduction of the life span by causes other than cancer.

As early as 1903, observations were made on the difference in sensitivities of various types of mammalian cells to radiation and the effects of radiation on various plant and animal forms, particularly microscopic biota. Typically, bone marrow cells divide rapidly, undergo many cell divisions, and are relatively primitive. They are extremely radiosensitive, as are the cells lining the stomach and intestinal tract. Neural tissue, however, is surprisingly radiation resistant. Initially, oncologists believed that leukemia was the neoplasm most frequently induced by radiation. About 1962, thyroid cancer was added to the list. Only in the past decade has female breast tissue been shown to be very radiosensitive; it is now believed, perhaps, to be the most sensitive. Upton estimates[28] that the order of frequency of occurrence of the site of cancer resulting from artificial irradiation (the data are mostly from high doses and high dose rates) is: the female breast, the thyroid, the blood-forming organs (producing leukemia and lymphoma), the lung, the gastrointestinal tract, and the skeleton.

The extrapolation to man of data from small laboratory animals would appear to be somewhat more straightforward for ionizing radiation than when the geometric distribution problems of nonionizing radiation are involved. However, it is difficult to extrapolate animal carcinogenesis to man for a number of reasons:[38]

1. Some laboratory animals are far more sensitive than man.
2. Any mammalian tissue, with the possible exception of neuronal tissue, will produce neoplasms if subjected to adequate radiation.



RECHERCHES

SUR UNE

PROPRIÉTÉ NOUVELLE DE LA MATIÈRE

ACTIVITÉ RADIANTE SPONTANÉE OU RADIOACTIVITÉ
DE LA MATIÈRE

PAR

M. HENRI BECQUEREL

MEMBRE DE L'ACADÉMIE DES SCIENCES

AVANT-PROPOS

Les premières expériences relatives à la découverte et à l'étude des phénomènes dont il va être question ont été publiées dans les *Comptes rendus des Séances de l'Académie des Sciences* il'y a sept ans. Le détail des recherches poursuivies en 1896 et 1897 devait faire à cette époque l'objet d'un premier Mémoire. Le désir d'élucider quelques expériences contradictoires, et l'obligation de ne pas abandonner un autre travail en cours d'exécution, ne me laissèrent pas le loisir de faire cette publication.

En 1898, les travaux que M. et M^me Curie entreprirent

T. XLVI. 1

Plate 6—Becquerel first reported observations of the darkening of a covered photographic plate by emanations from some natural substances in 1896. His 1904 volume[17] is the classic description of his experiments.

3. The incidence of carcinogenesis in some susceptible tissues seems linear with dose, but that of more resistant ones apparently is not.
4. The radiation biological equivalent for high linear energy transfer radiation may be dose sensitive.
5. Fractionation of dose or low continuous radiation to produce a given total dose is less effective than a single large dose.
6. Resistance is higher in adults than in juveniles.
7. There appears to be considerable genetic control even in the same species.

The bulk of human data on radiation-induced neoplasms comes from two sources: the use of radiation in medicine and the Japanese A-bomb survivors. The earliest observations were probably the relatively prompt radiation-induced malignancies among early radiologists. Follow-up studies of the early radiologists have shown longer term cancer excess as well.

Some well-known studies showing long-term cancer excess are in groups of individuals irradiated for the following medical reasons:

1. X-ray treatment of the spine for ankylosing spondylitis;
2. X-ray treatment for benign pelvic conditions;
3. Treatment for acute postpartum mastitis;
4. Irradiation of children for tinea capitis;
5. Treatment for thymic enlargement and similar conditions; and
6. *In utero* irradiation, generally for pelvimitry, resulting in childhood cancer.

Mammography has been found to have little benefit and relatively high risk for women less than 50 years old. The current policy of the National Cancer Institute is to discourage mammography for women below the age of 50 except in cases of particular concern. The typical dose was 1 to 2 rads, but this has been reduced to 0.3 to 0.8 rad (dependent on the size and firmness of the breast).

Early observation of the Japanese bomb survivors indicated that, after a few years, leukemia was clearly coupled to radiation exposure.[30,38] During the past decade, it has also been clear that a number of solid cancers are dose related. Typically, the A-bomb survivors received from 0 to approximately 300 rads, with an average of about 100 rads. With regard to somatic effects, excess mortality of the Japanese from all forms of cancer from 1950 to 1970 is about 50 to 78 deaths per million exposed persons per rem. (For the case of the spondylitics, excess mortality is apparently 92 to 165 deaths per million per rem for the first 27 years after irradiation.) Extrapolation of data from A-bomb survivors is complicated by the fast neutrons at Hiroshima (high linear energy transfer) and the burden of high linear energy transfer ingested alpha-emitter radionuclides. The potential biological effects from these two nuclear events could be quite different. The weapon used at Nagasaki produced almost no external neutron flux; the flux was primarily gamma. The weapon at Hiroshima, on the other hand, produced a substantial neutron flux as well as a gamma flux. (It has been claimed that some recent calculations refute the differences in spectra.)

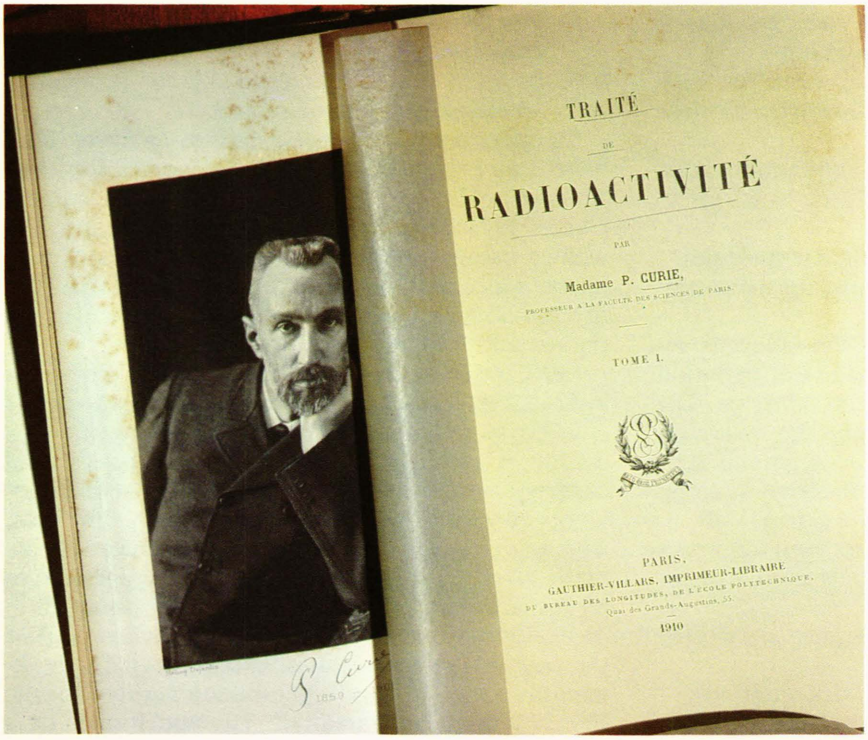
Unfortunately, the nuclear weapons program has provided a number of other sample populations: Marshall Islanders; populations in parts of Utah and Nevada; and the military cohorts involved in the formal weapon testing programs, the best known of which is probably Smoky. The final statistics and interpretation of analyses of these populations are still not available. However, there appears to be evidence that a cancer excess has been noted in some.

Discussion and controversy are still going on about the analysis of the Tri-State study (1959 – 62) on the production of childhood leukemia by diagnostic X-ray exposure of the adults.[3] This double-blind study with random controls considered some 2000 patients with leukemia. Bross claims,[39] based on his analysis, that the doubling dose for leukemia is about 3 to 5 rads. Typical diagnostic dosages were 0.1 to 10 rads.

A continuing study has been prompted by the claim that excess cancer has been observed among nuclear shipyard workers.[40] Controversy and debate still continue over the statistical basis of Mancuso's study[41] of the Hanford nuclear plant workers, which indicates an excess of certain types of cancer over a long period. The integrated dose range for the individuals in Mancuso's Hanford studies is 25 to 30 rads. The possibility of ingested internal emitters and the presence of carcinogens of a nonradiative nature apparently were not considered explicitly.

The definitive "bottom line" on the induction of human neoplasms by low-level radiation clearly has not been written yet. Here are some recent estimates:[42]

1. The original genetic basis of 5 rems over an average 30-year period to reproduction yields the general population standard of 0.17 rem per year. The 1972 BEIR report[30] estimates that this exposure would produce about 3000 to 15,000 excess cancer deaths annually for a U.S. population, with 6000 being the most probable number. This corresponds to a change of 2% in the spontaneous cancer rate or about 0.3% in the death rate from all causes.
2. About 163,800 cancer deaths may be expected over the lifetimes of a group of 1 million people. The 1980 BEIR report[29] estimates a range of 77 to 226 excess fatal cancers per million people per rad for a single 10-rad whole-body dose. For a continuous lifetime dose of 1 rad/year of low linear energy transfer radiation, 67 to 169 excess fatal cancers per million people will occur. (Calculations were performed for the conditions stated, i.e., a single 10-rad dose and continuous 1 rad per year. Values per rad do not necessarily imply that linear extrapolation is actually valid.)
3. The estimate in the 1977 UNSCEAR report[38] is



TRAITÉ

DE

RADIOACTIVITÉ

PAR

Madame P. CURIE,

PROFESSEUR A LA FACULTÉ DES SCIENCES DE PARIS.

TOME I.

PARIS,

GAUTHIER-VILLARS, IMPRIMEUR-LIBRAIRE

DU BUREAU DES LONGITUDES, DE L'ÉCOLE POLYTECHNIQUE,

Quai des Grands-Augustins, 55.

1910

Plate 7—Madame Curie's *Traitè de Radioactivitè*,[18] dedicated to her husband and co-worker Pierre Curie, killed in a street accident, provides a detailed account of the discovery of radium and the state of knowledge of radioactivity.

100 fatal cancers per million people per rem of low-dose radiation.

Unlike the history of ionizing radiation, the history of human exposure to nonionizing electromagnetic energy in the radio-frequency domain has shown no carcinogenic effects to date. For ionizing radiation, the difference between an effect and a hazard is difficult to define since any structural damage to the cell's DNA, unless overcome by a repair cycle or immunological response (destroying the damaged cell), is a potential hazard. We are thus dealing with a statistical problem. For nonionizing radiation, within the range of our present knowledge, it is clear that we may have a substantial number of "effects" that are not "hazards." For a simplistic example, the average healthy individual who runs up two flights of stairs will develop a fair number of physiological effects: his blood pressure, pulse, and respiratory rate will increase; he will perspire; his face will flush; and his feet may hurt. If the individual is healthy, the body's homeostatic capabilities will return all these parameters to their normal state within a few minutes. Unless he has some preexisting physical disability, or unless he carries the stair climbing to considerable excess in rate or duration, no damage will result. Similarly, many of the effects of radio-frequency radiation impinging on the body tend to be observable at present only as increased heat load on the body.

Foreign Service Health Status Study

Following the public disclosure by the Department of State of the microwave irradiation of the U.S. Embassy in Moscow during the period from 1953 to 1976, The Johns Hopkins University School of Hygiene and Public Health was asked in June, 1976, to prepare the *Foreign Service Health Status Study — Evaluation of Health Status of Foreign Service and Other Employees from Selected Eastern European Posts.*

Directed by Abraham Lilienfeld, M.D., University Distinguished Service Professor of Epidemiology, and James Tonascia, Ph.D., associate professor of biostatics and epidemiology, the study compared medical records and the results of a health questionnaire for Moscow embassy employees and their dependents against similar data for employees and dependents from eight other U.S. embassies and consulates in Eastern Europe. A total of 4388 employees and 8282 dependents was studied. Based on a review of the medical records and an analysis of the responses to the health questionnaire, the Hopkins researchers, carefully noting the limitations of their study, published their 250-page report in November 1978. They concluded that:

> "...with very few exceptions, an exhaustive comparison of the health status of the State and non-State Department employees who had served in Moscow with those who had served in other Eastern Europe posts during the same period of time revealed no differences in health status as indicated by their mortality experience and a variety of morbidity measures. No convincing evidence was discovered that would directly implicate the exposure to microwave radiation experienced by the employees at the Moscow embassy in the causation of any adverse health effects as of the time of this analysis."

Any comprehensive attempt to summarize a large number of observations made in the laboratory had best be left to other publications.[33,43] However, it may be worthwhile to attempt to categorize broadly the order of magnitude of effects by decades of irradiation intensities:

1. Exposures at greater than 100 mW/cm^2 (milliwatts per square centimeter) can produce definite thermal damage. Extended exposure will certainly cause cataracts and extensive tissue damage.
2. At 10 to 100 mW/cm^2, heat stress effects can be seen and developmental anomalies, both fetal and neonatal, have been observed in various nonhuman species.
3. The region of 1 to 10 mW/cm^2 is of greatest interest and concern for the question of standards at the present time. Developmental anomalies have been reported, however, with relatively poor statistics. Changes in blood characteristics, particularly changes in immunological response, have been observed. Breakdowns of the blood-brain barrier have been reported but have yet to be adequately quantified.
4. Between 100 μW/cm^2 (microwatts per square centimeter) and 1 mW/cm^2 we are at the "scientific meeting" level of argument where, because of poor statistics, it is not certain what effects have really been confirmed. One apparently confirmed quantitative effect of a subtle nature is the variation of the calcium-binding phenomena in brain tissue at specific frequencies.[36]
5. Below 100 μW/cm^2 no significant reports have been made of any hazardous effects. The Kiev group in the Soviet Union has reported various effects in this intensity region, but these reports are not necessarily accepted even by their Soviet colleagues.

One effect that certainly occurs is microwave "hearing" by large pulses. This is probably explainable by thermal impulse and, in any event, does not appear to pose a hazard. Genetic effects that would imply DNA damage have never been substantiated except at the highest levels of exposure where, characteristically, they are typical of any sort of comparable thermal load. Extended exposures of greater than 80 mW/cm^2 appear necessary to produce cataracts. (Some recent experiments, however, at The Johns Hopkins University indicate the possibility of corneal damage at lower levels.) Developmental effects have certainly been seen, but statistics are poor in the critical 1 to 10 mW/cm^2 region. Some behavioral effects appear to be real, such as avoidance reactions and perception rate changes; it is not clear that they have any hazardous significance.

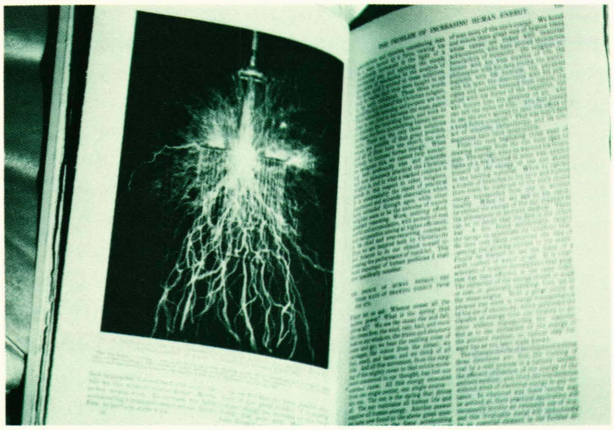


Plate 8—Nikola Tesla's article, "The Problem of Increasing Human Energy," in the June 1900 issue of *Century Magazine*, describes some of his high-powered induction coil generators of very high frequency radiation directed toward worldwide distribution of communications and electrical energy without wires.

For epidemiological studies to have any validity, the exposed and control cohorts must be relatively well defined and well matched. Finding suitable groups of subjects has been difficult. A retrospective study of approximately 20,000 Navy personnel showed no mortality statistics deviating from the general male population. The Johns Hopkins study of State Department personnel stationed in Moscow[44] showed no effects attributable to microwaves; frankly, none would have been expected by the researchers in the field for the exposure levels involved. Perhaps the bulk of epidemiological studies are those reported in Soviet and other Eastern European journals on worker populations in Eastern Europe, leading to the typical "neurasthenic syndrome" conclusion. These studies, which consist primarily of subjective observations of workers in electromagnetic environments, indicate the presence of highly subjective effects such as palpitation, sweating, headache, nervousness, lowering of sexual ability, and lack of appetite. (It is interesting to compare some of the conclusions of these papers with the opening quote from George Beard.) For the most part, these studies have had nonexistent or inadequate controls. One recent study that did give adequate attention to control groups did not show any effects statistically differing from the control group.[45]

A gross energy comparison between nonionizing radiation effects and ionizing radiation effects is interesting. If we assume a prolate spheroidal model of an average man with the *E* vector parallel to the principal axis, resonance occurs at about 70 megahertz. If we accept a working assumption currently under study by the American National Standards Institute that 4 watts per kilogram specific absorption rate is indicative of effects, a tenth of this (0.4 watt per kilogram) is then considered a permissible exposure level. (This corresponds to about 1 milliwatt per square centimeter incident at 70 megahertz.) In a work year of 240 days, this 0.4 watt per kilogram level would correspond to the deposition of 2.76×10^6 joules per kilogram. Remembering that 1 rad is defined as the deposition of 100 ergs per gram, the permissible level of 5 rads per year for occupational exposure is equivalent to 5×10^{-2} joule per kilogram. Thus, this presents some sort of measure of the reversibility of electromagnetic radiation compared to the irreversibility of ionizing radiation. This energy ratio is about 5.6×10^7. Even if we extrapolate to a presumed potential level of damage of perhaps a factor of 100 greater for nonionizing radiation and a factor of 500 greater (10 rads × 240 days) to produce probable radiation effects for ionizing radiation (100 to 200 rems cause prompt radiation effects, and 250 to 450 rems provide lethal dose/50 [50% of the subjects will die] for humans), the ratio still stands at about 10^7. The absorption of 100,000 rads results in only a 0.25°C raise in average body temperature.

STANDARDS FOR PERMISSIBLE EXPOSURE LEVELS

The setting of a standard has to consider the statistics of scientific observation of effects, the average exposure level of the environment, and the benefit to the individual or society derived from the use of the particular radiation relative to the risk. The setting of standards should be a continuous process as our knowledge of the scientific facts increases, as the applications of radiation change in nature and scope, and as the relative benefit to society increases or decreases in significance. Any limitation of exposure to a potential hazard must be based on risk/benefit criteria. For example, the benefits of radio-frequency/microwave radiation are well known; the risks at less than extremely high levels are probably small but still uncertain.

In the absence of a complete and verified scientific data base, one must determine the upper boundary of a possible permissible exposure level by a conservative evaluation of indicators of potential hazards. The lower boundary of the possible permissible exposure level range must be determined by the cost of restriction in domestic, commercial, industrial, and military uses of radio-frequency and nuclear energy. Should this lower boundary thus defined exceed the conservative estimation of possible risk, the conservative estimation must, nevertheless, be the prevailing upper exposure limit. A governing rule is ALARA: as low as reasonably achievable.

The evaluation of risk must consider not only the maximum permissible exposure level but also the actual average level for either the occupational or general population cases. For example, the "average" exposure for workers in the radiation industry is approximately 0.5 rem per year, not 5 rems. The problem of calculating risk/benefit has been severely perturbed by misinterpretations of what "permissible" exposure really means. A ''permissible'' dose is not a dividing line between safety and danger. The usual assumption in setting any permissible level, whether for ionizing or nonionizing radiation, is that the actual average would be far below this. The setting of that standard may involve considerations pertaining to the health and well-being not only of the individual subject to those standards and of his future generations but the population pool as a whole. A gross violation of this, for example, is in the use of ''jumpers'' in the nuclear industry, recently given a fair amount of press coverage. For relatively simple repairs that may have to be made in nuclear reactor plants, individuals are hired to ''burn out'' their radiation allowance by entering areas of high radiation level to perform unskilled tasks. This type of unconscionable distortion of the concept of the permissible level and the possibility that it will occur have to be weighted in the definition of a standard.

For ionizing radiation from 1942 to 1960, there was a fairly firm belief in a threshold concept, that is, repair processes within the cell provided a ''safe level'' below which no damage was done. After 1960 the general opinion was that no threshold existed. In the early period of assessing risk to low-level exposures, the genetic risk was considered the greatest. In the years from 1967 to the present, long-term carcinogenesis has probably been the dominant concern of the standard setters for ionizing radiation.[46]

Ninety percent of exposure to man-made sources arises from professional medical use. However, the Bureau of Radiological Health recently estimated that 30 to 40% of medical and dental X rays are unnecessary. Man-made nonmedical/nonoccupational dosage to the general public as of 1970 was about 6 millirems[30] (Table 3). Dosage from all the nuclear plants planned[30] by approximately 2000 AD is estimated to be about 0.4 millirem. The average natural background is approximately 100 millirems per year.[37] However, a recent paragraph in the *New York Times* indicated that a reading taken inside the Senate office building built of granite (typically mildly radioactive) was about 250 millirems.

The recommendation of the National Council on Radiation Protection and Measurements[48] is that the maximum exposure of a nonoccupational individual be limited to 0.5 rem in any one year and that the per capita dose of the general population be limited to a yearly average of 0.17 rem. We are concerned here not with the question of fallout from a weapon explosion or a catastrophic reactor accident, for example, which could give a relatively uniform dose per capita to a large population, but rather with essentially a point source, such as an operating nuclear power plant (including a nuclear release held within containment). If the exposure is 0.5 rem per year for an individual at the fence line, the average dose, even to relatively small populations in the vicinity of a reactor, would be very much less than 0.17 rem per year. For example, for a million people distributed

Table 3

ESTIMATED CUMULATIVE EXPOSURE OF POPULATION TO ELECTROMAGNETIC RADIATION (54-900 MHz) FOR 15 CITIES IN THE U.S.*

Power Density ($\mu W/cm^2$)	*Cumulative Percent*† *of Population*
0.002	19.5
0.005	49.5
0.01	68.7
0.02	82.4
0.05	91.4
0.1	94.7
0.2	97.0
0.5	98.8
1.0	99.4

*From Ref. 47, p. 31.4.1. © 1979 IEEE.

†For example, 19.5% are exposed to levels less than 0.002 $\mu W/cm^2$, 68.7% are exposed to levels less than 0.01 $\mu W/cm^2$, etc.

Microwave Intensity Within the Moscow Embassy, 1966—1977

The Foreign Service Health Status Study, published in 1978, made the following recommendation:

> ''There is also a need for an authoritative biophysical analysis of the microwave field that has been illuminating the Moscow Embassy.''

As a necessary first step in implementing this recommendation, Applied Physics Laboratory personnel examined State Department records in an attempt to reconstruct the spectral characteristics, exposure intervals, and the field intensities throughout the building. Thousands of documents were examined, varying from memoranda and cables to purchase orders and photographs, in an attempt to determine past measurement procedures and equipment calibrations and to establish a level of credibility for each measurement.

Robert C. Mallalieu of the Applied Physics Laboratory performed the field reconstruction, described in *A Model of the Microwave Intensity Distribution within the U.S. Embassy in Moscow, 1966 to 1977*. Microwave radiation was detectable only in the exterior rooms of the Embassy. The field structure in each room was quite complex due to interference between the direct signal, entering through the windows, and reflections from the walls and contents of the room. Fields of such complexity are exceedingly difficult to quantify in a way that permits estimation of personnel exposure. Power density values of 1 to 3 $\mu W/cm^2$ were typical of most of the exterior rooms. In a few small regions of constructive inteference, levels of 7 to 10 $\mu W/cm^2$ occurred at times over a half-year period within a few rooms near the upper southeast corner of the buildings. Only on rare and brief occasions were higher levels observed. Most of the energy was distributed irregularly between 2 and 4 gigahertz. Typically, the signals were present for one-fourth to one-half of each day.

around the site at a density of 1000 people per square kilometer, the dose would be 0.28 millirem per year. This is 1/1800th rather than a third of the maximum.[46]

Here are some typical occupational exposures per year for radiation users:

1. For about 140,000 personnel in the medical trades, approximately 290 millirems;
2. For industrial radioisotope operators, approximately 850 millirems; and
3. For nuclear power plant operators, approximately 760 millirems.

The current recommended occupational maximum permissible exposure is 5 rems per year or 3 rems per three months.

It would appear that because only a few millirems are the typical exposures above the natural background for most of the population and nothing in sight (with the exception of medical procedures) would appear to be likely to contribute more, the 0.17-rem permissible dose may be unnecessarily high. The Environmental Protection Agency has been proposing a new population standard of 25 millirems per year. Radford and others have suggested a maximum of 500 millirems per year for occupational exposure.

The present standards may be too high or too low for a number of reasons:

1. Low linear energy transfer/low dose rate may have less of a carcinogenic effect than the high dose rates that were the primary basis for estimation.
2. Conversely, some scientists have believed that the carcinogenic effects per unit dose may be higher at low doses because fewer cells susceptible to induction of cancer are killed.
3. A number of other factors, such as length of follow-up, size and variation of population, variation of exposure, and attenuation with depth within the body, have many uncertainties.
4. Extrapolation of laboratory experiments on small animals with relatively high doses typical of laboratory experimentation to the real world requires more knowledge than we now possess of mechanisms and variations in individual susceptibility.

If we compare ionizing and nonionizing radiation from the point of view of determining maximum permissible exposure, the significant biological end points as we understand them today for each type of radiation are totally different. For nonionizing radiation, specific prompt traumatic factors are determinant. Whether you consider this from the point of view of actual tissue damage at well over 100 mW/cm^2 or from the point of view of the excess body heat load, the current presumption is that these effects are identifiable and calculable, with little evidence that more subtle effects at lower levels constitute a hazard. For ionizing radiation, long-term genetic and somatic mutations are determinant.

Clearly there has been no epidemic of "microwave disease." However, the number and power of sources are increasing, as is the public sensitivity to any perturbations in the environment.

Where do we stand today? The fact is that we in the U.S. have no legal definition, no standard, for permissible exposure of either occupational groups or the general population. The "standard" that is usually referred to, 10 mW/cm^2, is, in fact, a set of values recommended by the American National Standards Institute for voluntary application.[49] As a result of the concern about microwave ovens and ionizing radiation devices, Public Law 90-602 was passed in 1968. This, however, is an emission standard—how much unintended radiation is permissible from specified devices, such as the microwave oven. The basic 10 mW/cm^2 "standard" that had initially been derived by applying a safety factor of 10 to observations of trauma at much higher values was coincidentally reinforced by another approach: the maximum heat load the human body can take without an increase in rectal temperature.[50] For a normal temperature–humidity index (THI), this is equivalent to approximately 10 mW/cm^2 of incident S-band radiation.

In contrast, the Soviets have officially adopted a permissible exposure standard of 10 $\mu W/cm^2$ for occupational 40-hour-per-week exposure, with 1 $\mu W/cm^2$ permitted for the general public. Similar values are characteristic of most Eastern European countries. Sweden has adopted a compromise occupational standard of 1 mW/cm^2, and Canada appears about to do so.[51]

Soviet and other Eastern European laboratories have reported observations of physiological and behavioral effects with laboratory animals at exposure levels far below those at which similar effects have been reported by Western authors.[52] In 1964, when the Moscow Embassy problem was exposed to a portion of the scientific community, these differences puzzled and alarmed us, but this is now 15 years and many thousands of research papers[53,54,55] later. In recent years, personal and professional contact has been established between Western and Eastern European scientists,[56] with mutual attendance at conferences and even initiation of a joint program of research between the U.S. and the Soviet Union.

During the course of the last decade's analysis of Soviet literature and the increasing personal interchange, several factors contributing to understanding the reported human and experimental observations and consequent different definitions of permissible exposure have surfaced:

1. Different traditions in physiological research derive from Sechenov[57] and Pavlov[58] on the one hand and the 19th century Western European schools of Bernard[59] and Müller[60] on the other. In the former case, total animal behavior subjectively observed can be considered ade-

quate criteria, while in the latter, measurable physiological change has to be demonstrated.

2. The Soviet Union and the U.S. have fundamental differences in their philosophies of environmental control. In the Soviet concept, any perceptible change in the environment is considered a pollutant; thus, an "effect" can be considered justification for defining excessive environmental perturbation. We normally have accepted the concept of a risk/benefit criterion involving the use of an adequate safety margin below a known threshold of hazard.
3. In both Soviet and American laboratories, considerable difficulties were experienced, particularly some years ago, in establishing accurate field measurements. In some cases, actual Soviet field strengths may have been a factor of 10 or so higher than reported.
4. Soviet scientific publication in the past, and to some extent at the present time, has suffered from inadequate peer review. Thus, a number of articles may have been published without adequate refereeing. More careful review of some papers would have resulted in withdrawal due to observational or statistical misinterpretations or inadequate presentation of protocol and data.

A number of personal contacts have indicated that the Soviet environmental picture may be changing. Their equivalent of our Environmental Protection Agency recently has recommended a temporary exposure standard for the general public of 5 $\mu W/cm^2$. (This is some improvement, at least.) We are also aware that industrial organizations in the Soviet Union, particularly those interested in expanding the use of radio frequency for industrial processes and the consumer-products people interested in manufacturing microwave ovens, are pushing for a reexamination by their Academy of Sciences of the scientific basis for the Soviet standards with an eye toward lessening their rigidity.

To what extent do existing or predictable occupational and population environments constitute potential hazards? The individuals who are most probably exposed to fairly substantial fields in the high frequency near-field region are industrial workers involved with heating, drying, and laminating equipment.[23] They have never been surveyed with proper epidemiological methodology. Other than the environment of industrial high frequency processes, long-term immersion in fields exceeding the 1 $\mu W/cm^2$ region is fairly rare[47] (Table 3). Another occupational group to consider are service technicians working on live broadcasting and relay towers. Military environments in all services can produce exposure levels in the 1 mW/cm^2 region; however, military and service personnel are generally exposed for limited time durations. Application of modified safety procedures can minimize these exposures further, probably without impairing system performance capability. Other regimes, both occupational and public, requiring careful examination are land-mobile systems such as police communications, where the near fields of the transmitting antennas can be closely coupled to the user.

CONCLUDING REMARKS

The U.S. research program on the biological effects of ionizing radiation started during the 1940's in the days of the Manhattan project and has had relatively substantial funding to the present. Since 1950, carcinogenesis caused by radiation has been the concern mainly of the Department of Energy and its predecessors. However, the National Cancer Institute is now considering an increased effort. The Institute currently spends about $5 million per year on the health effects of low-level radiation. If the recommendations of the Interagency Task Force[61] are to be fully implemented, amplification and some changes in emphasis may be necessary.

A critical point that comes out of the overwhelming bulk of scientific evidence to date is that ionizing radiation in any amount may statistically produce some biological damage and that nonionizing radiation in the amount that the general public is exposed to probably cannot. However, the amounts of ionizing radiation that are now present or are likely to be present, except for a major nuclear catastrophe or a gross increase of careless or unnecessary use in therapeutic and diagnostic practice, produce effects that are relatively small statistically compared to the genetic and somatic effects produced spontaneously by natural radiation and other causes.[29,30] The quantitative risk estimates for judicious use of radiation are considerably lower than are the risks of using many other things such as the automobile (which produced about 50,000 deaths per year), combustion of carbonaceous fuels (combustion of coal is estimated to produce about 48,000 deaths per year from pollutants), and the innumerable other chemical intrusions into our environment.[62,63] These are risks we have been willing to accept for many years in order to achieve what is apparently a desired level of convenience in our civilization. Thousands of deaths from steamboiler explosions occurred in the mid-19th century, unquestionably leading to many outcries for a return to normalcy.

A large number of government agencies and private organizations are concerned with the problems of establishing a proper scientific basis for maximum permissible exposures to nonionizing radiation for both the occupational and public sectors. The nucleus of an effective research community exists distributed among a number of different agencies and their contractors. Since 1971, the program has been coordinated by the Office of Telecommunications Policy, now the National Telecommunications and Information Administration,[51] advised by the Electromagnetic Radiation Management Advisory Council.[64] The primary reason why we are not much further along in our scientific understanding has been, to put it simply, lack of adequate funding. Lack of an appropriate scientific base and consequent lack of defensible exposure standards for nonionizing radiation have led to increasingly frequent panic reactions with little substantive reason for concern.

American industry prefers to have as few regulatory standards to meet as possible. However, I have been receiving an increasing number of comments from members of the communities that produce and operate electromagnetic equipment in industry (and in the military) who would find it highly desirable to have a logically derived, properly designated (as to frequency and exposure time), and legally enforceable standard on the books. Industry can then proceed to design and modify equipment according to the standard. The lack of a proper standard can result only in continually increasing confusion. The confusion that would be engendered in interstate commerce by a plethora of local, different, and probably technically improbable standards would far exceed in cost any reasonable amplification and acceleration of the processes of research and rule-making that should occur within the federal government.

The establishment of a clearly defined and legally enforceable standard on a "temporary" basis does not require the final completion of the scientific research that should be done in this field. Careful adjudication of the presently available data viewed against reasonable risk/benefit criteria, coupled with the lack of clinically perceptible injury in most of the occupational groups now at risk, should permit the establishment of a livable standard, provide reasonable assurance of safety, and avoid unreasonable constraints on our use of the precious radio-frequency spectrum.

The process of standard setting for any environmental perturbation is different from determining the details of biological interaction in that it must assess both the potential of hazard and the effect on the community as a whole. There is little that we do — driving an automobile, engaging in sports, performing normal household tasks — that does not involve some level of risk higher than the risk that could be expected from radiation, except under the most extreme and unusual conditions of radiation exposure. In all these areas, the level of legally enforceable protection has to be based on what is most necessary and most desirable in the national interest: defense, energy, communications, and personal well-being. Furthermore, the authority to establish these standards must carry with it the potential of administratively raising or lowering standards, without additional legislative action, as our knowledge of potential effects increases and user requirements change.

Certainly no unnecessary radiation is desirable. If no benefit accrues to the individual, why should he be irradiated? These statements, however, must be evaluated within the complexity of our social and economic structure. We have come to accept risk for benefit to society as a whole. One group may accept somewhat more risk for one environmental factor than the average, while other groups may do the same for other factors, thus benefiting each other.

Unknowledgeable, and occasionally careless, use and control of radiation have done some damage. However, compared with natural causes and other activities of man, relatively little harm has been done either somatically or genetically. This does not mean we can relax our vigilance. We must increase it, but we must do so in a manner consistent with our needs and with a quantitative scientific evaluation of the effects of radiation at the levels that actually occur in man's perturbation of the environment.

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