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E189

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On the Coupling of Microwave Radiation to Wire Structures

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***Abstract*—The general aspects of the excitation of wire structures under microwave illumination are presented and discussed. Numerical, analytical and experimental results are provided. A simple procedure is presented for bounding the response of certain canonical configurations. Results are obtained for a terminated single wire over a ground plane and for a two-wire transmission line under plane wave illumination. The variation of the induced current with line dimensions and frequency are considered. It is shown that the TEM mode current is a suitable approximation for the wire current with line separations up to and exceeding a wavelength.**

I. Introduction

UNDER microwave illumination, wire configurations within electrical systems will become receiving antennas and wave guiding structures (transmission lines). A convenient means of analyzing the response of these objects is the use of receiving cross sections [1]. Often, the characteristic dimension of the illuminated configuration is several wavelengths (at 30 GHz the wavelength is 1 cm). When the wire configuration is only a few wavelengths in length, then a numerical analysis is a practical approach. The NEC code, for example can be used [2].

Wave guiding structures may be more difficult to analyze. In addition to the TEM or transmission line mode, higher order modes should be considered. Leviatan and Adams [3] have investigated the effects of higher order modes on the responses of a two-wire transmission line driven from a point source and illuminated by a plane wave. They used Fourier spectral analysis to develop relatively simple solutions for the TEM mode and the so-called "leaky" modes. In addition to these modes, there is a branch cut contribution to the induced currents that was not obtained. A limited amount of results are presented.

Hsi *et al.* [4] considered the excitation of a wire located behind an aperture perforated conducting sheet. They used a numerical solution technique to obtain the higher order mode contribution to the wire current. Wire heights of 0.1λ and 0.25λ were considered. Their solution technique assumed only the TEM mode current is appreciable at a conveniently large distance from the aperture. When the wire height is sufficiently large that higher order modes propagate, then the TEM mode assumption is no longer strictly valid.

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Adams *et al.* [5] determined the response of transmission line antennas in the SHF frequency range by using a method of moments numerical solution. Their analysis did not attempt to identify specific modal contributions. However, the results do provide information of the relative importance of the TEM mode coupling from the standing wave and traveling wave pattern in the induced current distribution.

Barnes and Stevens [6] studied the transient response of an infinitely long wire above a conducting earth using scattering theory and TEM mode analysis (transmission line theory). They were primarily concerned with the adequacy of considering only the TEM mode in their coupling analysis.

This paper discusses the general trends of microwave coupling to wire structures and presents numerical, analytical and experimental data. A simple procedure based on the receiving cross section is presented for bounding the response of certain canonical configurations. Also, the response of transmission lines to microwave illumination is considered and discussed.

II. Receiving Cross Section

When characterizing the electromagnetic coupling from the exterior of an electrical system to a specific interior point (set of terminals), a convenient parameter is the *receiving cross section* defined by

$$\sigma_R = P_L/p^{\text{inc}}, \quad \text{sq. meters} \tag{1}$$

where P_L is the power delivered to a load, Z_L, connected across the specified terminals and p^{inc} is the incident power density. As shown by Park and Tai [1], the receiving cross section can be expressed by the general relationship.

$$\sigma_R = \frac{\lambda^2}{4\pi}\eta q p\, D(\theta, \phi). \tag{2}$$

Here, λ is the wavelength and q is the impedance matching factor defined.

$$q = \frac{4R_L R_{\text{in}}}{|Z_L + Z_{\text{in}}|} \tag{3}$$

where R_L and R_{in} are the resistive components of the impedances Z_L and, Z_{in} respectively. The impedance Z_{in} is the impedance seen when the subject terminals are driven forming a radiating antenna with ohmic efficiency varying from zero to unity and with directivity gain $D(\theta\phi)$. Note that

$$D(\theta, \phi) = \frac{4\pi r^2}{P_{\text{rad}}}\, p(r, \theta, \phi) \tag{4}$$

where $p(r, \theta, \phi)$ is the power density radiated in the (θ, ϕ) direction, and P_{rad} is the total radiated power. The ohmic efficiency is

$$\eta = P_{rad}/P_{in} \tag{5}$$

where P_{in} is the power supplied by the internal source when the subject terminals are driven interior to the electrical system. The quantity p appearing in (2) represents the polarization matching factor with a value varying from zero to unity. For linear polarization incident on the system and linear polarization transmitted from the driven interior terminals, the polarization factor is simply the magnitude of the cosine of the angle between the illuminating and the radiated fields.

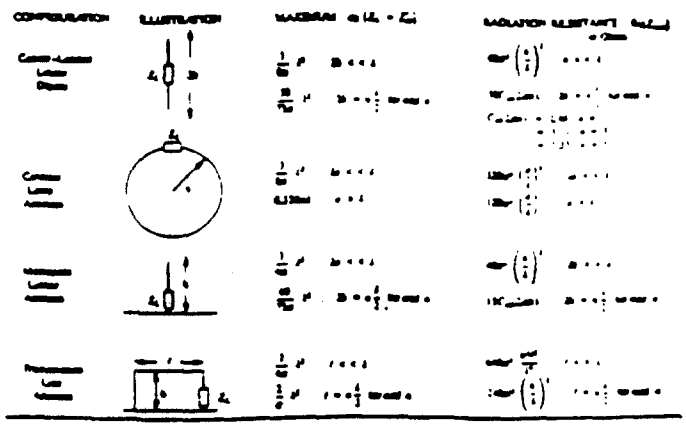
The receiving cross-section expression (2) is the most general formula characterizing the transfer of power from an incident field to a specific set of terminals. Note that for an aperture antenna the receiving cross section is the same as the effective area that is sometimes used for characterizing receiving antennas. Using (2) in (1) with

$$p^{inc} = |E^{inc}|^2/\zeta 0 = \zeta_0 |H^{inc}|^2 \tag{6}$$

where $\zeta_0 \approx 120\pi$ is the intrinsic impedance of free space, which relates the incident power density to the incident electric and magnetic field strengths, enables the determination of the received power in terms of the incident field strength. Table 1 presents the maximum receiving cross sections for certain canonical configurations.

Using the maximum receiving cross section provides an upper bound on the power coupled to the inferior terminals. From Table I, it appears that for a set of interior terminals the maximum power that can be coupled decreases with increases in frequency. This is somewhat misleading since the efficient extraction of power from an electrically small antenna is very difficult because of the very small resistive part of the antenna impedance, the radiation resistance. For example, the radiation resistance of a 10 cm dipole at 300 MHz (1 m wavelength) is only 2 Ω (see Table I for formula). Whereas the corresponding radiation resistance at 4.5 GHz is about 93 Ω (again see Table I for formula).

TABLE I
RECEIVING CROSS SECTIONS (EFFECTIVE AREAS) AND RADIATION RESISTANCES FOR A FEW WIRE CONFIGURATIONS [17], [13], [14]



III. TEM MODE EXCITATION

Using numerical solution techniques to determine the currents induced on transmission line configurations at microwave frequencies becomes computationally intensive as the electrical length increases. A recent study by Tabet *et al.* [7], utilizing the NEC code, shows that varying segment lengths exponentially away from sources, from 0.01λ to 0.35λ, and holding the 0.35λ segment length over the remainder of the structure, where the current does not vary rapidly yields reasonably accurate results. Even with this scheme, the analysis may become computationally intensive.

Adams and colleagues [5] performed numerical studies of field-to-wire coupling for a few antenna configurations illuminated at microwave frequencies. They found that the wire currents were developed in a pattern consisting of standing waves and traveling waves where the peak currents tended to remain relatively constant as the frequency increased. Their results were obtained for cases where the direction of the incident microwave beam and the polarization were chosen to yield the greatest peak currents. When they considered transmission line antenna configurations, their results indicated that the higher order (waveguide) mode excitation contributed little to the induced wire currents, even when the transmission-line separation was several wavelengths. This result seems to be confirmed also by Barnes and Stevens [6]. Consequently the subsequent analysis is directed toward obtaining only the TEM mode currents. Note that Table I provides the maximum receiving cross section and radiation resistance for a simple transmission antenna configuration for $h << \lambda$

A. Wire Over a Ground Plane

In order to determine the transmission line response when $h \geq \lambda$, consider a transmission line that is formed by a wire parallel to a ground plane with arbitrary termination impedances as shown in Fig. 1. Following the procedure of Taylor *et al.* [8], it is easily shown that the TEM mode current in the Z_1 termination is for a general electromagnetic field illumination,

$$I_1 = \frac{1}{D}\int_0^l K(z)[Z_c \cosh(\gamma z) + Z_0 \sinh(\gamma z)]\,dz - \frac{1}{D}[Z_c \cosh(\gamma \ell) + Z_0 \sinh(\gamma \ell)]\int_0^h E_z(x, \ell)\,dx + \frac{Z_c}{D}\int_0^h E_z(x, 0)\,dx \tag{7}$$

where the wire extends from $z = 0$ to $z = \ell$ along the ground plane at a height $x = h$ above the ground plane at $x = 0$, and

$$E_z(x, z) = 0.5[E_z^{inc}(x, z) + E_z^{ref}(x, z)] \tag{8}$$

$$D = (Z_c Z_0 + Z_c Z_1)\cosh(\gamma \ell) + (Z_c^2 + Z_0 Z_1)\sinh(\gamma \ell) \tag{9}$$

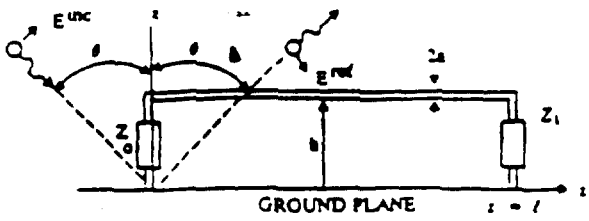


Fig. 1. Arbitrarily terminated transmission line formed by a wire parallel to a conducting plate. An incident plane wave and the ground reflected plane wave are shown.

$$K(z) = 0.5\left[E_z^{\text{inc}}(h,z) - E_z^{\text{inc}}(-h,z) + E_z^{\text{ref}}(h,z) - E_z^{\text{ref}}(-h,z)\right] \tag{10}$$

$$Z_c = \sqrt{(Z'_{\text{int}} + j\omega L')/(G' + j\omega C')} \tag{11}$$

$$\gamma = \sqrt{(Z'_{\text{int}} + j\omega L')(G' + j\omega C')}. \tag{12}$$

Here, E^{inc} is the direct field from the source and E^{ref} is the electric field of the signal reflected from the ground plane. The transmission line parameters Z'_{int}, L', G', and C' are the series internal impedance, series external inductance, shunt conductance and shunt capacitance per unit length, respectively. For the wire over a ground plane

$$Z'_{\text{int}} \approx \frac{1+j}{2\pi a}\sqrt{\frac{\omega\mu_0}{2\sigma_c\left[1-(a/h)^2\right]}} \tag{13}$$

$$G' = \frac{\sigma}{\epsilon}C' = 2\pi\sigma/\cosh^{-1}(h/a) \tag{14}$$

$$L' = \frac{\mu_0}{2\pi}\cosh^{-1}(h/a) \tag{15}$$

where a is the wire radius, σ_c is the wire conductivity, σ is the conductivity of the dielectric medium around the wire, and ϵ is the corresponding dielectric permittivity.

Results for various transmission line-illuminator-termination configurations are presented by Smith [9]. He considers electric and magnetic dipole sources as well as plane wave illumination. Formulas and graphical data are provided. However, the general trends of field-to-wire coupling can be seen from (7) by considering a specific illumination that yields relatively simple results.

Consider plane wave illumination such that the incident magnetic field is horizontal and perpendicular to the transmission line while the angle of incidence (measured from the vertical) is θ, see Fig. 1. Under these conditions, (7) yields for $Z_0 = 0$,

$$I_1 = \frac{2E_0 Z_c}{(\gamma^2 + \beta^2\sin^2\theta)D}\,\frac{\sin(\beta h\cos\theta)}{\beta\cos\theta} \cdot \left\{(\gamma^2+\beta^2)\sin\theta + \left[j\beta\gamma\cos^2\theta\sinh(\gamma\ell)\right.\right.$$

And for a lossless line $\gamma^2 = -\beta^2$. Then (16) yields

$$I_1 = \frac{j2E_0\sin(\beta\ell)}{Z_1\cos(\beta\ell) + jZ_c\sin(\beta\ell)}\,\frac{\sin(\beta h\cos\theta)}{\beta\cos\theta}e^{-j\beta\ell\sin\theta} \tag{17}$$

Here, E_0 is the amplitude of the incident electric field.

As seen from (17), the termination current will oscillate in frequency according to the $\sin(\beta\ell)$ term in the numerator with deep nulls and peaks in response. Also, at low frequency where $\beta h << 1$, the termination current will be proportional to h. As the frequency is increased, the wire current dependence will depend on h according to the $\sin(\beta h\cos\theta)$ factor. This will result in peaks and nulls in the response. The first null occurs for $\beta h\cos\theta = \pi$.

B. Two-Wire Line

A second configuration is considered to examine the relative importance of higher mode excitation. The configuration considered is shown in Fig. 2, which is similar to the structure analyzed by Leviathan and Adams [3]. Here, the line length is ℓ and the termination resistances are matched to the characteristic impedance of the two-wire line, i.e., $Z_0 = Z_1 = Z_c$. The current in Z_1 may be obtained from [9]

$$I_1 = \frac{1}{D}\int_0^\ell K(z)[Z_c\cosh(\gamma z) + Z_0\sinh(\gamma z)]\,dz - \frac{1}{D}[Z_c\cosh(\gamma\ell) + Z_0\sinh(\gamma\ell)]\int_0^d E_y(0,y,\ell)\,dy + \frac{Z_c}{D}\int_0^d E_y(0,y,0)\,dy \tag{18}$$

where

$$K(z) = -j\,E_0\sin\theta\,e^{-jk_y d/2}\sin(k_y d/2)\,e^{-jk_z z} \tag{19}$$

$$E_y(0,y,0) = -E_0\cos\theta\sin\phi\,e^{-jk_y y} \tag{20}$$

$$E_y(0,y,\ell) = -E_0\cos\theta\sin\phi\,e^{-jk_z\ell}e^{-jk_y y} \tag{21}$$

$$k_y = \beta\sin\theta\sin\phi \tag{22}$$

$$k_z = \beta\cos\theta. \tag{23}$$

Without loss of generality, the incident electric field is considered polarized parallel to the plane of incidence.

Substituting (19)–(23) into (18) yields

$$I_1 = 2E_0 e^{-jk_y d/2}\sin(k_y d/2) \cdot \left\{\frac{1}{2Z_c}\left[\frac{k_z - j\gamma}{k_z^2+\gamma^2}\sin\theta + \frac{\cos\theta\sin\phi}{k_y}\right]e^{-jk_z\ell} - \frac{Z_c}{D}\left[\frac{k_z - j\gamma}{k_z^2+\gamma^2}\sin\theta + \frac{\cos\theta\sin\phi}{k_y}\right]\right\} \tag{24}$$

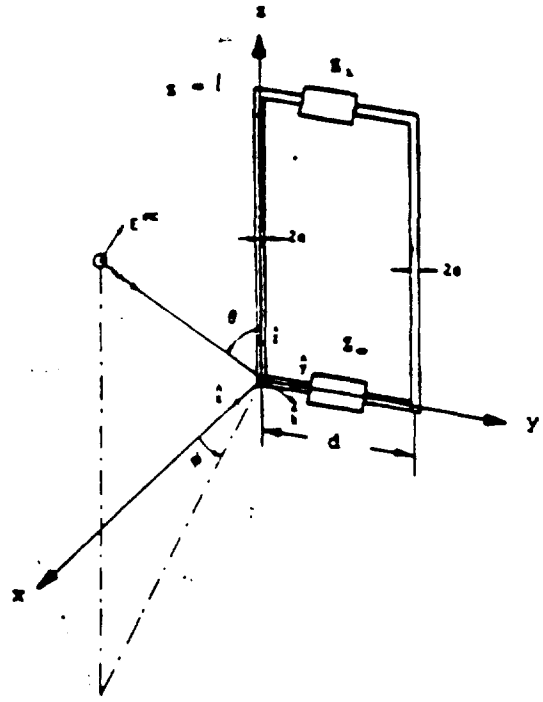


Fig. 2. Plane wave illumination of a terminated two-wire transmission line. The incident electric field is considered polarized parallel to the plane of incidence.

In general, $\gamma = \alpha + j\beta$ has a nonzero real part and

$$D \to \infty$$
$$\ell \to \infty.$$

Accordingly, the term in (24) with the D^{-1} multiplier vanishes for sufficiently large ℓ. Then approximating $\gamma \approx j\beta$ yields for the *half infinite* line length.

$$\left| \frac{I_1 \eta}{E_0 \lambda} \right| = \frac{\eta}{2\pi Z_c} \left| \frac{\sin(\beta d \sin\theta \sin\phi/2)}{\sin\theta} \right|. \tag{25}$$

The corresponding result for the *infinite* length two-wire line may be obtained by superposition. It is

$$\left| \frac{I_1 \eta}{E_0 \lambda} \right| = \frac{\eta}{\pi Z_c} \left| \frac{\sin(\beta d \sin\theta \sin\phi/2)}{\sin\theta} \right|. \tag{26}$$

The foregoing result is now compared with the results obtained from Leviatan and Adams [3]. Their analysis obtained not only the higher order mode contributions, but also the common mode contribution—the current components on the wires that are excited in phase. Fig. 3 exhibits the comparison of results. Since Leviathan and Adams show that their line current expressions, in the limit of small line separation, agree with the transmission line current expression derived by Lee [15], the departure of the line currents from the TEM mode current at low frequency, $d/\lambda < 0.2$, must be due to the common mode current. It is noted that the current induced on wire #1 exhibits a peak near $d/\lambda \sim$

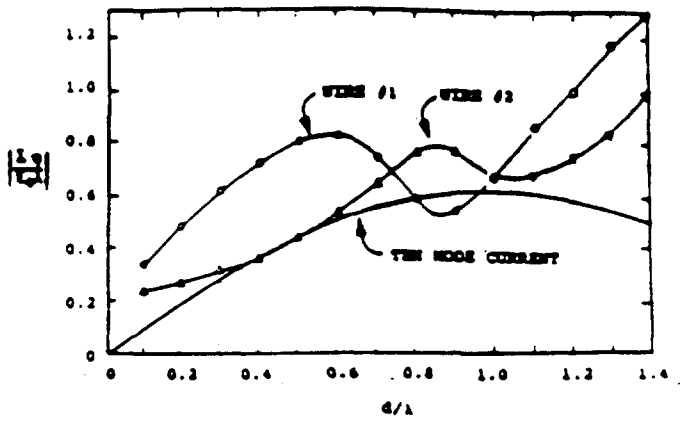


Fig. 3. Currents induced on a two-wire configuration from plane wave illumination versus wire separation for $d/a = 10$, and $\theta = \phi = \pi/4$.

0.8, while the TEM mode current peaks near $d/\lambda \sim 1.0$. Apparently the different peak locations must be related to the relative phase of the differential and common mode current contributions. Otherwise, reasonable agreement is obtained for a line separation as large as 1.25λ. Better agreement is expected for the "wire over a ground plane" configuration where there is no common mode current contribution.

As the line separation is increased to 2λ, the induced TEM mode current approaches zero. Consequently, the TEM mode approximation for the total current is not valid in that frequency regime.

IV. Measured Results

Microwave coupling to transmission line configurations has also been measured. Since the wavelength is near the characteristic dimensions of typical transmission line configurations, special considerations are often required. Moreover, an extension of the results to general configurations must be done with caution. With these precautions in mind, recent results will be discussed.

Anderson [10] has performed an experimental study of the power coupled to various transmission lines under illumination from 1–18 GHz. He considered 5 wire types with horizontal and vertical illumination and three heights above a ground -3/8", 2" and infinite (over absorber material). The 5 transmission line configurations included: a bare wire (BW), a twisted pair (TP), a standard RG58 coaxial cable (SC), an optimum braid RG58 (OC), and the shielded twisted pair (STP). With the incident illumination normalized to 1 mW/m^2, the maximum received power into 50Ω terminations was −30 dBm for BW, −42 dBm for TP, −80 dBm for OC, −70 dBm for SC and −70 dBm for the STP. Here, dBm is the power referenced to 1 mW. Usually the received power was greatest at low frequency (1–2 GHz) and relatively insensitive to wire height (less than 8-dB variation). This appears to be consistent with (17) for wire height variation. It is difficult to verify other conclusions since the line length and termination impedances are not provided.

Also, recently Brock *et al.* [11] modified the so-called IEMCAP program (*I*ntrasystem *E*lectromagnetic Compability

Analysis Program) to treat field-to-wire coupling from 1 GHz to 40 GHz. They incorporated measured data together with method of moments calculations. Results from the new algorithm appear to be much less conservative than those obtained from using transmission line approximations alone. The algorithm predicts that maximum coupling occurs for a line height of $\lambda/2$ and tends to hold that level of coupling for greater wire heights. This saturation coupling level decreases with frequency as $1/f$. These observations appear to be consistent with (17). The saturation coupling level may be the result of higher order modes contributing to the current when (17) predicts nulls.

There is a discrepancy between the results of Anderson and Brock *et al.* on how the microwave coupling to wires depends upon the wire height. This may be explained in part by the difficulty in obtaining accurate measurements for the low level signals such as those recorded by Anderson in determining the variation of the received power with wire height.

V. Coherence Effects

King and his colleagues [12] suggest that coupling to a given wire inside a shielded electrical system will involve a number of coupling mechanisms and multiple scattering. They suggest that the signal traveling from a given point of entry (POE) to a given terminal does so over many more or less random coupling paths as the frequency, angle of incidence or the polarization of the incident field changes. This is due to the manner in which the many cavity and cable resonance modes are excited, as well as many other factors such as cavity-to-cavity coupling. Further, in the case of coupling to a susceptible component pin, circuit trace and component resonances make the coupling path even more random-like, i.e., stochastic. Consequently, as the frequency changes, the phase as well as the amplitude of a signal arriving at a given terminal or pin via a given POE is likely to be a more or less stochastic process. Furthermore, the contribution of a given POE relative to other possibly contributing POEs may also be a stochastic process.

A multiport test object was constructed by King *et al.* and the coherence effect was studied experimentally. It was found that simple bounds on the receiving cross section can be formed by considering the induced voltages from each contributing POE simply added in phase, i.e., all sources are coherent.

VI. Conclusion

The general aspects of the excitation of wire structures under microwave illumination have been presented and discussed. Numerical, analytical and experimental data are provided. A simple procedure is presented for bounding the response of certain canonical configurations.

It has been shown that the TEM mode current can be used to estimate the total current induced on transmission line configurations under microwave illumination for line separations up to and exceeding a wavelength. Simple formulas and numerical results are provided. Two specific transmission line configurations are considered, a single wire with a ground plane return and a two-wire transmission line. Measured results are discussed and compared with theoretical results.

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E190

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Operant Behavior and Colonic Temperature of *Macaca mulatta* Exposed to Radio Frequency Fields at and Above Resonant Frequencies

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Five food deprived rhesus monkeys were exposed to 225-MHz continuous-wave, and 1.3-GHz, and 5.8 GHz pulsed radiation to determine the minimal power densities affecting performance. The monkeys were trained to press a lever (observing response) thereby producing signals that indicated availability of food. In the presence of the aperiodically appearing food signals, a deflection response on a different lever was reinforced by a food pellet. Continuous, stable responding during 60 min sessions developed and was followed by repeated exposures to radiofrequency radiation. The subjects, restrained in a Styrofoam chair, were exposed to free field radiation while performing the task. Colonic temperature was simultaneously obtained. Observing-response performance was impaired at increasingly higher power densities as frequency increased from the near-resonance 225 MHz to the above-resonance 5.8 GHz. The threshold power density of disrupted response rate at 225 MHz was 8.1 mW/cm^2; at 1.3 GHz it was 57 mW/cm^2, and at 5.8 GHz it was 140 mW/cm^2. These power densities were associated with reliable increases in colonic temperatures above sham exposure levels. The mean increase was typically in the range of 1 °C, and response rate changes were not observed in the absence of concomitant temperature increases. In these experiments increase of colonic temperature was a much better predictor of behavioral disruption than was either the power density of the incident field or estimates of whole body averaged rates of energy absorption.

Key words: operant behavior, observing responses, radiofrequency radiation, colonic temperature, rhesus monkeys

INTRODUCTION

The contemporary literature on biological effects of radiofrequency (RF) irradiation contains little information sufficient to predict thresholds of harmful behavioral effects in animals of different species at different frequencies. Although such irradiation has been shown to produce heating of both peripheral and internal body tissues that is dependent on the animal's mass and geometry and on frequency and intensity of the field [Michaelson et al, 1961], behavioral changes have not been as well characterized as the temperature deviations [for example, see the recent review by Stern, 1980]. Behavior has been shown to be affected by fields at both high and

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low power densities [Thomas et al, 1975], and behavioral thermoregulation is modulated even at relatively low power densities [Adair and Adams, 1980]. Nevertheless, few studies have attempted to quantify the relationship between thermal effect, behavioral changes, and various RFs. A major limitation is the unavailability of exposure chambers at appropriate and different RFs.

In those cases in which behavior has been investigated at different frequencies in the same organism by different researchers, different behaviors have often been examined thereby precluding generalization from one study to another [De Lorge, 1984]. Most behavioral experiments have used rats, thereby limiting the generality of findings. Behavioral measurements in these rat experiments have also tended to measure general motor activity as the primary index of a microwave effect. An assessment of the qualitative nature of a microwave effect is difficult to make when general motor activity is measured. For example, an increase in motor activity produced by microwaves fails to indicate either a beneficial or detrimental effect.

The qualitative nature of a behavioral effect can be assessed with behavior maintained by schedules of reinforcement [Catania, 1968] and such behavior has been found to be sensitive to microwave irradiation [Stern, 1980; Thomas et al, 1975]. Scheduled behavior can be arranged to simulate human behavior in specific cases. One such instance is performance of a vigilance task wherein an animal can be trained to produce observing-responses resulting in different stimuli that are to be detected [Holland, 1957].

An animal model much closer to man on the phylogenetic scale than the rat is the rhesus monkey *(Macaca mulatta)*. The rhesus monkey is also an excellent model for temperature sensitivity when applying the results to man [Kenshalo and Hall, 1974]. These characteristics and the fact that the rhesus is easily trained on schedules of reinforcement provide justification for using the rhesus monkey as a model for predicting effects of RF radiation on man. In addition recent reports on hyperthermia produced by exposing rhesus monkeys to RF radiation [Lotz, 1982] and dosimetric measurements of rhesus models [Olsen and Griner, 1981, 1982] provide information that allow construction of a relatively complete picture of the biological effects of microwaves.

The present study involved rhesus monkeys exposed at near resonant and above resonant frequencies while performing an observing response (vigilance task). The frequencies of irradiation were chosen to complement an earlier experiment in which rhesus monkeys performing an observing response task were exposed to microwaves at a frequency of 2.45 GHz [De Lorge, 1976]. The results of the present study in conjunction with the earlier study allow one to speculate on the behavioral effects of exposure of other animal species (particularly man) to nonionizing radiation at a corresponding range of frequencies and intensities. The results revealed increasingly higher thresholds of both behavioral disruption and increased temperature as the frequencies increased. Performance decrements typically were not observed unless colonic temperature increased by ~ 1 °C above the control level. The increases in body temperature were in general highly correlated with the behavioral decrement more so than were measures of absorbed energy, and much more so than were power density measures of the incident field.

MATERIALS AND METHODS

Subjects

Five male rhesus monkeys *(Macaca mulatta)*, offspring from the Naval Aerospace Medical Research Laboratory rhesus monkey breeding colony, served as subjects. The mean body mass (4.3–5.7 kg) of these animals increased over the 2-year duration of the study. The monkeys were food-deprived during the experimental stages of the study and were maintained at approximately 92% of their free-feeding body mass. Periodically, the animals were returned to ad libitum feeding so that new norms of 100% body masses could be established. The animals usually obtained their daily intake of food while performing in the experiment, but were supplemented in their home cage when necessary by a diet of Wayne Monkey Chow (Allied Mills, Chicago). Water was continuously available in the home cages.

Apparatus

Three microwave anechoic chambers, one for each frequency, were used. These chambers and their accompanying sources have been previously described in detail [De Lorge and Ezell, 1980; Lotz, 1982]. The chambers were shielded by metal and were lined with pyramidal absorber. Inside each chamber were two small loudspeakers (one for white noise, the other for discriminative stimuli) a closed-circuit TV camera, a 25-W incandescent lamp, and a Styrofoam chair. The noise level inside each chamber varied, but in general, with all devices active including the white noise, it was 74 dB on the C scale. The chambers were ventilated and the lamp was located directly above the center of the restraint chair. The primary differences among the three chambers were their different sizes. The 225-MHz chamber was the largest and the 5.8-GHz chamber was the smallest.

Continuous-wave RF energy at 225 MHz was provided by a military radio set (type GRT-3) in conjunction with a cavity type amplifier (MCL model 10270). A radar set (AN/TPS-1G, Hazeltine Corp, Little Neck, NY) provided the 1.3-GHz energy pulsed at 370 pps with a pulse duration of 3 μs. Another radar set (AN/TPS-4, Raytheon Manufacturing Co, Waltham, MA) provided the 5.8 GHz microwaves, pulsed at 662 pps with a pulse duration of either 0.5 or 2 μs. Custom made horns were used with the 225 MHz and 1.3 GHz systems, and a standard gain horn (Narda model 643, Narda Microwave Corp, Plainview, NY) was used with 5.8 GHz system. In all three chambers the front surface of the upright, seated rhesus monkey was irradiated by a horizontally propagated, vertically polarized beam.

Power density was measured in the absence of the animal and restraint chair by Narda microline isotropic probes. A model 8323 probe was used for fields at the 1.3 and 5.8 GHz frequencies, and a model 8624B probe was used for the 225 MHz frequency. The center of the animal's head was located 240 cm from the horn antenna in the 225 MHz study. This location corresponds to 0.78 times the far field distance. The animals in the experiments at the other two frequencies were positioned at various distances from the respective antennas; their locations were in the far field at low power densities and they were closer to the horn antenna at the higher power densities. In the 1.3 GHz experiment, the animals were never closer to the horn than 0.87 times the normal far field distance, and in the 5.8 GHz experiment they were never closer than 0.53 times the far field distance. The power densities reported in this paper refer to those measured in the region normally occupied by the center of a monkey's head while seated in the restraint chair. The center of the animal's head was aligned with the center of the horn in each chamber. Field uniformity at 225 MHz did not vary more than ± 7% over the space occupied by the restraint chair. Although the field was very uniform at the far-field distance in the other chambers. The 1.3-GHz field varied less than ± 10% over a 40-cm circle located at the center

of the animal's head. The 5.8-GHz field varied less than ± 20% over a similar space. As the animals were located closer to the horn the lower portion of their bodies received relatively less energy. This diminution was compensated somewhat by the fact that the animals were seated, so their legs were closer to the horn than was their torso.

A restraint chair was constructed of Styrofoam [Reno and De Lorge, 1977] and served throughout the study. The chair was equipped with two operant levers placed directly in front of the right and left hands, and a food receptacle was located on the top surface. The chair was equipped with an opening in the seat that allowed continuous monitoring of colonic temperature of the seated monkey. The chair was situated on Styrofoam guides in each of the chambers in a uniform manner. Food (750-mg Noyes Precision food pellet, P.J. Noyes Co., Lancaster, NH) could be delivered from outside the chamber via a plastic tube to a depression on the top surface of the chair, where it was obtained by the monkey by his tongue and lips.

A telethermometer (Yellow Springs Instruments (YSI) model 401, Yellow Springs, OH) was used to record ambient temperatures in all three chambers. Colonic temperature was recorded during a session by an electrothermic monitor (Vitek model 101, Boulder, CO) in the 225-MHz study, and by a telethermometer (YSI model 46 TUC and probe model 401) in the experiments at the other two frequencies. The probes were inserted approximately 10 cm past the anal sphincter of the monkeys after they were restrained in the chair and immediately prior to placement in the chamber. The YSI probes had been found not to be perturbed by microwaves at the two higher frequencies during placement in the animals.

Method

The animals were trained to press the two levers by the method of approximations [Catania, 1968]. Details of training and a description of the specific task can be found in De Lorge [1976] and De Lorge and Ezell [1980]. The final performance required a monkey to press the right lever repeatedly (an observing response). Each press produced either a 0.7-s tone at a low pitch (860–1,000 Hz) or a longer tone of 1.2-s at a higher pitch (1,250–3,703 Hz). The loudness of the tones was approximately 60 db on the C scale but specific frequency and loudness varied with the different chambers. The low-pitched tone (the signal that food was not available, S^{Δ}) occurred most frequently, whereas the higher tone (the signal indicating that food was available, S^{D}) occurred randomly on the average of once every 30 s. No tones occurred without a lever press. If the left lever was depressed (a detection response) during sounding of the higher-pitched tone, the tone would stop and a food pellet was delivered. Left-lever responses at other times produced a 5-s period during which right-lever presses produced only the low tone. If the left lever was not pressed during the high-frequency tone, the tone extinguished after 1.2 s and the reinforcement schedule would recycle. Right-lever presses during presentation of either tone had no consequences. The original reinforcement schedule involved a random interval averaging 1 min, but, as the study progressed, the animals' behavior became more efficient resulting in the shorter intervals between receipt of reinforcers.

The experiments occurred in the following order: A total of 328 sessions was devoted to the 1.3-GHz study; 133 sessions, to the 5.8-GHz study; and 53 sessions, to the 225-MHz study. Approximately 70 days separated each study. Sessions lasted for 60 min, and the animals were exposed, when scheduled, during the session.

Approximately 5 min was required to remove the animal from its transport cage and to restrain it in the chair while a temperature probe was inserted. The same amount of time was required to reverse the procedure following a session. Approximately 2 min elapsed from the time the animal was placed in a chamber until the experimental session was started. A PDP-8A computer in an adjoining room was used to control the experiment and to record data.

The animals were not exposed until several sessions of stable performance on the observing-response task had occurred. Typically, three exposures at each power density were scheduled for each subject. Exceptions to this procedure will be mentioned where appropriate. Power densities ranged from 5 to 11 mW/cm^2 in the 225-MHz exposures, from 20 to 95 mW/cm^2 in the 1.3-GHz exposures, and from 11 to 150 mW/cm^2 in the 5.8-GHz exposures. In several instances the power densities indicated in the results (Figs. 2-6) consist of means based on two separate exposure distances in the 1.3- and 5.8-GHz experiments. For example, the power density of 83 mW/cm^2 referred to in the 1.3-GHz study is actually a mean of several exposures at both 80 and 85 mW/cm^2. In general, exposures occurred in an ascending order. However all exposure sessions were followed by sham-exposure sessions, and following a weekend, if behavior was not at baseline levels, stable baselines were reestablished prior to microwave exposure. Additional exposures at most frequently used power densities occurred in a descending order near the end of each experiment. The exposure sequence in the 225-MHz study was random except that the initial power density was the lowest at which the animals were exposed. The different power densities in the 1.3- and 5.8-GHz experiments were achieved by moving the animals along the Z axis of the horn antenna, and at the lower two power densities by decreasing pulse duration in the 5.8-GHz experiment.

RESULTS

As a matter of convenience, the results of these studies are presented beginning with results of exposure at the lowest frequency and proceeding to the highest. Approximately 100 sessions elapsed before all five animals were consistently responding within and between sessions on the observing-response lever. Four of the animals reduced their rates of emitting incorrect responses on the detection lever to low and stable levels. One animal, subject 10, always made an excessive number of incorrect detection responses throughout the study, and at times these rates were greater that the observing-response rate. Nevertheless, this animal's performance was generally affected by microwaves in the same manner as was the behavior of the other animals.

The most obvious effect on performance while the animals were exposed at above-threshold microwave power densities was a reduction in observing-response rate. An example of typical performance is shown in Figure 1. This figure contains cumulative records of pressing on the observing-response lever by monkey 13 when exposed to 1.3-GHz microwaves. Selected power densities are indicated on the right and session numbers are shown at the top left corner of each set of records. Sham sessions occurred on one day followed by irradiated sessions the next day. The response pen stepped upward with each observing response and the response line reset after 280 responses (indicated at lower left) or when the session ended at 60 min (indicated by horizontal line at bottom). Hatch marks on the response line (slanted lines) denote reinforced detection responses. Deflections on the horizontal lines

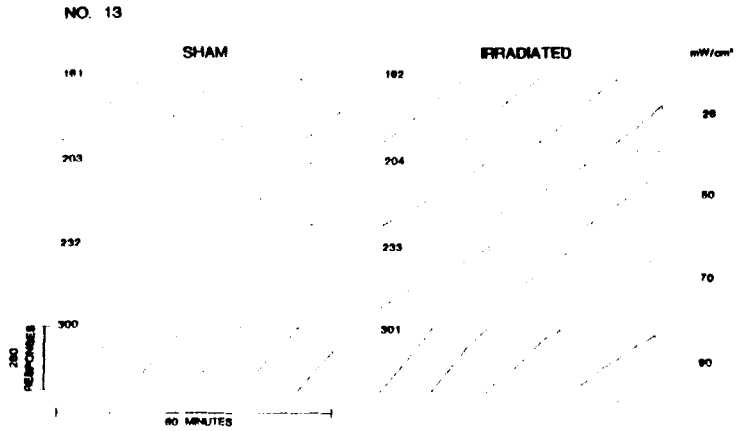

Fig. 1. Cumulative records of observing-responses of subject 13 when exposed to 1.3-GHz microwaves. A representative selection of exposures at various power densities as indicated in the right margin is shown. The numbers at the left of each record denote the session number. Data from sessions of sham irradiation are on the left, and those from associated sessions of irradiation are on the right.

denote the S^D. As observed in Figure 1 response rates during irradiation sessions were reduced beginning at 50 mW/cm^2, and this difference became somewhat greater in the latter part of each session as the power density increased. Another aspect of responding while exposed to microwaves was the more erratic pattern on the cumulative record. Animals frequently stopped responding completely. This change in pattern was greatest at 255 MHz when animals paused for as long as 15 min and often stopped responding for the last half of a session at 10 mW/cm^2. There was less of an effect when the monkeys were exposed at 5.8 GHz. At this latter frequency there was more of a gradual diminution of responding when the monkeys were exposed at the highest power densities and erratic response patterns were less obvious than during the 1.3-GHz exposures.

The averaged performance indices show a more definitive picture of behavioral changes than do the cumulative records alone. Figure 2 illustrates the ratio of observing-responses during irradiation to observing-responses during the previous sham session. At 225 MHz, there was a graded effect as the power density increased, although decreased responding was not reliably established until power density was elevated to 7.5 mW/cm^2. A large decrease in responding was evident at 10 mW/cm^2.

When the monkeys were exposed to 1.3 GHz, the graded effect was not observed. At 45 mW/cm^2 the animals actually increased rates of responding; however, this increase was primarily associated with the data of one animal (No. 10). At 50 mW/cm^2, no effect on observing-response rate was evident in the averaged data in contrast to the data of one monkey (Fig. 1), whereas at 63 mW/cm^2 the effect appeared in full force and became only slightly more pronounced as the power density increased to 93 mW/cm^2.

At 5.8 GHz, the observing-response rate was more variable, with rates sometimes increasing at some intermediate power densities. Such increases were not large

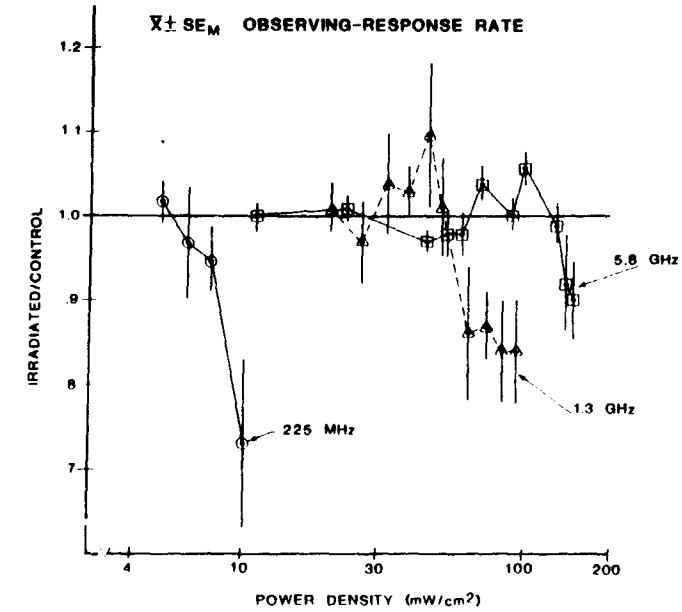

Fig. 2. Mean ratios of the number of observing-responses made during irradiation sessions to those made during sessions of sham irradiation. The horizontal line at 1.0 indicates no difference between the two conditions. Field frequencies are indicated by different symbols, and power densities are indicated on the abscissa. Vertical bars indicate the standard error of the mean. Each point represents the mean of means from five monkeys exposed three times. Exceptions to the number of subjects and exposures occurred at the highest power densities: sometimes only four subjects were exposed, or some subjects were exposed only twice.

and invariably depended on the responses of one animal. The only substantial decreases in response rate were first seen at 140 mW/cm^2 and became greater at 150 mW/cm^2. By observing the power density scales in Figure 2 one can see that as the frequency of the field increased, higher power densities were required to affect observing-responses.

The highest power density associated with a threshold performance decrement at 5.8 GHz, 150 mW/cm^2, also produced minor burns on the faces of three of the five monkeys. The worst of these burns occurred between the eyes and along the orbitonasal area. The erythema generally disappeared within a few days, except in one animal that continued to irritate the burned skin by removing scabious material. Similar facial burns did not occur at any other frequency.

The detection-response rate on the food lever was not consistently affected by microwaves at any frequency. No effect was observed at 225 MHz or 5.8 GHz, and only at power densities of 83 mW/cm^2 or higher was an effect, a decreased response rate, observed on occasion at 1.3 GHz.

There is one interesting finding regarding detection behavior that is illustrated by the irradiation-to-sham-irradiation ratios of detection-response latencies (Fig. 3).

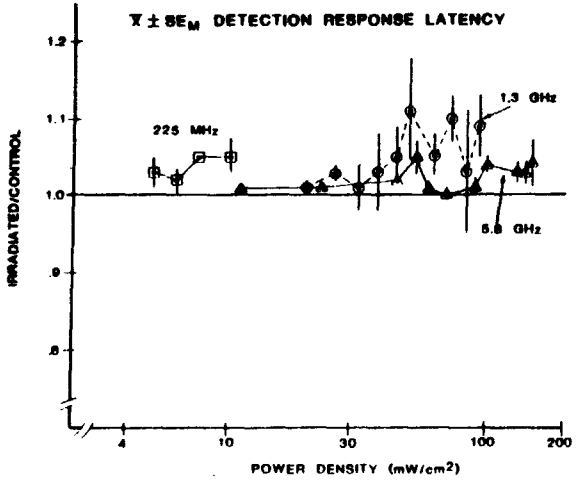

Fig. 3. Mean ratios of detection-response latencies during irradiation versus that of associated sessions of sham irradiation.

The effect was small but consistent. At all three frequencies and at most power densities the monkeys tended to take longer to make a detection-response during an irradiation session as compared with response latencies during sham-irradiation sessions. This ratio increased with increases in power density at all frequencies, although not in a linear fashion, and the correlation coefficients were significant at the .05 level in the cases of 225 MHz and 1.3 GHz ($r = .81$, $df = 3$; $r = .51$, $df = 10$) but not in the case of 5.8 GHz ($r = .41$, $df = 9$). Note also the decrease in the variance of these ratios as the animals progressed from their initial exposures at 1.3 GHz to 5.8 GHz and finally to 225 MHz.

Another effect was found in the postreinforcement pause (pause after a reinforced detection-response). When converted into ratios of mean pauses during irradiated sessions to mean pauses during sham-irradiation sessions, a graded effect was observed at the 225-MHz exposures shown in Figure 4. The animals paused longer during irradiated sessions and the pauses increased with the power density. Although a similar effect was observed at 1.3 GHz the pauses did not increase reliably until power densities were 63 mW/cm^2 or greater, and the increase did not vary closely with increases in power density. The effect of 5.8 GHz was variable and the only large difference in pause times was seen at 150 mW/cm^2. Even at that power density the pause time was not as substantially affected by microwave exposure as had occurred at the other frequencies.

Associated with the various performance changes were changes in colonic temperature as a function of exposure to the different frequencies. Figure 5 illustrates the average increases in colonic temperature as a function of power density and of the three different frequencies. The ordinates of each of the three curves indicate the mean temperature difference between increases that normally occurred during a 60-min session of sham irradiation and those that occurred during the respective exposure

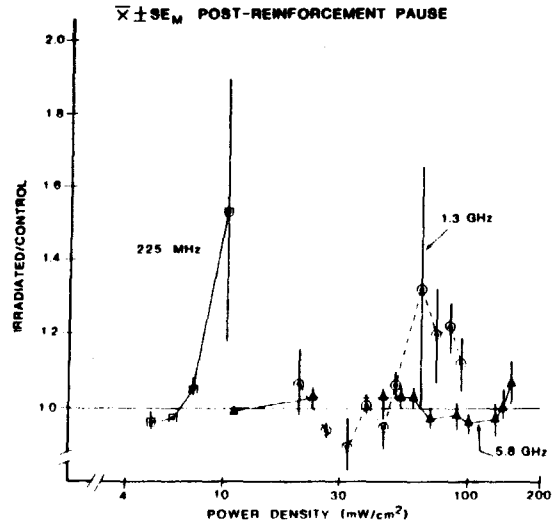

Fig. 4. Mean ratios of postreinforcement pause time during irradiation versus that of associated sessions of sham irradiation.

session. No error bars are shown but the standard error of the mean was typically 0.2 °C or less. The mean animal temperature at the start of exposure was 38.6 °C and an average increase of 0.15 °C generally occurred during the 60-min sham session. The curves in Figure 5 correspond to the lines of best fit as denoted by the various formulas shown in the figure. Frequency is indicated by arrows pointing to the appropriate curve. The curve formula is shown in brackets beneath the frequency designation. The exponential curve at 225 MHz is distinctly different from the curves at 1.3 and 5.8 GHz. Note that the highest temperature increases were observed at 225 MHz. Temperature curves for squirrel monkeys [De Lorge, 1979] and rhesus monkeys [De Lorge, 1976] exposed at 2.45 GHz also displayed exponential curves that were somewhat different from the present data. The 2.45-GHz exposures resulted in curves that were relatively flat initially and then accelerated dramatically as ΔTs reached 1 °C.

Estimates of the absolute threshold for disruption of observing response rates in terms of power density were made by taking the midpoint between the power density where no difference in rates occurred among irradiated and sham sessions and the power density where an obvious difference did occur in the two conditions (see Fig. 2). Performance during an irradiation session was judged not different from that of a sham-irradiation session if the standard error bars overlapped the equal-ratio line. The highest power density at which this occurred was designated the "no-difference" estimate. The judgment of an obvious difference in performance between sham-irradiation and irradiation sessions was made by selecting the power density at which a 10% of greater difference occurred between the two conditions, and the corresponding error bars did not overlap either the equal-ratio line or the error bars of the no-

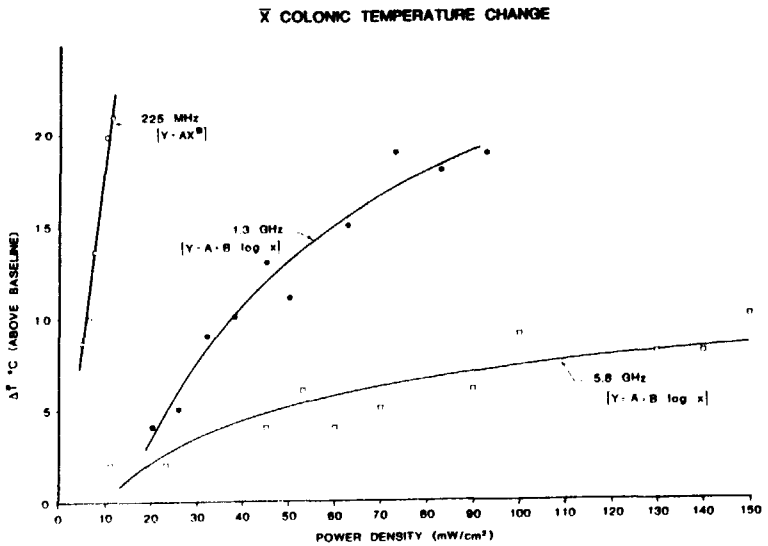

Fig. 5. Mean increases of colonic temperature above control (sham irradiation) levels as a function of power density (abscissa) when monkeys were exposed for 60 min at the various frequencies. Frequencies are indicated by arrows pointing to respective curves. The line-of-best-fit formula is in brackets below the frequency designation.

difference estimate. These midpoints or estimates of absolute thresholds are 8.1 mW/cm^2 at 225 MHz, 57 mW/cm^2 at 1.3 GHz, and 140 mW/cm^2 at 5.8 GHz. A threshold of 67 mW/cm^2 at 2.45 GHz was obtained from an earlier experiment [De Lorge, 1976].

The minimal power densities associated with 1 °C increments in colonic temperatures were also calculated at each microwave frequency. A similar calculation was made for the previous experiment in which the 2.45-GHz field was used and these data illustrate that an almost linear relation exists between power density and frequency when using a 1 °C colonic temperature rise as a measure of a biological effect of microwaves. The data points for temperature of the combined experiments were transformed into normalized specific absorption rates (SAR) by dividing estimates of SAR by the corresponding power density. The results are shown in Figure 6. The SAR at 5.8 GHz was obtained on flesh-simulating material by this investigator, and that at 225 MHz and 1.3 GHz was obtained on saline models by Lotz [1982]. The SAR estimate at 2.45 GHz was derived from formulas in Durney et al [1978]. Obviously more energy per milliwatt of power density was absorbed at 225 MHz than at the other frequencies, and the rate of energy absorption was an inverse function of frequency. Although more energy per milliwatt of power was absorbed at 225 MHz, substantially less absorbed energy was required to raise colonic temperature 1 °C (2.5 W/kg). In fact, approximately twice the energy absorption was required to raise temperatures 1 °C at the other three frequencies (4–5 W/kg). Power density requirements, on the other hand, were as much as 6, 10, and 24 times as great at 1.3,

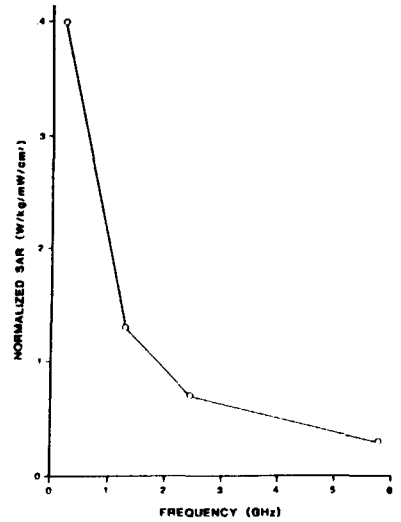

Fig. 6. Normalized specific absorption rates (SAR) of energy absorbed as a function of microwave frequency. The SAR is expressed in terms of (W/kg)/(mW/cm^2) as shown on the ordinate. This graph illustrates that a monkey exposed to a 225-MHz field at 10 mW/cm^2 would be absorbing energy at a rate of 4 W/kg. The 2.45-GHz point is from an earlier experiment [De Lorge, 1976].

2.45, and 5.8 GHz, respectively, than was needed at 225 MHz to raise colonic temperature 1 °C.

DISCUSSION AND CONCLUSIONS

Several consistent relationships have emerged from the foregoing experiments. Disruption of the observing-response, a behavior predicated on highly motivated performance, by microwave irradiation was closely related to increases in core temperature. The relationship is no doubt dependent upon various factors but, invariably, this behavior was not greatly disrupted unless body temperature increased by ~ 1 °C, or unless an animal was suffering superficial burns or was bothered by facial skin irritation. Other aspects of operant behavior such as the detection-response rate and post-reinforcement pause failed to show this relationship.

The results of this study illustrate that predictions of biological effects based solely on power density are poor. Similarly, the information shown in Figure 6 reflecting the dependence of SAR on frequency demonstrates that predictions based on normalized whole-body energy absorption are not very useful. A contribution of Don R. Justesen (Fig. 7) illustrates the relative stability of power-density and SAR measures corresponding to response-rate disruption thresholds as determined from the same data that Figure 6 was based on. An assessment of the efficiency of the two measures as predictors is made by comparing the ratios of the highest SAR (left ordinate) to the lowest with a similar ratio of the highest power density (right ordinate) to the lowest. The ratio, 17.5, associated with the power density measure is clearly

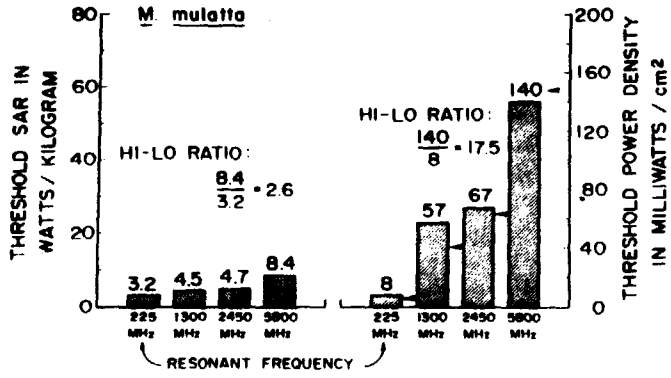

Fig. 7. Observing-response disruption thresholds in terms of SAR (left ordinate) and power density (right ordinate). Hi lo ratios correspond to relative SAR and power density values normalized to the near-resonant frequency of 225 MHz. The values above the bars are means based on five rhesus monkeys. The triangles in the right-hand portion of the figure correspond to the scale on the right and indicate the minimal power density needed to produce a ΔT 1 °C of colonic temperature. Don R. Justesen created this figure and has given his permission for its use in the present article.

larger and hence less efficient than the ratio, 2.6, associated with SAR. The power densities producing a 1 °C increment in colonic temperature parallel those associated with behavioral disruption as indicated by the arrowheads in Figure 7. By all accounts SAR is obviously a better predictor of response disruption than power density, but in both cases one has to take frequency into consideration. A more reliable, single index of behavioral disruption is a ΔT of colonic temperature of ~ 1 °C. Other investigations based on other animals, other frequencies, and other exposure durations might yield different outcomes although research in our laboratory has consistently substantiated the present findings [De Lorge, 1983].

The different rates of heating as illustrated by the power-density and temperature curves of Figure 5 indicate that various frequencies probably produce body temperature increases in various idiosyncratic ways. My speculations regarding these findings are that the 225-MHz data reflect a resonance heating effect by which an animal has extreme difficulty thermoregulating because blood is heated throughout the body and there is no way to replace heated blood with cooler blood.

The 2.45-GHz data may reflect potential hot-spot heating in the center of the rhesus head. According to Kritikos and Schwan [1975], animals of the physical dimensions of *M mulatta* (whose brain radius is greater than the 2.45-GHz wavelength in the brain—3.5:2 cm) should have a hot spot situated somewhat behind the center of the brain. Investigators have found localized heating exactly in the center of the head of a rhesus cadaver [Burr and Krupp, 1980] and in the center of the head of a model of a rhesus monkey [Olsen et al, 1980] at 1.29 GHz. Weil [1975] reported that the peak internal heating potential of a multilayered, 3.3-cm radius sphere is greater at 2.45 GHz than at the other three frequencies referred to in this study. Weil's [1975] research also documents the existence of a hot spot in front of the center of a sphere similar in size to the rhesus monkey brain. These hot spots have ratios of inner vs surface heating of approximately 4:1. If these hot spots do exist in the rhesus monkey

head at 2.45 GHz, the temperature curve obtained previously [De Lorge, 1976] might have been produced by a failure in the animal's thermoregulating mechanism at the highest power density and a facilitation of such mechanisms at the lower power densities. The curves at 1.3 and 5.8 GHz may illustrate normal thermoregulation in the monkeys; limbs or skin are not only differentially heated at these microwave frequencies, but are heated to a much greater extent than is the interior of the head [Burr and Krupp, 1980; Olsen et al, 1980]. At neither 1.3 nor 5.8 GHz were the animals of the present study ever exposed at power densities associated with ΔTs larger than 2 °C. However, at both 225 and 2,450 MHz, the animals did exhibit ΔTs in excess of 2 °C.

The results of the present study when applied to animals of other species—for example, man—will allow one to predict the general effect on behavior while an organism is being irradiated at near-resonant and supraresonant frequencies. No doubt additional research is necessary to validate such a claim, but with use of elevated body temperature as a general indication of the level of microwave energy absorption, predictive curves similar to those generated in the present study could be constructed.

ACKNOWLEDGMENTS

Mr. Clayton Ezell was responsible for building the restraint device and its holder, and for the daily routine of conducting these animal experiments. His assistance was invaluable and the completion of this series of studies could not have occurred without him.

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The animals used in this study were handled in accordance with the principles stated in the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Animal Resources, National Research Council, DHEW, NIH Publication No. 80-23, 1980.

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Thermal Action of 2.45 GHz Microwaves on the Cytoplasm of Chinese Hamster Cells

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In order to demonstrate possible specific effects of microwaves at the cellular level V-79 Chinese hamster cells were exposed to 2.45-GHz radiation at power levels of 20–200 mW/cm^2 and at specific absorption rates of 10–100 mW/g. Intracellular cytoplasmic changes were observed by fluorescence polarization using a method based on the intracellular enzymatic hydrolysis of nonfluorescent fluorescein diacetate (FDA). At levels of absorbed energy below 90 J/g, modifications of microviscosity and mitochondrial state were absent, but a slight stimulation of enzymatic hydrolysis of FDA was observed which may be explained by microwave-induced alterations of cellular membranes possibly due to differences in heating pattern of microwaves compared to water-bath heating. At levels of absorbed energy above 90 J/g, the decrease of enzymatic hydrolysis of FDA, increase in degree of polarization, and increase of permeation of the fluorescent marker correlated well with the decrease in cell viability as measured by the exclusion of trypan blue. At equal absorbed energy, microwaves were found to exert effects comparable to classical heating except that permeation was slightly more affected by microwave than by classical heating. This suggests that membrane alteration produced by microwaves might differ from those induced by classical heating or that microwaves may have heated the membrane to higher temperatures than did classical heating.

Key words: 2.45-GHz radiation, fluorescence polarization, cytoplasm, Chinese hamster cells, microwaves

INTRODUCTION

In recent years, hyperthermia alone or in combination with radiotherapy has become an interesting tool for treating certain cancers [Hahn, 1978]. Local hyperthermia has been produced by hot water, microwaves, longer wavelength radiofrequency fields, or ultrasound [Hahn, 1978]. Among the methods used, microwaves are considered to be especially useful for obtaining efficient, well-controlled heating of certain tumors [Hornback et al, 1977; Johnson et al, 1979; Gaboriaud et al, 1981]. However, more information about possible specific biological effects produced by microwaves is needed to optimize the therapeutic effects of microwave-induced hyperthermia.

Specific effects of electromagnetic waves have been explored in various ways. Some authors have employed low power levels to avoid significant rise in temperature

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EPIDEMIOLOGICAL STUDIES OF RADIOFREQUENCY RADIATION EXPOSURE

A Report to the California Public Utilities Commission

**As Part of an Informational Workshop
on Cellular Telephone Transmitting Facilities
held
July 21, 1993
San Francisco, California**

by

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TABLE OF CONTENTS

		Page
I.	Introduction	1
II.	Cancer and Mortality	1
III.	Reproductive and Developmental Effects	17
IV.	Ocular Effects	17
V.	Summary of Studies	17
VI.	Methodological Issues	18
VII.	RF Epidemiological Data and Decision-Making	19
Bibliography		21
Appendix 1:	Some Terminology of Epidemiology	23
Appendix 2:	Viewgraphs Presented at Informational Workshop on Cellular Telephone Transmission Facilities, held by the California Public Utilities Commission in San Francisco, California on July 21, 1993.	25

TABLES

Table 1: Microwave Exposure Levels at the U.S. Embassy in Moscow 1

Table 2: Moscow Embassy Study -- Observed and Expected Number of Deaths, Standardized Mortality Ratios (SMRs), and 95% Confidence Intervals (CI) by All Causes of Death, Specified Causes of Death from Cancer, and Post for Male and Female State and Nonstate Department Employees Combined 3

Table 3: Number of Deaths from Disease and Mortality Ratios[a] by Hazard Number: U.S. Enlisted Naval Personnel Exposed to Microwave Radiation During the Korean War Period 4

Table 4: Mortality in Washington State and California: U.S. Federal Communications Commission (FCC) Amateur Radio Operator Licensees, January 1, 1979 to December 31, 1984 6

Table 5: Mortality of Rad Lab Staff and Physicians, Through December 31, 1974, for All Causes of Death and Cancers. Part A. Standardized Mortality Ratios (SMRs) for Staff Aged 25 Years or More at Entry, Expected Values Based on Rates in Physicians. Part B. Mortality Risk Ratios for Staff members vs. Physicians Using Cox's Proportional Hazards Model 11

Table 6: Age-Adjusted Mortality Rates Per 1,000 Person-Years for All Causes of Death and Selected Cancers for Rad Lab White Male Staff Members by Exposure Ranking Group Based on Predominant Division of Work, Followed Through December 31, 1986 12

Table 7: Incidence Rates Per 100,000 Per Year (1971-1980), for Polish Military Personnel Grouped by Work Exposure to Radiofrequency and Microwave Radiation and by Age 14

Table 8: Studies of Radiofrequency Radiation and Cancer in Adults 15

EPIDEMIOLOGICAL STUDIES OF RADIOFREQUENCY RADIATION EXPOSURE

I. Introduction

The purpose of this report is to briefly review the epidemiological literature concerning human exposure to radiofrequency electromagnetic radiation as part of an information gathering procedure by the California Public Utilities Commission with respect to cellular telephone transmitting facilities.

Because of the emerging public concern about any potential risk of developing cancer through the use of cellular telephones, this report focuses on studies about cancer incidence and mortality. Such studies are described in detail. Studies concerning other endpoints are only briefly described but have been reviewed in detail in an earlier report (U.S. EPA, 1984).

Cellular telephones operate at frequencies from 800-900 megahertz (MHz). However, epidemiological studies have largely examined exposures at other frequencies, chiefly those used for radar systems. The frequencies used for radar are higher. Amateur radio frequencies, also the subject of epidemiological investigations, are lower. There are, thus, no studies directly focused on cellular telephone frequencies, exposures, or usage. However, two studies underway at the National Cancer Institute are addressing cellular telephones and may provide useful information about potential health risks in the future.

To aid the reader, a brief glossary of important epidemiological terms is appended.

II. Cancer and Mortality

Lilienfeld et al. (1978) studied mortality and morbidity of Foreign Service employees and their dependents to assess the potential health consequences of microwave irradiation of the U.S. Embassy in Moscow. The microwave irradiation of the U.S. Embassy in Moscow was first detected in 1953 and subsequently varied in intensity, direction, and frequency over time. The frequencies ranged from 0.6 to 9.5 gigahertz (GHz) (Pollack, 1979; U.S. Senate, 1979). The measured average power densities over time are given in Table 1. The health status of Foreign Service employees and those from other agencies who had served in the U.S. Embassy in Moscow from 1943 to 1976 was compared with that of employees at eight other embassies or consulates in Eastern Europe over the same time period.

Extensive efforts were launched to identify and trace the populations. Information on illnesses, conditions, or symptoms were obtained from: (1) employment medical records, which were fairly extensive because of examination requirements for foreign duty, and (2) a self-administered health history questionnaire. Death certificates and other sources were used to ascertain mortality status. Standardized mortality ratios for various subgroups were calculated for each cause of death, were standardized for age and calendar period, and were specific for sex. Similar procedures were used to develop summary indices of morbidity.

Table 1: Microwave Exposure Levels at the U.S. Embassy in Moscow

Time Period	Exposed Area of Chancery	Power Density and Exposure Duration
1953 to May 1977	West Facade	Maximum of 5 $\mu W/cm^2$ 9 hrs/day
June 1975 to Feb. 1976	South and East Facade	18 $\mu W/cm^2$ 18 hrs/day
Since Feb. 7, 1976	South and East Facade	Fractions of a $\mu W/cm^2$ 18 hrs/day

Source: Lilienfeld et al., 1978.

A total of 4388 employees and 8283 dependents were studied. More than 1800 persons with 3000 dependents were employed at the U.S. Embassy in Moscow, and 2500 persons with more than 5000 dependents were employed at the comparison posts. Ninety-five percent of the employees were traced. Receipt of completed questionnaires was less successful, with an overall response rate of 52% for State Department personnel.

Based on information in medical records, various health problems were generally similar, with two exceptions. Moscow employees had a threefold greater risk of acquiring protozoal infections than comparison post employees. In general, both sexes in the Moscow group had somewhat higher frequencies of most of the common kinds of health conditions reported. Lilienfeld et al. (1978) stated, "However, these most common conditions represented a very heterogeneous collection, and it is difficult to conclude that they could have been related to exposure to microwave radiation since no consistent pattern of increased frequency in the exposed group could be found."

Some excesses were reported by Moscow employees in the health history questionnaire. Both sexes reported more eye problems due to correctable refractive errors. More psoriasis was reported by men and anemia by women. The Moscow employees, especially males,. reported more symptoms such as irritability, depression, difficulties in concentration, and loss of memory. It is possible, however, that a bias due to awareness of potential adverse effects is operating, since the strongest differences were present in the subgroup with the least exposure.

The observed mortality was less in both male and female employees than expected, based on U.S. mortality rates (Table 2). The male employees had lower mortality than did female employees. Cancer was the predominant cause of death in both sexes. The risk of leukemia was elevated both at Moscow [standardized mortality ratio (SMR=2.5)] and at comparison posts (SMR=1.8). Neither SMR was statistically significant. Comparison post employees had a statistically significant excess risk (SMR=3.3) of nervous system tumors. In general, the Moscow and comparison groups were similar in overall and specific mortality. However, the population was relatively young; it may have been too early to detect long-term mortality effects.

The authors concluded that no convincing evidence implicated microwaves in the development of adverse health effects at the time of the analysis. However, they noted the limitations inherent in the study: uncertainties associated with the reconstruction of the employee populations and dependents, difficulties in obtaining death certificates, a low rate of response to the questionnaire, and limited statistical power of the study. An important limitation relates to ascertainment of exposure. Unknowns relative to individual mobility within the embassy and variation of field intensities within the building are present in this study. No records were available on where employees lived or worked, so one had to rely on questionnaire responses to estimate an individual's potential for exposure. The highest exposure level [18 microwatts per square centimeter (μW/cm2)] was recorded for only 6 months in 1975-1976; thus, the group exposed to the most intense fields had the shortest cumulative time of exposure and of observation in the study. In any event, these intensities are considered to be very low. It is also not clear what exposures may have been experienced by employees at the comparison posts.

Robinette and Silverman (1977) and Robinette et al. (1980) examined mortality and morbidity among U.S. naval personnel occupationally exposed to radar. Records of service technical schools were used to select subjects for the study; the men graduated from technical schools during the period from 1950 through 1954. Exposure categorizations were made on the basis of occupational specialty. The exposure group (probably highly exposed) consisted of technicians involved in repair and maintenance of radar equipment. The "controls" (probably minimally exposed) were involved in the operation of radar or radio equipment. It was estimated from shipboard monitoring that radiomen and radar operators (in the low-exposure group) were generally exposed at less than 1 milliwatt per square centimeter (mW/cm2), and gunfire control and electronics technicians (in the high-exposure group) were exposed to higher levels during their duties. Over 40,000 veterans were included in the study and were about equally distributed in these two major exposure classifications. The mean age in 1952 of the low-exposure group was 20.7 years and of the high-exposure group, 22.1 years. In conjunction with naval personnel, an index of potential exposure, termed Hazard Number, was developed for a limited portion of the population. This number was based

Table 2: Moscow Embassy Study -- Observed and Expected Number of Deaths, Standardized Mortality Ratios (SMRs), and 95% Confidence Intervals (CI) by All Causes of Death, Specified Causes of Death from Cancer, and Post for Male and Female State and Nonstate Department Employees Combined

Cause of Death	Moscow			Other Posts		
	Number of Deaths		SMR	Number of Deaths		SMR
	Observed	Expected	(95% CI)	Observed	Expected	(95% CI)
All Causes (0.5, 0.7)	49	105.3	0.47 (0.4-0.6)	132	223.7	0.59
Malignant Neoplasms	17	19.0	0.89 (0.5-1.4)	47	41.1	1.1 (0.8-1.5)
Digestive Organs	3	4.6	0.65 (0.4-1.9)	11	10.8	1.0 (0.5-1.8)
Brain Tumors/CNS Neoplasms	0	0.9	0.0	5	1.5	3.3 (1.1-7.7)
Pancreas	1	1.0	1.0 (0.0-5.6)	1	2.2	0.5 (0.0-2.5)
Lung	5	5.8	0.86 (0.3-2.0)	11	12.2	0.9 (0.4-1.6)
Leukemia	2	0.8	2.5 (0.3-9.0)	3	1.7	1.8 (0.4-5.3)
Hodgkin's Disease	0	0.5	0.0	0	0.7	0.0
Breast	2	0.5	4.0 (0.5-14.4)	3	1.2	2.4 (0.5-7.0)
Uterus	1	0.2	5.0 (0.1-27.9)	0	0.0	0.0
Cervix	1	0.1	10.0 (0.3-55.7)	0	0.0	0.0

Source: Lillenfeld et al., 1978.

on the duty months multiplied by the sum of the power ratings [equipment output power of gunfire-control radars (ship) or search radars (aircraft)] where technicians were assigned.

Medical information was obtained through Navy and Veterans Administration records. Records were searched for information on: (1) mortality, (2) morbidity via in-service hospitalizations, (3) morbidity via Veterans Administration (VA) hospitalizations, and (4) disability compensation. Mortality was ascertained through the VA beneficiary system. Mortality ratios were calculated for both the low and the high group, standardized for year of birth and using the combined experience of both groups as the standard population.

For the low-exposure groups, mortality ratios were only slightly elevated for diseases of the circulatory system (1.07); the cancer residual, other malignant neoplasms (1.19); and the total residual, other diseases (1.08). Cancers of the digestive tract (1.14), respiratory system (1.14) and lymphatic and hematopoietic systems (1.18) were elevated for the high-exposure group, but none of the increases was statistically significant. The differences in mortality from malignant neoplasms of the lymphatic and hematopoietic system, although elevated, were not statistically significant.

As seen in Table 3, comparisons were also made within the high-exposure group across Hazard Number categories. In this case, only two comparisons were statistically significant: (1) the difference in respiratory tract cancer between those with a Hazard Number smaller than 5000 versus larger than 5000, and (2) the

Table 3: Number of Deaths from Disease and Mortality Ratios[a] by Hazard Number: U.S. Enlisted Naval Personnel Exposed to Microwave Radiation During the Korean War Period

Cause of Death	International Classification of Diseases (8th Rev.)	Low Exposure	Number of Deaths			
			High Exposure			
			Hazard Number			
			Total	0	1-5000	5000
All Diseases	000-796	325 (1.04)	309 (0.96)	63 (0.82)	160 (0.91)	86 (1.23)
Malignant Neoplasms	140-209	87 (0.96)	96 (1.04)	22 (0.99)	45 (0.90)	29 (1.44)
Digestive Organs	150-159	14 (0.85)	20 (1.14)	6 (1.49)	11 (1.14)	3 (0.78)
Respiratory Tract	160-163	16 (0.85)	24 (1.14)	4 (0.82)	10 (0.86)	10 (2.20)
Lymphatic and Hematopoietic System	200-209	29 (0.83)	26 (1.18)	6 (1.09)	12 (1.04)	8 (1.64)
Other Malignant Neoplasms	Residue	37 (1.19)	26 (0.82)	6 (0.78)	12 (0.70)	8 (1.17)
Diseases of Circulatory System	390-458	167 (1.07)	150 (0.93)	36 (0.94)	73 (0.83)	41 (1.17)
Other Diseases	Residue	71 (1.08)	63 (0.92)	5 (0.30)	42 (1.13)	16 (1.08)

Source: Robinette et al., 1980.

[a] Mortality ratio (in parentheses) standardized for year of birth; the combined experience of the low and high exposure groups is taken as the standard.

test for trend for all diseases combined. These results may be fortuitous since one or two positive findings might be expected when many statistical comparisons are made. Also, among men whose work received the highest hazard rating, elevated but nonsignificant risks were seen for all cancers combined (SMR=1.44), cancer of the lymphatic and hematopoietic system (SMR=1.64), and the residual category of miscellaneous cancers (SMR=1.17) as well as circulatory diseases (SMR=1.17). In general, the group with the highest hazard rating showed the highest SMR values.

Differential health risks with respect to hospitalized illness around the period of exposure were not apparent. Subsequent VA hospitalizations and disability awards provided incomplete information. Because the study focused largely on the use of automated VA record systems, it was not possible to determine non-Navy or non-VA hospitalizations, nonhospitalized conditions, reproductive histories, or subsequent employment histories.

The mortality data were obtained from death certificates. Obtaining background information from next-of-kin was not feasible. Smoking histories could not be obtained. Since actual individual exposure could not be reconstructed retrospectively, only an estimate of the potential exposure of the individuals was possible. Longer follow-up of the population would be useful.

Milham (1985b) investigated mortality among amateur radio operators who were members of the American Radio Relay League and whose deaths were reported in the League's magazine between 1971 and 1983. Proportional Mortality Ratios (PMRs) were calculated. Death certificates were obtained for 280 deaths in Washington State and for 1411 deaths in California. Expected values were generated using 1976 U.S. age-specific white male death frequencies. It was reported that PMRs were significantly elevated for all leukemias and for acute and chronic myeloid leukemia, considered separately and together. The author also noted a strong association between League membership and an occupation with potential exposure to EM fields. For cases from the State of Washington, the PMR for amateur radio operators who were also in electrical-exposure occupations was 2.64. The PMR for operators whose obituary did not mention such a job was 2.10. There may be biases in this study that could result from the method of identifying deaths from the League's magazine. For example, not all deaths of members may be reported. Deaths of ex-members may not be reportable, and the experience of ex-members may be different than that of continuing members. On the other hand, this study illustrates use of an innovative and accessible source of survival information useful for an exploratory study.

Milham (1988a) next investigated the mortality of 67,829 men licensed as amateur radio operators between January 1, 1979, and December 31, 1984, with the Federal Communications Commission (FCC) and who resided in California and Washington State. Deaths were sought in California and Washington State. SMRs were calculated using U.S. death rates to estimate expected deaths.

Observed deaths (Table 4) were significantly lower than expected for all-cause mortality and for mortality from all malignant neoplasms combined, pancreatic cancer, cancer of the respiratory system, all circulatory diseases combined, all respiratory diseases combined, and all accidents. SMRs were elevated for several cancer sites, and statistically significant excesses were found for specific sites in lymphatic and hematopoietic tissues, namely, acute myeloid leukemias (SMR=1.76) and multiple myelomas and other neoplasms of the lymphoid tissues, considered together (SMR=1.62). The latter category includes lymphomas other than lymphosarcomas and reticulum-cell sarcomas and Hodgkin's disease. It was not stated why this heterogeneous group of lymphomas was considered with multiple myelomas; separate analyses were not presented. It would seem to be more appropriate to evaluate deaths from multiple myeloma separately. However, Milham noted that the observed deficit for lymphosarcomas and reticulosarcomas (ICD8: 200) (SMR=0.47) nearly cancelled out the excess observed for deaths from other neoplasms of the lymphoid tissue (ICD8: 202.0). The risk of Hodgkin's disease (SMR=1.23) was also elevated but not significantly. For the leukemias, the SMRs were elevated at all sites for which deaths were observed, but, as mentioned, only deaths from acute myeloid leukemias were found to be significantly in excess.

This is a study with a large population (67,829 licensees; 232,499 accumulated person-years; 2485 deaths). The study found excess risks for various cancers of the lymphatic and hematopoietic system, especially acute myeloid leukemia, among amateur radio operators in Washington State and California, some of whom also may have experienced occupational exposure to EM fields. Excess risks are seen at several cancer sites but are especially concentrated at tissues of the lymphatic and hematopoietic system. The risk of acute myeloid leukemia was significantly elevated. Leukemias generally predominate in younger ages. Chronic leukemias were low.

Since licensing is required for amateur radio operators, enumeration of the population should be reasonably complete although licensing per se does not provide information on usage and exposure. Milham cites survey data that found that amateurs practice their hobby about 6 hours per week. It would seem that licensees would have exposure but the extent and degree is not clear and is probably variable. However, the potential for exposure misclassification would tend to bias estimates towards the null.

These results may or may not bear on risks from other frequencies, either of RF or ELF radiation, or even on the operating frequency. Amateur radios operate at the low end of the RF band of the electromagnetic spectrum. Modulations to lower frequencies are known to occur. Among Washington

Table 4: Mortality in Washington State and California: U.S. Federal Communications Commission (FCC) Amateur Radio Operator Licensees, January 1, 1979 to December 31, 1984

	Observed	Expected	SMR[a]
All Causes	2,485	3,478.9	71*
All Malignant Neoplasms	741	836.9	89*
Esophagus	22	19.4	113
Stomach	30	29.6	102
Large Intestine	88	79.0	111
Rectum	14	18.2	77
Liver	11	16.8	65
Pancreas	27	41.9	64*
Respiratory System	209	315.6	66
Prostate	78	67.6	114
Urinary Bladder	16	24.1	66
Kidney	19	20.1	94
Brain	29	20.8	139
Lymphatic and Hematopoietic Tissue	89	72.1	123
Lymphosarcoma/Reticulosarcoma	5	10.6	47
Hodgkin's Disease	5	4.1	123
Leukemia	36	29.0	124
Lymphatic	9	8.7	103
Acute	3	2.5	120
Chronic	6	5.5	109
Unspecified	0	0.8	0
Myeloid	18	12.9	140
Acute	15	8.5	176*
Chronic	3	3.5	86
Unspecified	0	0.9	0
Monocytic	0	0.6	0
Unspecified	9	6.7	134
Acute	6	3.4	176
Unspecified	3	2.5	120
Other Lymphatic Tissues	43	26.6	162*
All Circulatory Diseases	1,208	1,731.7	70*
All Respiratory Diseases	127	252.5	50*
All Accidents	105	164.5	64*

[a]SMR = Standardized mortality ratio.
*$p<0.05$
Source: Milham, 1988.

State licensees, Milham found that about 31% had jobs that involved potential EM-field exposure. Exposure to many different frequencies among part of the population is, thus, a possibility. Confounding exposures to chemicals are possible but could not be evaluated in this study. Further studies of amateur radio operators and their exposures may be warranted.

Milham (1988b) extended the above analysis by examining the mortality in the amateur radio operators according to their Federal Communications Commission (FCC) license class. Depending on one's level of expertise and experience, an individual will be granted one of five specific licenses, i.e., novice, technician, general, advanced, or extra. These license classes can, thus, serve to some extent as surrogates for duration of exposure. There were, as might be expected, some differences in age by license class. The average age of persons per class was: novice, 38.4 years; technician, 44.3 years; general, 49.5 years; advanced, 51.4 years; and extra, 49.2 years.

As in the previous analysis, SMRs were derived, and expected deaths were calculated by applying age, sex, race, year of death, and cause-specific U.S. mortality rates to age-stratified years at risk. Results were presented for each license class for a limited number of causes of death, i.e., all causes combined, all malignant neoplasms, brain cancer, all lymphatic and hematopoietic neoplasms, all leukemias, myeloid leukemia, and multiple myeloma and other lymphomas, considered together. The SMR for Hodgkin's disease was elevated in the earlier analysis, but mortality from Hodgkin's disease by license class was not reported in this paper.

All-cause mortality in all license classes was significantly lower than would be expected based on general U.S. mortality. SMRs for the most advanced license class, extra, were the lowest for all-cause mortality and for deaths from all malignant neoplasms. These results may indicate that some survival, socioeconomic, or other sort of bias may be operative. Generally, SMRs were lowest among the deaths of licensees in the novice class, the youngest group. Milham states that, in a sense, the novice class provides an internal control group. It would be interesting to see results in any further analysis of amateur radio operators, if novice operators are treated as a control subset of the population.

Other than the lower SMRs in the novice class, there is no other gradient in the SMRs by license class. In fact, SMRs are generally highest in the second level license class, technicians. This group had a statistically significant excess of deaths from all lymphatic and hematopoietic neoplasms, considered together. Deaths in the general license class resulted in a significantly elevated SMR for multiple myeloma and other lymphomas (202-203). With the exception of the novice class, SMRs were generally elevated, although not significantly, for all classes for the lymphatic and hematopoietic cancers reported. This excess risk was also true for deaths from brain cancer, but none of the observed increased SMRs was significantly different than expectation.

This study reanalyzes results from the earlier report by specified strata. These strata are surrogates for duration of exposure and, possibly, level of exposure. The greatest risk seems to be centered in the technician license class which is the class between novice and the more advanced license classes. This group was also intermediate in average age. The similarity in age for the three upper classes may mask any differences between those groups. No clear or distinct gradient by class was observed. It appears, therefore, that either license class may not be a good exposure surrogate (special unknown conditions may be operative for technician class licensees or their operational activity may differ), or class exposure may have nothing to do with cancer.

The Environmental Epidemiology Program in the State of Hawaii Department of Health (1986) investigated cancer incidence in census tracts with and without broadcast towers in Honolulu, Hawaii. This study was prepared for and reported to the City Council of the City and County of Honolulu in 1986.

Cancer incidence data was collected from the Hawaii Tumor Registry which registers all newly diagnosed cases of cancer in the State, except cases of squamous and basal cell carcinoma of the skin. Cases were identified from all hospitals, and private pathology laboratories as well as from searches of death certificates. Less than 2% of cases were identified solely from death certificates, and 94% of cases were microscopically confirmed.

Nine census tracts with broadcast towers and two without towers were examined. Expected number of cases for the census tracts were calculated using age- and race-specific rates for the State for the period 1979-1983. Standardized incidence ratios (SIRs), representing the ratio of observed to expected values, were computed, and tested at a significance level of p=0.01. Confidence intervals were not presented.

Age-adjusted rates and SIRs by sex were presented for each census tract and for tracts categorized as having towers (N=9) and not having towers (N=2). For all tracts with towers combined, the summary SIR for all cancers was 1.45 for males and 1.27 for females, and both values were significant at p=0.01. The SIRs for all cancers for both sexes in the two tracts without towers, taken together, did not differ from unity (male SIR=1.05, female SIR=0.85). The SIR, for leukemias were also elevated, but statistical significance at the p=0.01 level was not achieved. The SIRs for individual census tracts were significantly elevated for all cancers among males for eight of the nine tracts with towers, and not elevated for the two tracts without towers. Among females, the SIRs for all cancers was significantly elevated in only two census tracts, and these contained towers. Four other tracts with towers had elevated SIRs, but the excess was not statistically significant. Age-adjusted rates and SIRs were also examined in individual tracts-for leukemias in both sexes, but the number of cases was very small, making the results unstable. It was noted that there was a tendency for elevated SIRs for both sexes in census tracts with towers.

Because of its diverse ethnic populations, ethnicity and race are critical factors to consider in health studies in Hawaii. Race was a factor controlled in the study; however, the authors stated that small numbers precluded simultaneous adjustment for age, race, and sex. After adjusting for race, the SIR for all cancers for tracts with towers was 1.88 ($p < 0.01$). The SIR for all cancers for the tracts without towers was 1.07 and was not significantly elevated. For individual tracts, the SIRs were again significantly elevated for eight of the nine tracts with towers. The one tract with towers that did not demonstrate an excess in all cancers after adjustment for race was the same tract that did not show excess cancer after controlling for age and sex. For the two tracts without towers, the SIR for all cancers was significantly elevated in one (SIR=1.31) but not in the other, after adjusting for race; this did not occur in the analysis that controlled for age and sex although the one tract had consistently higher rates and SIRs than the other. Again, analyses for leukemias yielded very small numbers of cases in individual census tracts. No result was statistically significant, but tracts with towers, individually and overall,, presented elevated SIRs for leukemias.

In summary, using State rates as the standard schedule of rates, the observed deaths in tracts with towers for all cancers were significantly greater than expected values of cancer incidence. Tracts without towers did not appreciably differ.

This study is of a type that can be called an ecological study or that is of an ecological design. This means that relatively broad populations (here, from census tracts) are examined rather than individuals. It is difficult to determine causal relationships from such studies. And this difficulty is aggravated by typically weak measures of exposures. In this case, broadcast towers are located in certain census tracts, but it is not known if the cases of cancers were exposed to RF radiation or, if so, at what levels. The dichotomous estimate of exposure is only a crude proxy; some tracts have towers, others do not. Studies of this design also cannot usually address confounding factors except those that are broad demographic characteristics such as age, sex, or race, readily available from vital and census records.

The authors pointed out the limitations inherent in the study, including issues such as personal exposure, latency, duration of exposure, confounders, and so forth. They do not comment, however, on "urban/rural" differences that could be a factor in Oahu. The tracts with towers largely constitute downtown Honolulu and Waikiki; the tracts without towers are more centrally located on the island, have less dense population centers, and have some agricultural lands and mountainous/valley areas. The study does indicate that further investigation are warranted.

This study followed an EPA measurement study of exposures near broadcast towers in populated areas in Honolulu (U.S. EPA, 1984). Conservation and preservation concerns have led to restrictions on the siting of commercial broadcast towers. As a result, most tower sites impinge on populated areas. The EPA study measured emissions close to towers and generally found that levels of RF radiation tended to

approach or exceed various voluntary exposure guides. The RF exposures in Honolulu may be unique given environmental restrictions, topography, and population density patterns in relation to radiating sources. Several military and navigational sources also exist on Oahu. The EPA data, plus the data from this study, point out the potential need for analytical studies of Hawaiian populations that, it feasible, examine health indices with more detailed exposure assessment.

Hill (1988) investigated the mortality of 1492 men in a radar research and development project at the Massachusetts Institute of Technology (MIT) during World War II at what was known as the Radiation Laboratory (Rad Lab). The term radar is an acronym that refers to the use of electromagnetic energy for detecting and locating reflecting objects. Radars generally operate within the microwave portion (0.3 to 3.5 GHz) of the electromagnetic spectrum. The cohort was scientific, technical, and senior management staff members ever employed at the Rad Lab between October 1940 and January 1946. The population was identified from records retained by MIT and was traced from World War II through 1986. Only 4.6% of the subjects were not traced beyond the 1940s. Over 67% were traced into the 1980s, and about 80% were traced into the 1970s. There were 52,805 person-years accumulated.

Vital status of the cohort was determined from various sources, including state death certificates, city/town clerk reports, and Social Security Administration records of earnings reports or beneficiary claims. Cause of death data were based on death certificates or city/town clerk reports. Comparisons were to U.S. white males and to a population of white male physician specialists. Internal comparisons were also made.

Two approaches were used to estimate the exposure environment at the Rad Lab. First, summary estimates based on the parameters of two typical radar systems of 1943 vintage were calculated. It was estimated that the maximum power density in the near field of the systems' antennas could be about 2 to 5 mW/cm^2, corresponding to a specific absorption rate (SAR) of 0.1 to 0.4 watts per kilogram (W/kg). Second, a surrogate estimate of exposure was derived from the job patterns in Lab Divisions which were organized around the basic equipment and systems being tested and developed. A three tier ranking system was used (1=little or none, 2=low or moderate, and 3=highest) to represent a gradient of potential exposure of the various jobs and projects in relation to each other, e.g., administrative (low) < work with receivers (medium) < work with transmitters (high). The radiation levels that would define such groupings could not be determined. The longest divisional assignment of an individual was used to rank his exposure. Over half the population was ranked as most highly exposed by mostly working with transmitters or operating systems. The rest of the cohort was about equally divided between low or moderate exposure. About 25% of the men in ranking group 2 (moderate) had worked on Beacons and LORAN (navigational systems). These systems fall in the Low Frequency rather than the microwave portion of the electromagnetic spectrum.

There was no information available on confounding exposures. SMRs were calculated to compare the Rad Lab cohort to U.S. white males and to physician specialists. In addition, the direct method of standardization, to adjust for age, was also used in comparisons to physician specialists and in internal comparisons. The Rad Lab cohort was also compared to physicians using Cox's proportional hazards model to handle differences in time-dependent variables (age or length of follow-up) and to estimate risk ratios. This is another approach to age adjustment. The only independent variable evaluated was cohort (Rad Lab staff or physician); the cohorts were already uniform with respect to race and sex. No other potentially relevant variables were available on physicians to permit comparisons to Rad Lab cohort members.

With respect to expected mortality based on U.S. rates, overall mortality in the population was lower than expected. This probably reflects a "healthy worker' effect and the socioeconomic status of the population, and may be evidence that the protective benefit (or, rather, the selection bias) of actively working is enhanced in professional occupations (here, physical scientists largely believed to be employed at universities, in government, or in high technology industries). Several specific causes of death were elevated, but no excess was statistically significant. These increases occurred for certain cancers (skin, prostate, testis, and cancers whose nature was unspecified) and mental disorders. With censoring to include only men at least 25 years of age at entry to the study and to end follow-up in 1974, elevated SMRs were again seen for selected cancers (pharynx, gallbladder and bile ducts, pancreas, skin, prostate,