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Jing-Feng Miao was born in Jiangsu Province, China, on January 10, 1937. He graduated from Nanjing Institute of Technology, Nanjing, China, in 1962.

Currently, he is a faculty member of the Radio Engineering Department, Nanjing Institute of Technology, doing teaching and research work in the field of microwave devices and circuits. From August 1981 to August 1982 he was a Visiting Scholar at the University of Texas at Austin, in the Department of Electrical Engineering. His research interest is mainly in microwave solid-state devices and circuits, and millimeter-wave integrated circuits.

Tatsuo Itoh (S'69–M'69–SM'74–F'82) received the Ph.D. degree in electrical engineering from the University of Illinois, Urbana in 1969.

From September 1966 to April 1976 he was with the Electrical Engineering Department University of Illinois. From April 1976 to August 1977 he was a Senior Research Engineer in the Radio Physics Laboratory, SRI International, Menlo Park, CA. From August 1977 to June 1978 he was an Associate Professor at the University of Kentucky, Lexington, In July 1978 he joined the faculty at the University of Texas at Austin, where he is now a Professor of Electrical Engineering and Director of Microwave Laboratory. During the summer 1979 he was a Guest Researcher at AEG-Telefunken, Ulm, West Germany.

Dr. Itoh is a member of the Institute of Electronics and Communication engineers of Japan, Sigma Si, and Commission B of USNC/URSI. He serves on the Administrative Committee of IEEE Microwave Theory and Techniques Society. He is a Professional Engineer registered in the State of Texas.

Biological Effects and Medical Applications of RF Electromagnetic Fields

OM P. GANDHI, FELLOW, IEEE

(Invited Paper)

***Abstract*—The paper summarizes replicable biobehavioral effects including ocular and auditory effects and the low-level efflux of calcium ions from chick and cat cortex tissues exposed to sinusoidally modulated fields. Highlights of studies of long-term and ultra-long-term low-level exposures on rat behavior and blood and urine biochemistry are also given. The new ANSI C95 recommended safety standard and its rationale are presented, as are some of the present and potential medical applications including hyperthermia for cancer therapy. The paper concludes with identified gaps in knowledge where more research is needed.**

I. Introduction

THERE IS a great deal of concern on the part of the public about the purported biohazards of RF electromagnetic radiation, and also an anticipation among the researchers in this area of beneficial medical applications such as for electromagnetic hyperthermia as an adjunct for cancer therapy, electromagnetic heating for blood and organ thawing and for hypothermia, and also the possibility of the use of this radiation for diagnostic imaging applications. Among the (popular press) reported effects of microwave radiation are: cataract formation, fatigue, sleeplessness, sexual dysfunction, carcinogenic properties, etc. Name a malady and it has been ascribed to microwave radiation. Unfortunately, the adverse publicity given the alleged biohazards of nonionizing radiation has conditioned the public to be suspicious of any and all of the applications of this energy. This has resulted in obstructive and costly litigation and unnecessary delays in new installations in the public domain even of the types that were set up without questions in the past. An example here is the microwave repeater stations, hundreds of which were set

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The author is with the Department of Electrical Engineering, University of Utah, Salt Lake City, UT 84112.

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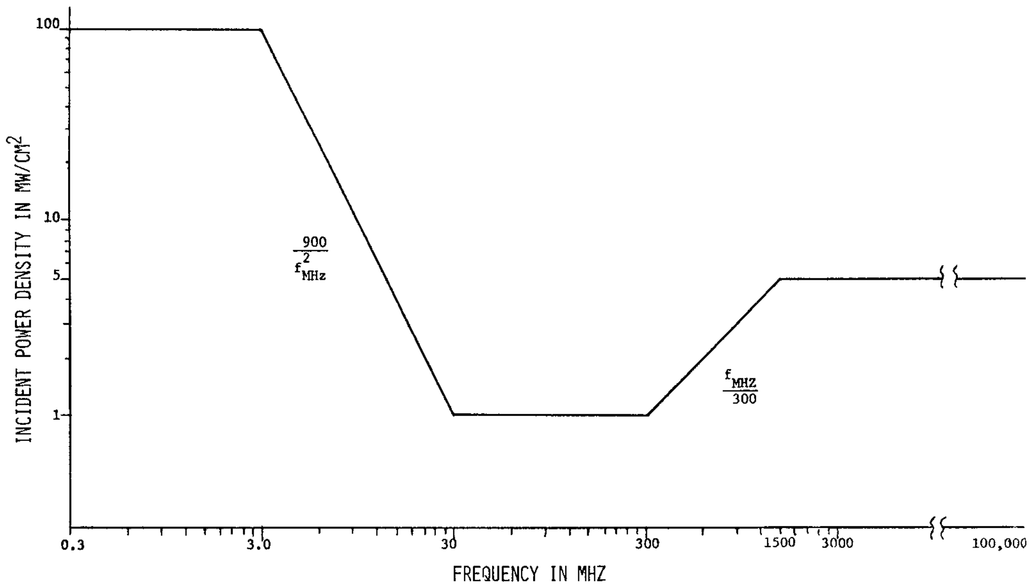

Fig. 1 Radiofrequency protection guide for whole-body exposure of human beings (based on whole-body-average SAR limit of 0.42 W/kg).

up coast to coast for the long-distance telephone system in the forties and fifties.

In this paper we will highlight the current knowledge in the field, including the contributions that engineers have made in dosimetry—the science of quantifying electromagnetic absorption and its distribution for various exposure conditions. This work has influenced the promulgation of a new, lower, frequency-dependent safety guideline in Canada [1], [2], and a recent approval of the same by American National Standards Institute's (ANSI) Committee C95 in the United States [3]. We will also describe the several promising beneficial medical applications which are likely to be clearly delineated in the next five to ten years. The paper will conclude with the identified gaps in the knowledge where more research is needed [4].

II. The New RF Protection Guide

The new radiofrequency protection guide for whole-body exposure of human beings recently accepted by ANSI C95 is illustrated in Fig. 1. A reduced exposure level of 1 mW/cm^2 over the frequency band 30 to 300 MHz is recommended on account of the experimentally observed and theoretically predicted resonance [5]–[7] of whole-body absorption of electromagnetic energy for frequencies where the length of the body is parallel to the E-field vector and is approximately four tenths the free-space wavelength of the incident fields. Under these conditions of maximum absorption, it has been shown that the absorption cross section may be 3 to 4.5 times the physical cross section, rather than the previously assumed quasi-optical cross section of roughly one half the physical cross section, the latter, of course, being true at quasi-optical frequencies an order of magnitude or larger than the resonance frequency. The frequency band 30 to 300 MHz is associated with the whole-body resonance of absorption for the various human sizes from infants to adults, with a recognition that the maximum absorption for feet in conductive contact with ground occurs for roughly one half the free-space resonant frequency or for frequencies such that the length of the body is approximately two tenths the wavelength of the incident fields. The frequency dependences on either side of the resonant region 30 to 300 MHz are selected to account for the frequency dependence of whole-body absorption of biological bodies, these being an absorption cross section reducing as f^2 in the below-resonance region, and as $1/f$ in the supraresonant region with an asymptotic approach to the "optical" cross section which is (1-plane-wave power reflection coefficient) or about one half the physical cross section in the quasi-optical region $f \geqslant 10 f_r$, where f_r is the resonant frequency. The highlights of the advances in dosimetry are given in Section VI. Suffice it to say at this stage that on the basis of present knowledge it is possible to state that for the worst-case exposure conditions ($\boldsymbol{E}$ along the long axis of the body), the whole-body-average (mass-normalized) specific absorption rate (SAR) of electromagnetic deposition shall not exceed 0.4 W/kg for any of the human sizes for the field strengths depicted in Fig. 1. It is recognized that local values of SAR may be an order of magnitude or higher than the whole-body-average SAR at electrical "hot spots". Because of the highly variable nature (with wavelength, polarization, posture of the body vis-à-vis the incident fields, etc.) of these hot spots and the absence of data linking biological effects to specific hot spots, the whole-body average SAR is taken to be a valid predictor of the biological effects. Such measures have indeed previously been used for clinical medicine where mass-normalized whole-body doses of pharmacological agents are administered for therapeutic purposes. In the absence of verified reports of injury to or adverse effects on the health of human beings who have been exposed to RF EM fields, the ANSI guide has been based on the most sensitive measures of biological effects—the behavioral effects on laboratory animals. Unfortunately, there is a paucity of reliable data on chronic exposure. The assumption, therefore, is made that reversible disruption during an acute exposure may mean irreversible injury during the chronic exposure. Since the thresholds of reversible behavioral disruption have been found for whole-body averaged SAR's on the order of 4 to 8 W/kg [8], [9] (in spite of the considerable difference in carrier frequency—600 MHz to 2450 MHz, species—rodents versus primates, and mode of irradiation—cavity, waveguide, and plane wave), the ANSI guide is prescribed to ensure that under the worst-case circumstances (E-vector parallel to the length of the body, grounded and ungrounded conditions), the whole-body averaged SAR shall not exceed 0.4 W/kg for any of the human sizes. This will be discussed at length in Section VI on dosimetry. Similar to the previous ANSI guides, the exposure levels given in Fig. 1 may be exceeded for time durations shorter than six minutes, provided that the time average of the power density for any 0.1 h interval does not exceed the limits that are prescribed. Also, at frequencies between 0.3 and 1000 MHz, the protection guide may be exceeded if the radiofrequency power of the radiating device is 7 W or less.

It is recognized that the assumption of a planewave exposure is simplistic and is not a realistic approximation of most exposures. Significant leakage fields are encountered in close proximity to RF EM sources [10], [11], which may pose a risk to the health of the equipment operators. Fortunately, the SAR's deposited under these circumstances may be considerably smaller than the far fields of numerically equal density [12], [13], particularly, as is often the case, where the physical extents of the fields are fairly narrow compared to a free-space wavelength. Planewave exposures, therefore, give an upper limit of the whole-body-averaged SAR's as compared to partial-body near-field exposures of similar spatially-averaged power densities. Planewave power densities have therefore been used in the formulation of the ANSI guideline.

III. Electromagnetic Fields in the Environment

The integrated median exposure densities (50 to 900 MHz) measured in fifteen metropolitan areas of the United States are shown in Table I [14]. The data were obtained at 486 locations distributed throughout these cities and collectively represent approximately 14000 measurements of VHF (TV and FM radio) and UHF (TV) signal field strengths. A computer algorithm was developed which uses these measurement data to estimate the broadcast exposure at nearly 47000 census enumeration districts in these metropolitan areas. The percent of population exposed to a cumulative power density of less than 1 μW/cm^2 thus estimated is also shown in Table I. Note that on an average no more than 0.5 percent of the population in these areas is exposed to power densities in excess of 1 μW/cm^2, with 95 percent of the population exposed to less than even 0.1 μW/cm^2.

Significantly higher leakage electric and magnetic fields have been measured [10], [11] for several occupational situations, notably those in proximity to RF sealers and diathermy apparatus. Leakage electric fields as high as 200–1000 V/m (far-field equivalent power density on the order of 10–250 mW/cm^2) and magnetic fields on the order of 0.2–2 A/m (far-field equivalent power density of 1.5–150 mW/cm^2) have been routinely measured for these equipments. Fortunately, for most of these spatially localized fields, the whole-body-averaged SAR's are likely to be considerably smaller [12], [13] than those associated with planewaves (of infinite extent) at the corresponding field intensities.

TABLE I
Population Exposure in Fifteen U.S. Cities (50–900 MHz).
(Source: R. A. Tell and E. D. Mantiply [14].)

City	Median Exposure (μW/cm^2)	Percent of Population Exposed $\leq 1\mu$W/cm^2
Boston	0.018	98.50
Atlanta	0.016	99.20
Miami	0.0070	98.20
Philadelphia	0.0070	99.87
New York	0.0022	99.60
Chicago	0.0020	99.60
Washington	0.009	97.20
Las Vegas	0.012	99.10
San Diego	0.010	99.85
Portland	0.020	99.70
Houston	0.011	99.99
Los Angeles	0.0048	99.90
Denver	0.0074	99.85
Seattle	0.0071	99.81
San Francisco	0.0020	97.66
ALL CITIES	0.0048	99.44

IV. Biological Effects[1]

A partial listing of the biological effects of RF EM fields that have been extensively studied is given in the following:

a) Cellular effects—chromosomes—genetic effects;
b) Growth and development effects;
c) The effects on the gonads;
d) Cardiovascular effects;
e) Hematopoietic effects;
f) Effects on immunity.

For a detailed discussion of these studies, the reader is referred to an overview paper by Michaelson [16] and the extensive bibliography given at the end of that paper. In order to establish threshold power densities, most of the experiments have been conducted for acute exposures and have been for short terms (up to three weeks). No hazardous effects have been observed for whole-body-average SAR's less than about 8 W/kg. The data base for chronic long-term exposures is fairly limited.

Some important effects and their experimentally observed thresholds are given in the following.

A. Ocular Effects [17]

In experimental animals such as rabbits and dogs, eye lens opacifications have been observed for locally applied incident power densities in excess of 100 mW/cm^2 but not at lower power densities. It should be mentioned here that whole-body exposures at such high power densities would be lethal; highly intense fields have, therefore, been applied

[1] For some recent overview references, see [15].

only to the region of the eye, causing in many cases a reddening of the skin peripheral to the eye. While the majority of the experimental investigations of microwave cataractogenesis have involved single or multiple acute exposures at power densities of 80–500 mW/cm^2, a study of chronic low-level exposure effects in the CW far-field intensity of 10 ± 3 mW/cm^2 at 2450 MHz for 8 h/day, 5 days a week for periods of 8 to 17 weeks [18] did not reveal any abnormal ocular changes for rabbits for six months of subsequent observations.

B. *Auditory Effects* [19]

Human subjects exposed to sharp pulses of microwave radiation are able to "hear" the occurrence of thumping sound at the pulse repetition frequency [20], [21]. The sound appears to the subject to originate from within or behind the head. The threshold for human hearing is on the order of 16 mJ/kg of pulsed energy absorption. Exposure of solid materials as well as liquids and gases to pulsed microwaves has been shown to result in acoustic or elastic waves and ascribed to radiation pressure or electrostriction [22]–[24]. A commonly accepted theory [25] for microwave hearing is the launching of acoustic waves due to thermoelastic expansion. According to this theory, there is a miniscule ($\sim 10^{-6}$ °C/s), but rapid rise (~ 10 μs) of temperature in the brain as a result of microwave energy absorption, which creates thermoelastic expansion of the brain matter, which then launches an acoustic wave of pressure that is detected by the hair cells in the cochlea via bone conduction. Because of the low average power densities associated with the pulsed microwaves, a great deal of attention has been paid to the hearing phenomenon as being representative of the low-level effects of microwave energy. The concensus at the present time, however, is that the auditory response is just an effect rather than posing a health risk to the individual.

C. *Behavioral Effects*

The most sensitive measures of biological effects have been found to be based on behavior. Thresholds for reversible behavioral disruption (mostly activity decrements) were found to range narrowly between 4 to 8 W/kg in spite of considerable differences in carrier frequency (600 to 2450 MHz), species (rodents to primates), and modes of irradiation (cavity, waveguide, and planewave). This is in spite of the fact that time-averaged power densities associated with these thresholds of disruption have ranged (by calculation or measurement) from 5 to 50 mW/cm^2. The various studies have involved performance of trained tasks [8], [26], [27] in the microwave environment by rats and rhesus and squirrel monkeys. Justesen and King [28] utilized a 2450-MHz (CW) multimodal metallic cavity to investigate conditioned operant behavior in rats. They used a recurrent cycle of exposure, 5 min on and 5 min off, over a 60-min period for whole-body-averaged SAR rates of 3.0, 6.2, and 9.2 W/kg. The animal's performance usually stopped within 60 min, with an energy absorption rate of larger than or equal to 6.2 W/kg. D'Andrea, *et al.* [26] used food-deprived rats trained to perform a lever-pressing task for food reward. For irradiation at 600 MHz, 10 mW/cm^2, CW (SAR of 6 W/kg), the animals were found to stop working within a matter of 45 min, while irradiation at lower power densities of 7.5 and 5 mW/cm^2 did not result in work stoppage within the experimental observation time of 55 min. At the time of work stoppage, nearly all animals engaged in licking behavior, possibly to induce evaporative cooling, which continued after the animal was removed from the radiation chamber and placed in his home cage. No reliable carry-over of behavioral effects were observed from one radiation session to the other.

As aforementioned in Section II, the SAR's associated with behavioral effects have had an impact on selection of the power density levels to ensure that the whole-body-averaged SAR's for any of the human sizes will not exceed 0.4 W/kg for the worst-case exposure conditions at any of the frequencies.

D. *Calcium Efflux*

Enhanced efflux of calcium ions $^{45}Ca^{2+}$ has been observed [29]–[31] from isolated chick and cat cortex tissues exposed to sinusoidally modulated fields. Calcium ions are essential in transductive coupling of a wide range of immunological, endocrinological, and neurobiological events at cell membrane surfaces. The effect has been found to be very sensitive to both modulation frequency (Fig. 2) and power density (Fig. 3), showing "windows" of interaction for modulating frequencies simulating the brain's own natural electrophysiological activity (between 6 and 20 Hz) and of power density (from 0.1 to 1.0 mW/cm^2). Similar effects have been observed essentially regardless of the carrier frequency—ELF fields and carrier frequencies of 147 and 450 MHz have been used. Using carefully replicated biochemical assays, this effect has also been observed by Blackman, *et al.* [32].

Being one of the few reliable effects of low-level electromagnetic fields, this effect is of a great deal of interest. It is therefore recommended that further studies be carried out to determine the *in vivo* biological consequences of these observations. Of particular interest may be the irradiation of the experimental animals at frequencies corresponding to head resonance [33], [34] ($\sim$ 2450 MHz for medium-size rats) where enhanced energy deposition can be obtained in the CNS from relatively weaker fields.

It should be mentioned in comparison that observations of brady cardia in isolated turtle and rat hearts [35], [36] exposed to low levels of microwave radiation (SAR $\sim$ 1.5–2.5 W/kg) were not observed for intact animals. The authors concluded that the compensating mechanisms in intact animals are robust enough to compensate for the effect observed in the isolated hearts.

E. *Drugs-Microwave Synergism*

Synergistic effects between microwave radiation and psychoactive drugs such as chlordiazepoxide and amphetamine have been observed by Thomas *et al.*, [37], [38], but not by other researchers [39], [40]. In all cases,

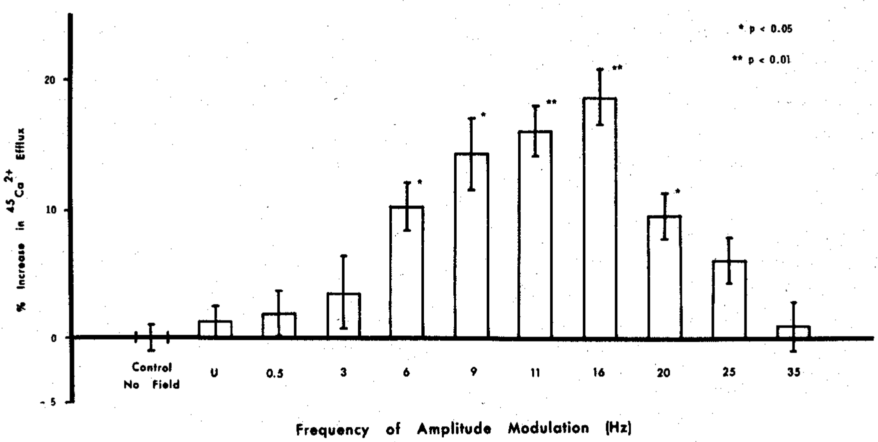

Fig. 2 Effects of 147-MHz VHF fields on $^{45}Ca^{2+}$ efflux from the isolated forebrain of the neonatal chick. The results are given $\pm$SEM. (Source: S. M. Bawin, L. K. Kazcmarck, and W. R. Adey [29].)

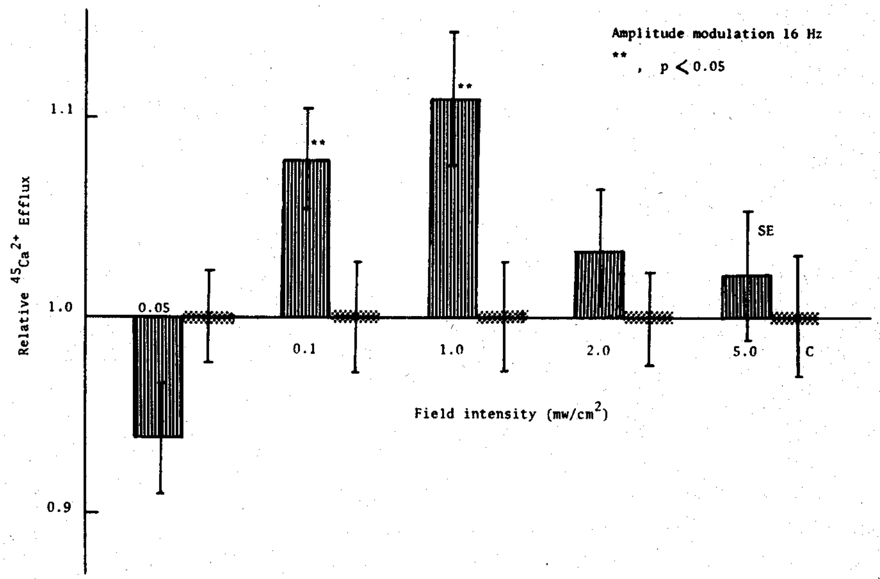

Fig. 3 Effects of 450-MHz fields (amplitude modulated at 16 Hz) on efflux of $^{45}Ca^{2+}$ from chick cerebral hemispheres. Cross-hatched bars show levels of efflux from control specimens. (Source: S. M. Bawin, A. R. Sheppard, and W. R. Adey [30].)

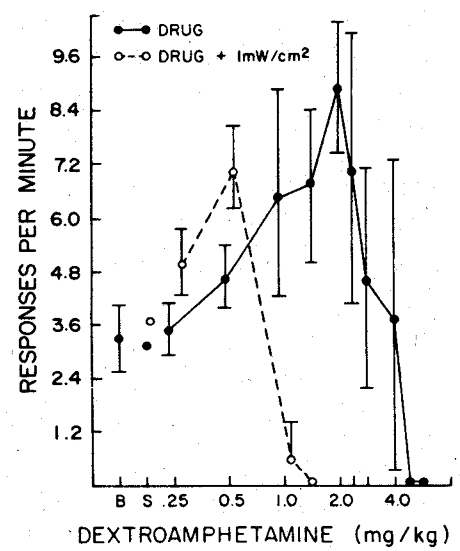

Fig. 4 DRL response of male albino rats (means $\pm$SD) immediately after a single 30-min exposure to microwave irradiation (2450-MHz, 2-μs pulse duration, 500 pps).

pulsed microwave radiation (2450-MHz, 500-pps, 2-μs pulse width, peak power density 1 W/cm^2) was used. An example of the observed synergistic effects is illustrated in Fig. 4 where the performance of animals is shown as a function of the drug dose with and without microwave radiation. Potentiation or suppression of the effects of the studied drugs is observed for an average power density of 1 mW/cm^2. The effect is apparently not robust enough to have been found replicable by subsequent experimenters. More research is, however, needed in this area since such drugs are widely used and abused in contemporary society.

V. Effects of Chronic Low-Level Irradiation

A weakness of the research in this area is that very few studies have been done with long-term exposures to microwave radiation. The primary reason for this is that the long-term studies are expensive and, with the paucity of observed low-level effects for short-term exposures, it is difficult to select the parameters (irradiation conditions, animal species, and biological protocols) for chronic exposure experiments. A few studies with exposures lasting up to sixteen weeks have been conducted [41]–[44]. The first-ever ultra-long-term study is also currently under way at the University of Washington [45], [46].

In one of our sixteen-week exposure studies [41], Long–Evans male rats were exposed to 2450-MHz CW microwaves at a power density of 5 mW/cm^2 with an SAR of 1.23 ± 0.25 W/kg. The animals (15 radiated and 15 control) were exposed eight hours a day, five days a week in a monopole-above-ground radiation chamber while housed in individual well-ventilated plexiglas holding cages. The control animals were simultaneously sham-exposed in an identical chamber with low-level background noise that was matched in both the radiation and sham-radiation chambers. Daily measures of body mass and of food and water intakes indicated no statistically significant effects of microwave irradiation. Measures of locomotor activity, based on revolutions of individual running wheels (over twelve-hour periods with access from the overnight home cages of the animals), showed no significant effects of irradiation. Blood sampled after 2, 6, 10, and 14 weeks of exposure indicated alterations of sulfhydryl groups and of red and white blood-cell counts only for the sixth week data. This is shown in Tables II and III. Measures of levels of 17 ketosteroids in urine at weeks 1, 5, 9, and 12 of exposure, and mass of adrenals, heart, and liver at the end of the sixteen-week period of exposure, revealed no indications of stress. Biweekly stabilimetric tests immediately after exposure revealed a significant depression of behavioral activity by 15 microwave-exposed rats as compared with 15 sham-exposed animals.

It is interesting that in spite of no difference between the groups on average wheel-running activity (over a twelve-hour period), a significant reduction in stabilimetric activity was found immediately after the animal's removal from the radiation chamber. The lowered stabilimetric activity of the irradiated rats may reflect an animal's attempt to cope with a thermal burden induced by microwave radiation. This explanation is consistent with that presented by Moe, *et al.* [43], for reduced activity (and other responses) during chronic exposure to 918-MHz microwaves at 10 mW/cm^2. The finding of no difference between groups in wheel-running activity overnight, however, would reflect the temporary nature of the microwave-induced thermal burden.

The sixteen-week exposure studies for 915-MHz CW microwaves [42] at a power density of 5 mW/cm^2 and an SAR of 2.46 ± 0.29 W/kg gave results that were very similar to those detailed above. No significant differences were once again found for daily measures of body mass and of food and water intakes and of hematological measures, 17 ketosteroids in urine samples, and of mass of adrenals, heart, and liver postmortem. Furthermore, cortical EEG's sampled after conclusion of microwave exposures also revealed no significant differences.

For experiments with rats exposed to 500-μW/cm^2, 2450-MHz, CW microwaves seven hours/day, seven days a week for three months, behavioral testing of shock sensitivity monthly and terminal tests of open-field activity and

TABLE II
MEAN VALUES OF HEMATOLOGY MEASURES (± SEM) (2450 MHz, 5 mW/cm^2 CW, EIGHT HOURS/DAY, FIVE DAYS/WEEK). (SOURCE: J. A. D'ANDREA, ET AL., [41].)

		2450 MHz or Sham Exposure				
	Adaptation	Week 2	Week 6	Week 10	Week 14	Recovery
Red Blood Cell Count (× 10^6/mm^3)						
Sham exposed	6 65 (±0 50)	6 41 (±0 16)	6 64 (±0 10)	6 60 (±0 13)	7 84 (±0 14)	6 86 (21)
2450 MHz exposed	6 69 (±0 13)	6 37 (±0 19)	5 63 (±0 07)	6 54 (±0 13)	8 23 (±0 15)	6.49 (23)
White Blood Cell Count (× 10^3/mm^3)						
Sham exposed	13 80 (±1 18)	13 59 (±1 34)	10 08 (±0 57)	10 08 (±0 70)	9 79 (±0 87)	10 19 (59)
2450 MHz exposed	11 72 (±0 99)	13 25 (±1 15)	15 19 (±1 43)	9 08 (±0 69)	9 28 (±0 68)	9 82 (75)
Hemoglobin (g/dl)						
Sham exposed	15 36 (±0 22)	14 76 (±0 37)	15 58 (±0 18)	15 46 (±0 25)	16 08 (±0 34)	17 33 (35)
2450 MHz exposed	14 42 (±0 69)	14 85 (±0 44)	16 36 (±0 20)	15 26 (±0 27)	16 59 (±0 37)	16 89 (42)
Hematocrit (percent)						
Sham exposed	45 30 (±0 46)	46 79 (±0 55)	45 79 (±0 35)	47 14 (±0 47)	47 89 (±0 31)	47 71 (± 48)
2450 MHz exposed	45 69 (±0 55)	47 08 (±0 46)	47 00 (±0 34)	46 92 (±0 60)	48 35 (±0 45)	47 92 (± 40)
Polymorphic Neutrophils (percent)						
Sham exposed	25 43 (±2 68)	17 71 (±1 14)	16 64 (±0 85)	19 43 (±1.82)	22 21 (±1 23)	23 57 (2 39)
2450 MHz exposed	19 85 (±2 23)	17 15 (±1 43)	17 39 (±1 22)	18 92 (±1 34)	19 46 (±1 35)	19.85 (2 17)
Lymphocytes (percent)						
Sham exposed	73 07 (±2.76)	80 64 (±1 14)	81 29 (±0 75)	78 93 (±1 98)	71 71 (±1 72)	70 57 (2 77)
2450 MHz exposed	78 85 (±2.25)	81 65 (±1 39)	81 54 (±1 36)	79 39 (±1 35)	73 92 (±1 57)	74 92 (2 14)

TABLE III
MEAN VALUES OF BLOOD CHEMISTRY MEASURES (± SEM) (2450 MHz, 5 mW/cm^2 CW, EIGHT HOURS/DAY, FIVE DAYS/WEEK). (SOURCE: J. A. D'ANDREA, ET AL , [41].)

		2450-MHz or Sham Exposure				
	Adaptation	Week 2	Week 6	Week 10	Week 14	Recovery
Cholinesterase (I U /l)						
Red Blood Cell						
Sham exposed	10 12 (±0 37)	11 04 (±0 31)	12 87 (±0 51)	13 73 (±0 56)	15 7 (±0 43)	10 45 (34)
2450-MHz exposed	9 60 (±0 31)	10 93 (±0 23)	12 26 (±0 35)	13 54 (±0 37)	14 99 (±0 52)	10 12 (23)
Plasma						
Sham exposed	3 38 (±0 15)	3 21 (±0 18)	3 34 (±0 16)	3 00 (±0 14)	3 74 (±0 19)	3 19 (17)
2450-MHz exposed	2 90 (±0 17)	3 00 (±0 17)	2 88 (±0 16)	2 71 (±0 16)	3 18 (±0 21)	2 80 (16)
Sulfhydryl Levels (mM)						
Sham exposed	8 30 (±0 30)	10 24 (±0 41)	9 08 (±0 24)	10 24 (±0 55)	9 26 (±0 37)	11 15 (56)
2450-MHz exposed	8 57 (±0 24)	10 32 (±0 23)	10 95 (±0 30)	10 85 (±0 78)	9 66 (±0 29)	10 82 (67)

shuttle-box avoidance responding has shown significant differences between groups [47]. In our experiments with similar parameters, albeit for sideways irradiation in a monopole-above-ground chamber [48] as against the dorsal exposure from a horn antenna [47], we have failed to see the alterations of behavioral and biochemical parameters reported by Lovely *et al.* [47].

An interesting ultra-long-term study is presently underway at the University of Washington [45], [46]. This study uses 100 male albino rats with a starting average weight of 200 g exposed to a whole-body-averaged SAR of 0.4 W/kg at the beginning of the experiment to less than 0.15 W/kg for anticipated 800 g weight at the end of the experiment. The animals are exposed at 2450 MHz in individual circularly-polarized waveguides [49] at an incident power density averaged over the cross section of the waveguide of 0.48 mW/cm^2. One hundred control animals are being sham-exposed in similar waveguides, with all animals housed under specific-pathogen-free barrier conditions (SPF) with temperature and humidity controlled to 21 ± 1°C and 50 ± 5 percent RH. The higher animal irradiation

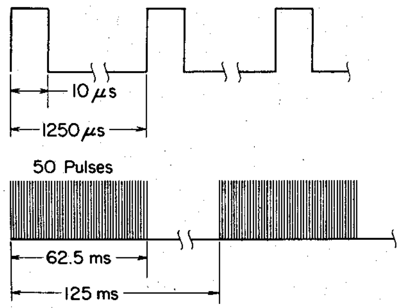

Fig. 5. Modulation characteristics of the microwave irradiation for the ultra-long-term study. Fifty pulses per group, each of which are 10 μs in duration, with a period of 1.25 ms. (Source: A. W. Guy, et al., [46].)

frequency of 2450 MHz has been chosen to simulate human exposure at 450 MHz, the latter frequency being in the range of the Air Force PAVE PAWS system [50]. Each of the exposure waveguides is fed with pulsed microwave power, with pulse trains consisting of fifty 10-μs wide pulses separated by 1.25-ms intervals. This is the equivalent of an 800-pulses-per-second source being square-wave modulated at a rate of 8 Hz with equal on/off duration of 1/16 second. The modulation characteristics shown in Fig. 5 provide an 8-Hz modulation component corresponding to the dominant EEG frequency in the rat [51]. The RF exposure is amplitude modulated based on the reported effects of $^{45}Ca^{2+}$ efflux increase observed in chick and cat brain by Adey *et al.* [29]–[31], and later replicated by Blackman *et al.* [32].

The animals are being exposed 23 hours a day, 7 days a week, with the remaining hour devoted to cage cleaning and determination of the various parameters for each of the animals. After the first fifteen months of the three-year project, the following highlights have been reported [46] for the experiment.

A. Health Status

Through the first fifteen months of the project, 15 exposed and 17 sham-exposed animals have died spontaneously or due to anesthetic trauma. An additional 10 animals from each group were sacrificed following one year of exposure to provide histopathological data. The remaining 148 rats remain free of any pathogenic contamination within the barrier facility. No specific microwave-induced lesions have been found during necropsies or preliminary characterization of tissue specimens.

B. Metabolism

Body mass and food and water consumption have been monitored daily. Oxygen consumption and carbon dioxide production have also been monitored in subpopulations of the exposed and sham-exposed groups. The data indicate no significant alterations of metabolism as a result of microwave exposure.

C. Blood Chemistry Evaluations

Blood samples have been collected eleven times during the fifteen months from all surviving animals. Analysis of eighteen serum chemistry parameters, ten hematology parameters, thyroxine (T_4), and a protein fraction evaluation indicate no significant alteration from normal values due to microwave exposure.

D. Whole-Body Analysis

Following first year of exposure, ten rats from each treatment condition were sacrificed. During necropsy, specific organ mass measurements were made. The carcasses were then subjected to total composition analysis, fat profile analysis, and spectral analysis for mineral content. No significant differences were found in any of these measures of cumulative metabolism between irradiated and control animals.

E. Immunology

As part of the interim sacrifice procedure, a number of immunological competency evaluations were completed on spleen tissue removed during necropsy. Significant differences exist between treatment conditions in response to stimulation with five B- and T-cell specific mitogens. Significant differences also were found to exist between treatment conditions in B- and T-cell populations following culturing. There was no detectable RF-radiation-caused impairment of the reticuloendothelial system, humoral immune system, cellular immune system, nor differences in the number of splenic complement receptor positive cells relative to the sham-exposed animals.

F. Corticosterone

As a measure of "stress," quarterly evaluations of the corticosterone levels were determined for the blood coincident with the regularly scheduled bleeding sessions. These evaluations provide no indication of cumulative stress related to microwave exposure.

G. Behavior

All animals were placed in an automated open-field activity monitor for three min at six-week intervals. No significant differences were observed for this behavioral activity between irradiated and control animals.

VI. Electromagnetic Absorption in Man and Animals [6], [7]

Biological studies of the effects of electromagnetic (EM) radiation have used laboratory animals such as rats, rabbits, etc., for behavioral and/or biochemical changes. For these studies to have any projected meanings for humans, it is necessary to be able to quantify the whole-body power absorption and its distribution for the irradiation conditions. It is furthermore necessary that dosimetric information be known for humans subjected to irradiation at different frequencies and for realistic exposure conditions.

Unlike the field of ionizing radiation, where the absorption cross section of a biological target is directly related to its geometrical cross section, the whole-body EM energy absorption has been shown [5], [52]–[58] to be strongly dependent on polarization (orientation of electric field $\boldsymbol{E}$ of the incident waves), frequency, and physical environments such as a conducting ground and other reflecting surfaces. A prescribed power density of, say, 10 mW/cm^2 tells almost nothing about the absorbed dose except, perhaps, at very high frequencies where the wavelength of irradiation is an order of magnitude or more smaller than the dimensions of the animal. This is best illustrated by examples from Schrot and Hawkins' work [59] on times of lethality of rats and mice at several frequencies and for different polarizations of incident waves. For a free-space irradiation power density of 150 mW/cm^2 at 985 MHz, mice oriented along the electric field (E-orientation) convulsed in an average time of nine min, while similar animals oriented along the microwave magnetic field (H-orientation) lived through an experimental observation time of sixty min without significant stress. Also, identical power densities at several frequencies resulted in substantially different times to convulsion. For mice irradiated with an incident power density of 150 mW/cm^2 in the E-orientation, mean times to convulsion of 3260 and 160 s were observed for 710 and 1700 MHz, respectively.

A. Techniques

1) Carefully proportioned, reduced-scale models of man have been used to determine the mass-normalized rates of EM energy absorption (specific absorption rates or SAR's) at different frequencies and for different conditions of irradiation. This work is detailed in [60]. The highlights of these results have been checked by experimentation with small laboratory animals [56], [61] from 25-g mice to 2245-g rabbits. The SAR's are determined by measuring the colonic temperature elevation of anesthetized animals or by calorimetric determination of the absorbed dose by freshly euthanized animals.
2) Prolate spheroidal [53], [55], [62] and ellipsoidal [63] models have been used for theoretical calculations for man and animals at frequencies up to and slightly beyond the resonant region. For very high frequencies, a geometrical optics method has been developed to estimate the power absorption in prolate spheroidal [64] and cylindrical models [65] of man. It is shown that the dependence of whole-body-averaged SAR on both frequency and polarization of the incident fields may be estimated using prolate spheroidal or ellipsoidal models, but the distribution of energy deposition through the body cannot be determined with such crude models.
3) Moment method solutions [54] for an improved block model of man [57] have given good correlation with experimental data. These calculations have also led to the identification of the frequency regions for peak absorption (resonance) in arms and the head [57].

B. Free-Space Irradiation Condition

The condition that has been studied the most extensively [52]–[57] is that of free-space irradiation of single animals. The whole-body absorption of EM waves by biological bodies is strongly dependent [52], [53] on the orientation of the electric field ($\boldsymbol{E}$) relative to the longest dimension (L) of the body. The highest rate of energy deposition occurs for $\boldsymbol{E} \| \hat{L}$ (E-orientation) for frequencies such that the major length is approximately 0.36 to 0.4 times the free-space wavelength (λ) of radiation [5]. Peaks of whole-body absorption for the other two configurations (major length oriented along the direction ($\boldsymbol{k}$) of propagation, $\boldsymbol{k} \| \hat{L}$ or k-orientation, or along the vector ($\boldsymbol{H}$) of the magnetic field $\boldsymbol{H} \| \hat{L}$ or H-orientation) have also been reported [52], [56] for $\lambda/2$ on the order of weighted average circumference of the animals.

Curves for whole-body absorption (fitted to the experimental data [56], [60]) for models of man exposed to radiation in free space are given in Fig. 6. For each of the orientations, configurations corresponding to higher power deposition are used. In Fig. 7 is shown a comparison between the experimental data and the various theoretical models for the most-absorbing E-orientation. For this orientation, the whole-body absorption curve (Fig. 7) may be discussed in terms of five regions.

Region I—Frequencies well below resonance ($L/\lambda <$ 0.1–0.2): An f^2 type dependence derived theoretically and checked experimentally by Durney *et al.* [66].

Region II—Subresonant region ($0.2 < L/\lambda < 0.36$): An $f^{2.75}$ to f^3 dependence of total power deposition has been experimentally observed for this region.

Region III—Resonant region ($L/\lambda \simeq 0.36$–0.4): A relative absorption cross section [60] defined by electromagnetic absorption cross section[2]/physical cross section, S_{res} on the order of 0.665 $L/2b$ (derivable also from antenna theory) has been measured for this region, where L is the major length of the body and $2\pi b$ is its weighted average circumference. For a 70-kg, 1.75-m tall adult human being, $L/2b \simeq 6.3$ and S_{res}, therefore, is 4.2 at the resonance frequency f_r in megahertz on the order of $(62–68) \times 1.75/L_m$, where L_m is height of the individual in m.

Region IV—Supraresonant region to frequencies on the order of 1.6 S_{res} times the resonance frequency (for human beings, this covers the region $f_r < f < 7f_r$): A whole-body absorption reducing as f_r/f from the resonance values has been observed.

Region V—$f \gg f_r$ region: The EM absorption cross section should asymptotically approach the "optical" value which is (1-power reflection coefficient) or about one half the physical cross section.

A major contribution of the numerical calculations with the block model of man (see curve A in Fig. 7) is to reveal a fine structure to whole-body absorption in the supraresonance region. Minor peaks in this region at 150 MHz and at 350 MHz are ascribed to maxima of energy deposition in the various body parts [34] such as the arm and the head, respectively.

The calculations for multilayered models [67], [68] of

[2] This is defined by the rate of energy deposition divided by the incident power density.

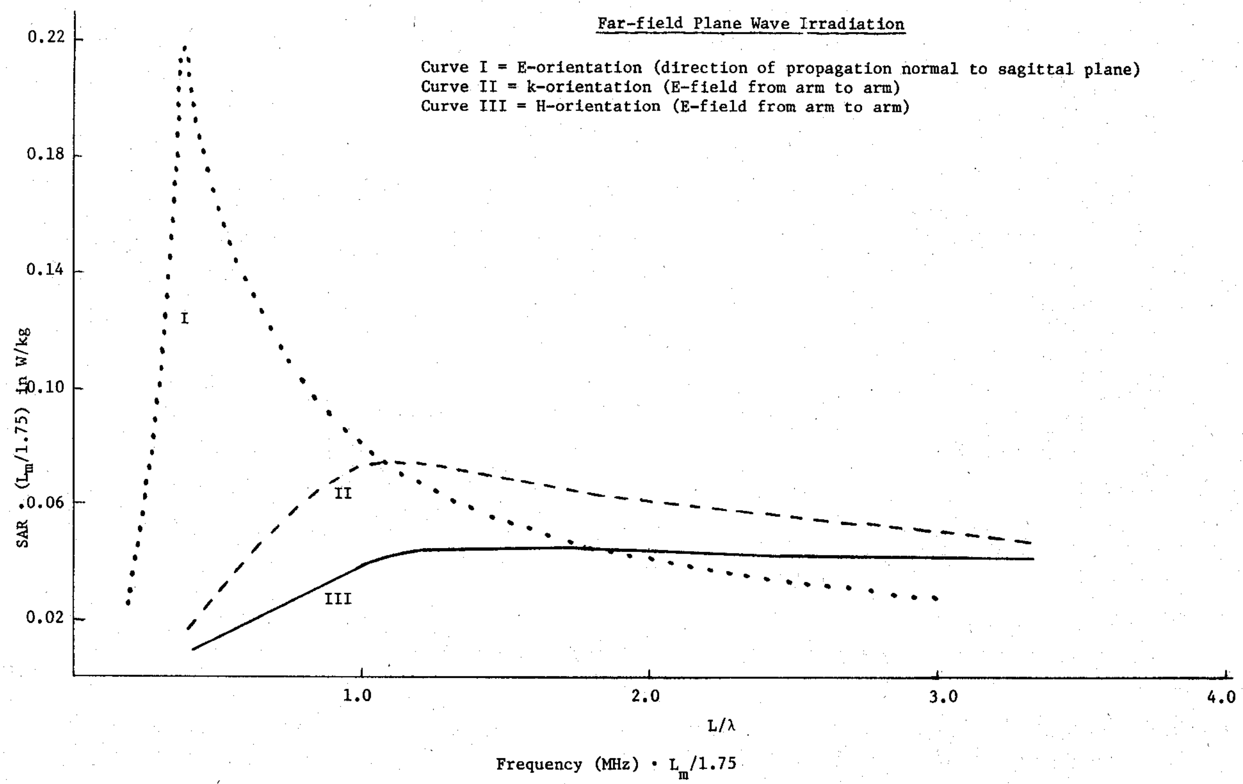

Fig. 6 Whole-body-averaged SAR for models of human beings for incident fields at 1 mW/cm^2 [6].

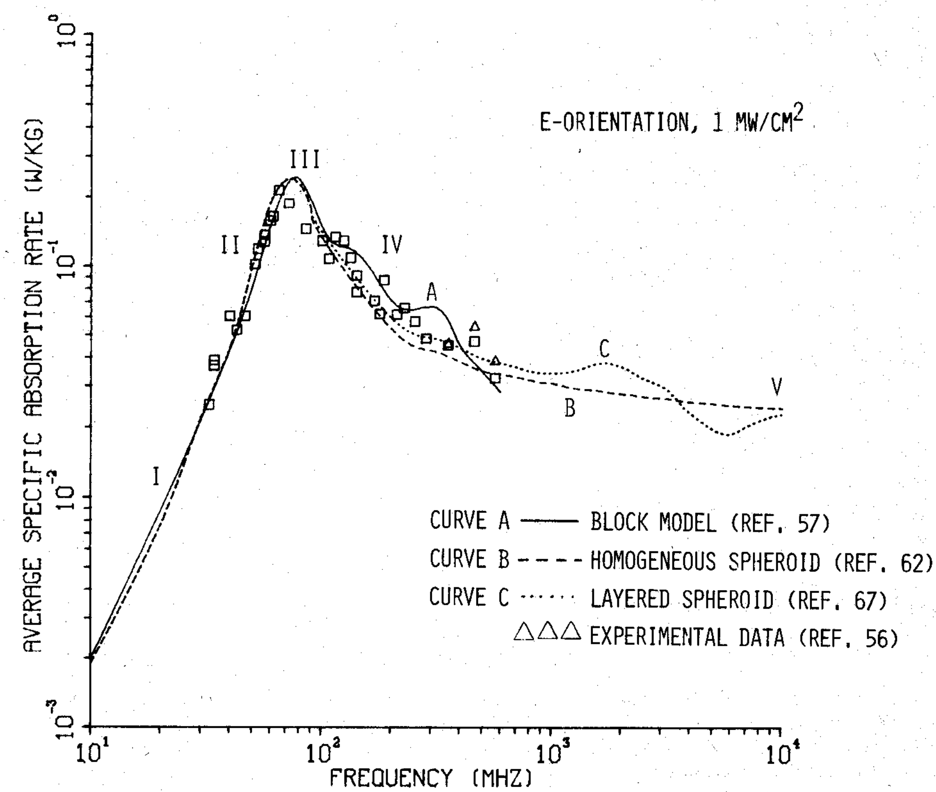

Fig. 7 Whole-body-averaged SAR for a model of man exposed to a broadside incident plane wave for *E*-orientation (incident power density = 1 mW(cm^2) [69].

man show that layering may be neglected at frequencies below 500 MHz where homogeneous models are appropriate, or above 10 GHz where absorption is generally restricted to the skin. As seen in curve *C* (Fig. 7), a broad layering-caused peak in whole-body absorption occurs for a frequency of 1800 MHz, where a deposition 34 percent

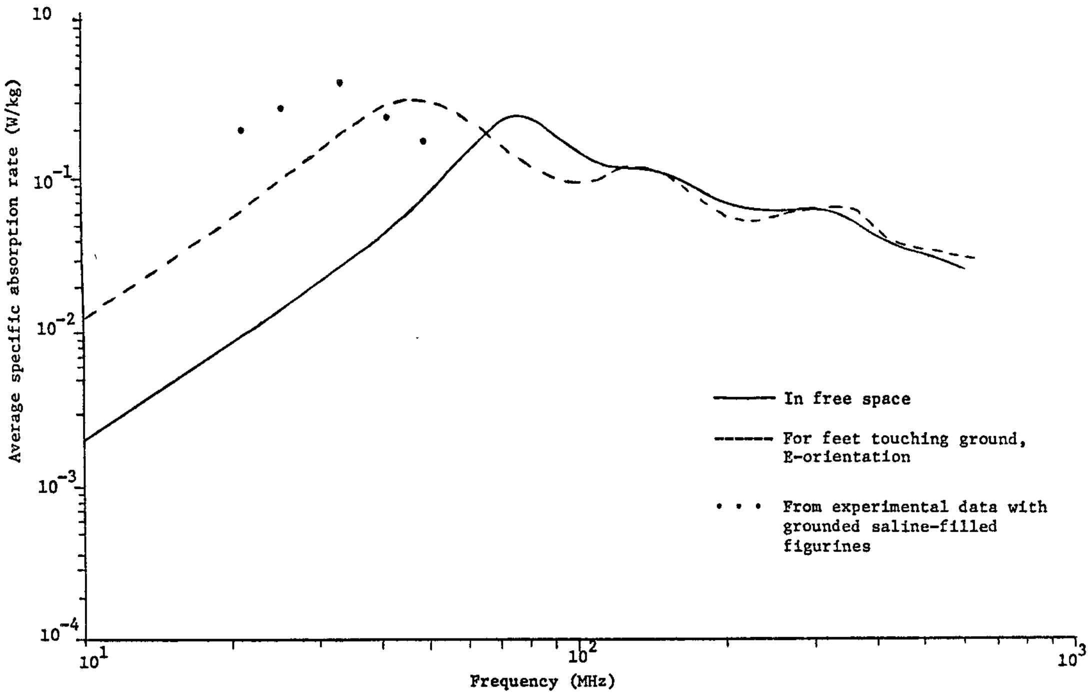

Fig. 8 Whole-body-average SAR for homogeneous model of man. Incident power density of 1 mW/cm^2; E-orientation; k ventral to dorsal for numerical calculations and from arm to arm for experiments with saline-filled figurines [69].

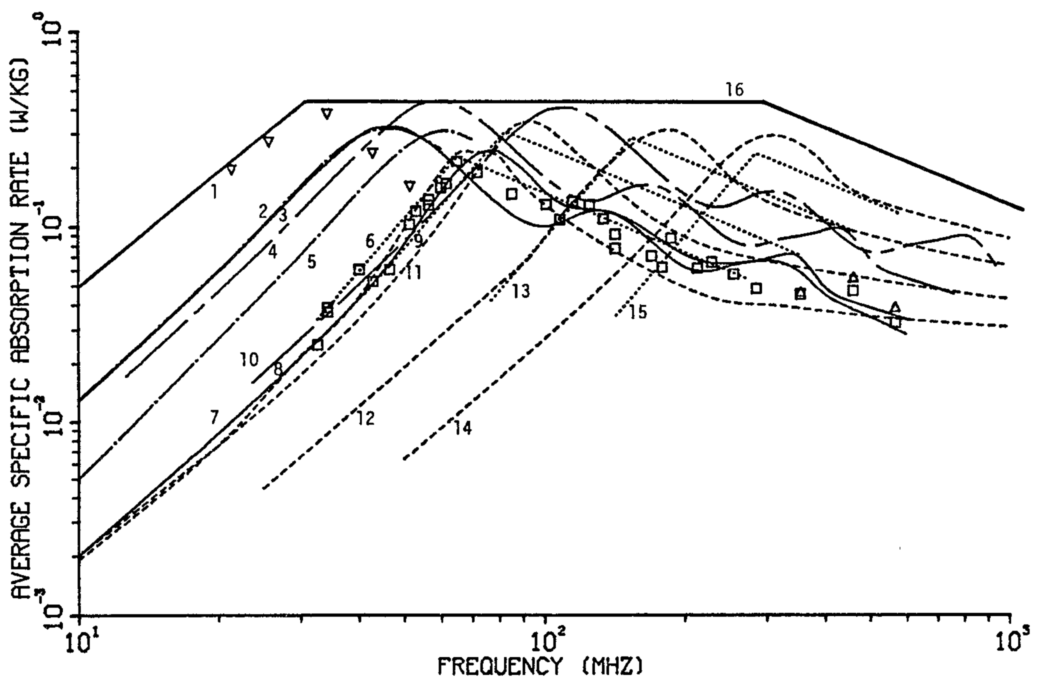

Fig. 9 Whole-body-averaged SAR for an adult human, ten-year-old child, one-year-old child, and a human infant. Power density = 1 mW/cm^2. The results of various researchers are used for cross comparison. The outer envelope (curve 16) gives the maximum SAR for any of the human sizes at a given frequency. Legend for curves (left to right): 1. Experimental results scaled from saline-filled figurines under grounded conditions—adult human (from Fig. 8). 2. (solid curve) Numerical calculations with a block model of man—conductive contact with ground (from Fig. 8). 3. (chain-dot) Empirical—adult human in conductive contact with ground [62]. 4. (chain-dash) Scaling of curve 2 for ten-year-old child (grounded contact). 5. (chain-dot) Empirical—adult human 3 cm from ground plane [62]. 6. (dot) Empirical equation (from [61])—adult human in free space. 7. (solid) Numerical calculations for a block model of man in free space with figurine experimental data shown by open squares and phantom experimental data shown by open triangles [56], [57]. 8. (dash) Prolate spheroidal model of man in free space [62]. 9. (dot) Empirical equation [61]—ten-year-old child. 10. (chain-dash) Scaling of curve 2 for one-year-old child (grounded contact). 11. (dash) Prolate spheroidal model of ten-year-old child [62]. 12. (dash) Prolate spheroidal model of a one-year-old child [62]. 13. (dot) Empirical equation [61]—one-year-old child. 14. (dash) Prolate spheroidal model of a human infant [62]. 15. (dot) Empirical equation (from [61])—human infant.

TABLE IV
METABOLIC RATES IN W/KG FOR NORMAL HEALTHY HUMAN BEINGS OF VARIOUS AGES.

	Adult Human Being (20-24-Year-Old Male)	Ten-Year-Old Child	One-Year-Old Child	Human Infant
		Whole-Body-Average Values		
Sleeping	1.1			
Resting quietly (~basal condition)	1.3	2.0	2.75	2.75
Sitting upright	1.5			
Standing (clerical work)	1.8			
Walking, 3 mph	4.3			
Bicycling	7.7			
Swimming	11.0			
Running up stairs	18.00			
		Local Values		
Brain	11.0			
Heart muscle	33.0			

larger than that for the homogeneous model (curve B) is obtained.

C. Ground Effects

Only highly conducting (metallic sheet) ground of infinite extent has been considered to date. All measurements and calculations of grounding effects have assumed that a man is standing on or above such a ground. Fig. 8 shows the calculated values of SAR for the block model of man with feet in conductive contact with ground and compares the same with the values calculated for free-space irradiation. A somewhat higher SAR at a new resonant frequency that is roughly one half that for free-space irradiation conditions is observed for a man model in conductive contact with ground.

D. Considerations for an Electromagnetic Safety Guide

In Fig. 9 are plotted fifteen individual curves [69] for the SAR's for a 70-kg, 1.75-m tall average-sized man; a 1.38-m tall, 32.2-kg, ten-year-old child; a 0.74-m tall, 10-kg, one-year-old child, and a 0.4-m long, 3.5-kg average-sized human infant under various conditions. The theoretical and experimental results of various researchers are used in plotting these graphs. An incident power density of 1 mW/cm^2 is assumed for the highest absorption (E-orientation) condition. Ground contact conditions are assumed for an adult human, a ten-year-old child, and a one-year-old child, but not for a human infant.

Fig. 9 also shows an overall "umbrella" type curve 16, which gives the maximum SAR for any of the human sizes under the various conditions. Peaks of absorption for the various human sizes fall in the frequency band 30 to 300 MHz. There is in general an f^2 type rise in SAR on the low-frequency side and a $1/f$ type fall in SAR for the supraresonant region. For 1 mW/cm^2 measured[3] environmental fields over a whole-body exposure situation, it is clear from Fig. 9 that the maximum whole-body-averaged SAR over the peak absorption region of 30 to 300 MHz is always less than or equal to 0.42 W/kg. Maximum SAR at "hot spots" may be as much as an order of magnitude [6] higher, but these SAR's are highly variable with the irradiation parameters and exposure conditions. These SAR's may be compared to the typical metabolic rates [70] for human species that are listed in Table IV.

[3]It is assumed here, of course, that any reflection-caused enhancements of power densities are already accounted for in actually-measured fields of 1 mW/cm^2.

The ANSI C95 recommended safety guide shown in Fig. 1 is the inverse of curve 16 of Fig. 9. The allowed power densities are calculated such as to ensure a whole-body-averaged SAR of less than or equal to 0.42 W/kg over the frequency band 3–100000 MHz.

VII. MEDICAL APPLICATIONS

There is a great deal of anticipation about the beneficial applications of electromagnetic fields for medical applications. The use of electromagnetic heating in *diathermy* is well established [71]–[75]. A wide variety of applications, particularly in rehabilitative medicine, have been discussed in [71]–[74]. Some of these are [74]:

1) for relief of pain resulting from muscle spasm;
2) for joints where there is some acute chronic inflammatory process;
3) to improve range of motion and relieve joint stiffness associated with collagen diseases;
4) chronic periarthritis;
5) fibrositis or myofibrositis;
6) to increase blood flow and improve circulation;
7) chronic inflammatory pelvic diseases, etc.

The most interesting and advanced among the potential application areas is electromagnetic *hyperthermia* (local, regional, or whole-body) as an adjuvant for cancer therapy [76]–[85]. Other promising areas for application of electromagnetic technology are: noninvasive biomedical *imaging* [86]–[89], electromagnetic heating for revival of hypothermic subjects and for *organ* and *blood thawing* [90], [91], microwave *radiometry* [92]–[94], and several miscellaneous medical applications [95], [96].

Electromagnetic energy offers several distinct and unique advantages of in-depth heating and rapid control. The engineering design, however, is a challenging electromagnetics problem in that inhomogeneous lossy dielectric properties of the tissues coupled to complex exposure profiles must be solved in order to obtain accurate rates of heating and temperatures for the various regions of the exposed body—a challenge that is just beginning to be met because of significant recent advances in near-field inhomogeneous modeling techniques [97]–[99]. Because of these developments, there are expectations for even bigger strides in the future [98].

A. Hyperthermia

By far the most exciting new medical application is the use of electromagnetic hyperthermia as an adjuvant to cancer therapy, since malignant cells are generally more

TABLE V
SELECTED CANCER STATISTICS AND HYPERTHERMIA CONSIDERATIONS.
(SOURCE: J. G. SHORT AND P. F. TURNER, [78])

Site	Estimated New Cases	Estimated Deaths	Possible Regional or Local Hyperthermic Approaches ULT	CAP	IND	MIC	Problems and Considerations
Buccal cavity and pharynx	24 400	8650	NI	NI	NI	NI	Proximity to eyes, complex geometry–reflections, uneven heat deposition. Specialized applicators. High vascular perfusion.
Esophagus	8400	7500	–	OR	NI	OR	Local metastases at first diagnosis. Large blood vessels adjacent. Difficult thermometry (danger of mediastinitis).
Stomach	23 000	14 100	–	NI OR	NI	OR	Local metastases at first diagnosis. Difficult geometry and placement of applicators. Some success with WBH and hyperthermic irrigation.
Colon	77 000	42 800	–	NI	NI	NI OR OP	Right colon not accessible by orificial applicator (too deep). Adjacent loops of bowel containing liquids and gases. Thermometry difficult.
Rectum	35 000	9100	–	OR	NI	OR IN	Metastases in regional lymph nodes may be difficult to heat.
Liver and biliary	11 600	9200	NI	NI	NI	NI IN	Most sensitive tissue to heat. Large organ. Usually good differential heating of tumors. Gall bladder contents may overheat.
Pancreas	23 000	20 200	NI	NI	NI	NI OR OP	Deep, inaccessible. Intestinal mucosa are heat sensitive. Thermometry difficult. May require surgical implantation–active and passive radiators and temperature probes.
Larynx	10 400	3500	NI	–	–	NI OR	Good candidate for hyperthermia–accessible, early symptoms, second chance laryngectomy if hyperthermia fails.
Lung	112 000	97 500	–	NI	NI	NI OP	Often far advanced at first diagnosis, metastasis common. Geometry difficult–air, bone, major vessels. Thermometry tricky.
Bone and connective tissue	6400	3350	NI	–	NI	NI	Commonly metastasize to lung. Problems relate to size and location, etc.
Breast	106 900	34 500	NI	NI	NI	NI IN	Deep surface against muscle may be harder to heat. Metastases to axillary lymph nodes often small (1 mm). Synchronous phased array?
Melanoma	13 600	4300	NI	–	–	NI	Metastasize widely.
Uterus	53 000	10 700		OR IN	NI	OR IN OP	Nonsurgical candidates have local extension which is deep for external applicators, distant from intrauterine cavity.
Ovary	17 000	11 100	–	–	NI	NI OP	Many tumors cystic, large, easily ruptured–thermometry difficult. Tumors deep in pelvis. Disseminate through peritoneal cavity.
Prostate	64 000	21 000	NI	OR	–	NI OR	Metastasize to lower spine.
Brain	11 600	9500	IN		NI	IN OP	Reflections, resonance, fluid-filled ventricles, proximity to eyes. Surgical procedure for invasive applicators and temperature probes. Hyperthermic chemotherapeutic perfusion?
Thyroid	9000	1000	NI	–	NI	NI	Adjacent tissue has many large blood vessels and important nerves.
Leukemia	21 500	15 400	–	–	–	–	Diffuse disease. Whole body hyperthermia with chemotherapy and/or X-irradiation? Extracorporeal hyperthermia of blood?
Lymphoma	38 500	20 300	NI	NI	NI	NI	Often diffuse. May be difficult to heat preferentially. Dosimetry may be difficult.
Bladder	35 000	10 000			NI	OR	Temperature probe placement tricky in invasive tumors. Some success with hyperthermic irrigation.
Kidney	16 200	7500	NI	NI	NI	NI IN	May require X-ray placement of temperature probes and IN applicators.
All sites	765 000	395 000					

Abbreviations: ULT-Ultrasound, CAP-Capacitive RF, IND-Inductive RF, MIC-Radiative UHF, microwave, NI-Noninvasive, IN-Invasive, OR-Natural orifice (orificial), OP-Operative (surgical exposure), WBH–Whole body hyperthermia.

sensitive to thermal damage at temperatures in the range of 41–45°C than are normal cells [78]. A detailed listing of selected cancer statistics and hyperthermia consideration is given in Table V. Recent advances in RF, microwave, and electronic control technologies have led to studies at a number of laboratories in which electromagnetic hyperthermia is being used as an adjunct to ionizing radiation or chemotherapy for treatment of localized tumors [79], [81], [83]. A number of clinicians have also begun to investigate the use of electromagnetic energy for regional hyperthermia [79], [82]. There also is a rapidly increasing interest in whole-body hyperthermia [80], [84], [85] with and without regional boosting, particularly for patients with advanced cancers involving widely spread metastases. Clinical studies of whole-body hyperthermia have used only conventional heating techniques to date (melted paraffin immersion with or without inserted hot water sacks for regional boosting [80], hot water "space suits" [84], [85], and extracorporeal heat exchange by perfusion). Even though electromagnetic heating has not yet been used for whole-body hyperthermia, it is felt that frequencies on the order of 50–150 MHz may offer the advantages of deep heating, precise control, and reducing the time to about 1/2 h to reach the final hyperthermic temperature of 41.8°C as compared to 1-1/2 to 3 h by current techniques [85] which rely upon surface heating and blood mediation to elevate the body temperature. For clinical use, a coupling efficiency of 80 percent would allow a 1000-watt RF source to raise the temperature of a 70-kg man by 0.16°C/min. Work is currently in progress [97] to account for the inhomogeneous dielectric properties of the body to properly design multielement electromagnetic applicators to obtain physician-prescribed subregional rates of heating over the various parts of the body, which may be relatively uniform (2:1) or highly focalized, if needed, over certain regions. Because of the *in situ* heating of the tissues and less reliance on blood conduction, an even deposition of energy through the body by electromagnetic heating may be less stressful to the patient with a possibility of being able to get by with analgesia alone. In the present methods, whole-body anesthesia is administered for up to 6–9 h that are needed for the desired 4–6 h of chemotherapy session at the elevated temperatures [84], [85].

It is recognized that the quantity of perhaps greater interest is the temperature distribution over the entire body. Modeling of the human body for temperature distribution is not as advanced as is the electromagnetic modeling. Detailed information on the nonlinear, anisotropic heat flow due to hemodynamics is needed for accurate thermal modeling. An inhomogeneous thermal block model of man is presently being developed [99], which, coupled with the electromagnetic model, should allow design of electromagnetic applicators for physician-prescribed temperature distributions for the various parts of the body rather than the rates of heating (SAR's) as is possible at the present time [97].

B. Biomedical Imaging

An exciting development in the field of biomedical imaging is the possibility of using nuclear magnetic resonance (NMR) to discriminate between various tissues [100]–[107]. The method is based on the different relaxation times T_r of the proton spins of water in normal and malignant tissues. T_r ranges from 0.3 to 0.6 s for water in normal tissues, whereas for tumors the corresponding values are 0.5 to over 0.8 s. From early pioneering research by Damadian [100] and Lauterbur [101], the method has developed to a stage where it has been applied for biomedical imaging [102]–[107]. Even though the quality of the NMR images is no match to X-ray images, the method is already beginning to be useful medically because of its correlation with the status of tissue water.

Pilot studies have recently been started in several laboratories [86]–[89] to evaluate the use of electromagnetic scattering from the human body or parts thereof for biomedical imaging. Even though serious questions have been raised about the spatial resolution capabilities of electromagnetic methods on account of the larger wavelength of incident radiation (as compared to, say, ultrasonic waves), Larson and Jacobi [86] have conducted experiments to try to obtain 4-GHz microwave images of an isolated canine kidney. Using moment methods, exploratory work is also being done at the University of Utah [87] to obtain complex dielectric properties of the tissues at 100 to 300 locations from the RF *E*-field measurements at several locations surrounding the body. In this approach, it is envisaged that some of the receiving antennas could also be interchangeably used as transmitting antennas.

Whereas in X-ray imaging techniques the propagating beam is well-collimated and, therefore, easy to manipulate, the electromagnetic propagation and scattering from inhomogeneous dielectric bodies is quite complicated. The vector fields are subject to diffraction and scattering. Complete Maxwell's equations, therefore, need to be solved to obtain the lossy dielectric properties from the measurements. In spite of the many difficulties, the promise of electromagnetic biomedical imaging remains high because of the highly pertinent nature of the information that one would get—dielectric properties which are very sensitive to the water content of the tissues. Another use of the information so obtained would be its pertinence and therefore direct applicability for individualizing the electromagnetic hyperthermia regimens.

Microwave radiometry [92]–[94] relies upon the detection of the intensity of black-body radiation from the various parts of the body in the frequency band on the order of hundreds of megahertz to several tens of gigahertz. The premise here is that since this radiation is not as highly absorbed by the skin as is the infrared (thermal emission), one should be able to detect somewhat deeper (on the order of centimeters) thermal anamolies that may therefore help in many of diagnostic applications similar to those for conventional thermography. Examples here are the detection of the location and extent of breast cancer, tumor of the thyroid, determination of the extent of burns and frostbite, detection of rheumatoid arthritis, placental location, etc. A great deal of work has been done by Barrett and Myers at MIT (frequencies 1–4 GHz) and by Edrich and colleagues at Denver Research Institute using higher frequencies in the millimeter-wave band. Even though substantial progress has been made in obtaining true positive detections, the quality of images leaves a lot to be desired. Considerably more work with data processing and proper electromagnetic modeling of the tissues and the pick-up antenna/s is needed before the perceived advantages of microwave techniques over infrared thermography can be realized.

C. Miscellaneous Applications

In the field of neurobiology, rapid microwave heating [108]–[112] of the animal head (to temperatures in the range of 55 to 90°C) is being increasingly used as a technique for sacrificing animals and inactivating brain enzymes, eliminating, thereby, postmortem changes in many heat-stable neurochemicals such as acetylcholine, L-DOPA, gamma aminobutyric acid, cyclic AMP, cyclic GMP, etc. The determination of the distribution of these neurochemicals is an indicator of the central nervous system (CNS) and is consequently an important tool for neurobiological research, i.e., in the evaluation of the effects of hormones or drugs on the CNS. The microwave technique offers the advantage of inactivating brain enzymes in milliseconds as compared to much longer durations for the competing freezing methods. Rapid freezing methods such as the freeze-blowing technique [113], though offering relatively fast inactivation times, suffer from the loss of anatomical features. This does not permit regional determination. There are concerns, too, in that enzyme systems may recover during thawing, leading to additional artifactual changes.

Electromagnetic energy is also being evaluated for use in several miscellaneous biomedical applications and these are discussed at length in a review article by Iskander and Durney [95]. Some other highly promising, but not yet completely evaluated, applications of electromagnetic energy are for blood and organ thawing [90], [91], for warming of neonatal infants post-open-heart surgery, for wound healing [96], and for enhanced rates of post-surgical healing, etc.

From the foregoing it is obvious that there are several potential and highly useful biomedical applications of electromagnetic energy. Recent advances in electromagnetic bioengineering, including the proper modeling of the inhomogeneous tissue properties and the realistic near-field exposure conditions, have poised the field for major advances in the foreseeable future.

VIII. Concluding Remarks

To sum up, knowledge in this field is where the understanding of the effects of ionizing radiation used to be some thirty years ago, i.e., in its infancy but rapidly advancing. There is a great deal unknown about the biological effects of nonionizing radiation. Some of the areas that need to be investigated [4] are:

1) mechanisms of interaction of EM fields with biological systems;
2) comparative biological effects of exposures to CW, modulated, and pulsed EM fields;
3) assessment of biological effects of intermittent or continuous exposure to weak EM fields over long terms (months to years);
4) absorption of energy and its distribution in the body for complex exposure profiles and prediction of the biological effects that would be produced by such an absorption.

Even though the present knowledge is not complete enough to rule out the biohazards of microwaves and other radiofrequency electromagnetic fields, what is known is reassuring for the general population. The strengths of fields to which 99 percent of the North American population is exposed are hundreds of times below current U.S. guidelines of permissible intensity levels for safe exposure and, indeed, are below the most restrictive limits imposed by any government world wide. With the exception of individuals in some occupational situations [10], [11], the intensities, to which the remaining one percent of the population is exposed, are also well below the current U. S. guidelines.

There are several promising biomedical applications of electromagnetic energy that need to be investigated thoroughly. The most visible of these is the electromagnetic hyperthermia as an adjunct to cancer therapy. It is necessary, however, that competent interdisciplinary teams consisting of physicians, biologists, and engineers work in these areas to convert the hopes into realities. It is unfortunate that the level of funding is totally inadequate, and most of these highly likely applications are therefore not getting a proper and thorough evaluation.

Engineers have played a key role in the area of electromagnetic dosimetry where the knowledge has advanced rapidly and has had its impact in shaping a new frequency-dependent electromagnetic safety standard in Canada [1], [2] and a recent approval of a new ANSI C95 guideline in the United States [3]. As professionals, engineers are also likely to play an important part in the design of sophisticated equipment for inducing hyperthermia and its thermometry and for other biomedical applications.

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Om P. Gandhi (S'57–M'58–SM'65–F'79) received the B.Sc. (honors) degree in physics from Delhi University, Delhi, India, and the M.S.E. and Sc.D. degrees in electrical engineering from University of Michigan, Ann Arbor.

He is a professor of Electrical Engineering at the University of Utah, Salt Lake City. He is an author or coauthor of one technical book and over 140 journal articles on microwave tubes, solid-state devices, and electromagnetic dosimetry and has recently written the textbook *Microwave Engineering and Applications* published by Pergamon Press. He has done pioneering work in quantifying the electromagnetic absorption in man and animals including the whole-body and part-body resonance conditions—work that formed an important basis for the new ANSI C95 recommended safety level with respect to human exposure to RF fields. He has been a principal investigator on over a dozen federally funded research projects since 1970, and serves or has served as a Consultant to several government agencies and private industries.

Dr. Gandhi received the Distinguished Research award of the University of Utah for 1979–1980 and a special award for "Outstanding Technical Achievement" from the Institute of Electrical and Electronics Engineers, Utah Section, in 1975. He edited a "PROCEEDINGS OF THE IEEE" Special Issue (January 1980) on Biological Effects and Medical Applications of Electromagnetic Energy. In addition to his membership on numerous national professional committees, he has been a Member of the Board of Directors of the Bioelectromagnetics Society and serves on the Editorial Board of its journal "Bioelectromagnetics." He is currently serving as the Chairman of the IEEE Committee on Man and Radiation (COMAR). His name is listed in *Who's Who in Engineering*, and *Who's Who in Technology Today*.

Human Whole-Body Radiofrequency Absorption Studies Using a TEM-Cell Exposure System

DOUGLAS A. HILL, MEMBER, IEEE

***Abstract*—A system has been constructed for measuring radiofrequency absorption in the human body resulting from exposure to high-frequency (HF) electromagnetic radiation. The exposure chamber is a 6.1×7.3×13.0-m rectangular-coaxial transverse-electromagnetic (TEM) cell. The absorbed power, determined from signal-averaged measurements of incident, reflected, and transmitted power, is measured to a precision of 0.06 percent of incident power (0.003 dB in insertion loss). A detailed analysis of systematic errors in the method has shown that a directional-coupler directivity approaching 50 dB is necessary for high accuracy in absorbed-power measurements and that any dielectric-loading effect of the subject on the cell absorption is undetectable. The total systematic error in determining absorption rate per unit exposure rate is about ±35 percent of the measurement. Operating frequencies are currently limited to the 3 to 20-MHz range due to the occurrence of the first cell resonance, associated with the TE_{01} mode, at 20.7 MHz. The first set of human whole-body absorption results is presented for three subjects exposed in free space to 11 μW/cm^2 at 18.5 MHz in six different body orientations with respect to the TEM wave. The measured absorption rates for the two principal E orientations are larger than the published predictions by a factor of 2 to 3.**

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The author is with the Radiation Biology Section, Defence Research Establishment Ottawa, Ottawa, Canada, K1A 0Z4.

I. INTRODUCTION

WHILE permissible human exposure levels for radiofrequency radiation (RFR) (10 kHz–300 GHz) are currently under active discussion, much information is lacking. For example, the absorption of RFR by humans has been studied only indirectly by calculating or measuring the heating patterns for various models. The calculations—too numerous to be individually referenced—have recently been reviewed by Durney [1]. Measurements of