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Behavioral and Cognitive Effects of Microwave Exposure

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This paper presents an overview of the recent behavioral literature concerning microwave exposure and discusses behavioral effects that have supported past exposure standards. Other effects, which are based on lower levels of exposure, are discussed as well, relative to setting exposure standards. The paper begins with a brief discussion of the ways in which behavioral end points are investigated in the laboratory, together with some of the methodological considerations pertinent to such studies when radio frequency (RF) exposure is involved. It has been pointed out by several sources that exposure to RF radiation can lead to changes in the behavior of humans and laboratory animals that can range from the perceptions of warmth and sound to lethal body temperatures. Behavior of laboratory animals can be perturbed and, under certain other conditions, animals will escape and subsequently avoid RF fields; but they will also work to obtain a burst of RF energy when they are cold. Reports of change of cognitive function (memory and learning) in humans and laboratory animals are in the scientific literature. Mostly, these are thermally mediated effects, but other low level effects are not so easily explained by thermal mechanisms. The phenomenon of behavioral disruption by microwave exposure, an operationally defined rate decrease (or rate increase), has served as the basis for human exposure guidelines since the early 1980s and still appears to be a very sensitive RF bioeffect. Nearly all evidence relates this phenomenon to the generation of heat in the tissues and reinforces the conclusion that behavioral changes observed in RF exposed animals are thermally mediated. Such behavioral alteration has been demonstrated in a variety of animal species and under several different conditions of RF exposure. Thermally based effects can clearly be hazardous to the organism and continue to be the best predictor of hazard for homosapiens. Nevertheless, similar research with man has not been conducted. Although some studies on human perception of RF exist, these should be expanded to include a variety of RF parameters. Bioelectromagnetics Supplement 6:S39–S62, 2003.

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INTRODUCTION

Exposure to radio frequency (RF) fields can lead to changes in the behavior of humans and laboratory animals and to other effects. These effects range from the perceptions of warmth and sound to high body temperatures that can result in grand mal seizures or death. Between these two extremes, the behavior of laboratory animals can be either perturbed or stopped dead in its tracks. Under certain other conditions, animals will escape and subsequently avoid RF fields, but they also will work to obtain a burst of RF energy when they are cold.

As has been the case for the last 30 years or so, studies reporting changes in the behavior of laboratory animals in the presence of RF fields have provided substantial insight into the most probable mechanism of interaction of these fields with intact organisms. This mechanism relates to the generation of heat in the tissues that results in the activation of thermal sensors in the skin and elsewhere in the central nervous system. Studies of human thermal sensation generated by RF exposures [e.g., Hendler et al., 1963; Justesen et al., 1982; Blick et al., 1997] reinforce the conclusion that behavioral changes observed in RF exposed animals are thermally motivated. Indeed, measured elevations of surface and deep body temperatures often accompany specific behavioral changes demonstrated in the laboratory setting [Brown et al., 1994]. The phenomenon of behavioral disruption [de Lorge, 1983], which has served as the basis for human exposure guidelines since the early 1980's [ANSI/IEEE C95.1-1982, 1982; NCRP, 1986; ANSI/IEEE C95.1-1992, 1992; ANSI/IEEE C95.1-1999, 1999], still appears to be a very sensitive RF bioeffect. Such behavioral alteration has been demonstrated in a variety of animal species under many different conditions of RF exposure. In more recent years, however, other behavioral studies have provided evidence for different kinds of behavioral alteration that may not have a thermal basis [D'Andrea, 1991].

This paper presents an overview of the recent behavioral literature in an effort to discover if other mechanisms, not based on thermal events, may be sufficiently supportive as a basis for setting exposure standards. This review covers approximately a 35 year period; but much of this research was completed prior to 1985, after which extremely low frequency (ELF) studies were favored. Research investigating the effects of mobile phone exposures is now important. Considering the sizable literature, not all papers dealing with behavioral effects can be included. Obvious issues include whether, for example, there was adequate dosimetry, proper experimental design, and adequate statistical evaluation. Nevertheless, the most important criterion is the importance of any study in delineating characteristics of exposure that could be harmful to humans. The next section begins with a brief discussion of the ways in which behavioral end points are investigated in the laboratory, together with some of the methodological considerations pertinent to such studies when RF exposure is involved.

Behavioral End Points

The study of behavior can be used to address a variety of end points encompassing the measurement of human sensation, investigation of higher mental processes of learning and memory, and explorations of cognitive processes, motivation, and emotion. Studies of behavioral responses have been conducted in natural environments, the clinic, and the research laboratory. The latter will be stressed in this review because the control exerted over relevant variables, both dependent and independent, can be far more rigorous in the laboratory setting.

Ongoing behavior, especially complex learned behavior, can be very sensitive to small changes in the environment; hence, behavior is often used to explore the potential toxicity of environmental stimuli in terms of response thresholds. Because of this sensitivity, behavioral changes may be observed in the presence of RF fields at levels below those that produce measurable changes in systemic physiological responses of intact organisms or end points for in vitro preparations. Whether exposure exceeding a threshold is harmful or benign to an organism is an independent question that should be explored elsewhere.

Descriptions of Behavior and Methodologies

Innate behaviors. Innate behaviors are naturally emitted responses of a particular animal species and differ from learned behaviors. Rodent species, such as mice, rats, hamsters, etc., are often used in RF research. Many kinds of motor activity, including locomotion, sniffing, grooming, scratching, rearing, and nest building, are examples of innate or naturally occurring behaviors, some of which are uniquely identifiable in these species. Motor activities that occur individually or in combination comprise an animal's normal and spontaneous behavioral repertoire. For many years, two methods have been used to assess such behavior, both in the laboratory and in the field, the more traditional of which is direct observation of individual and well defined components of behavior. In studies to quantify the effects of RF exposure on behavior, locomotor behavior in an open field test apparatus has been used most frequently. The open field is a large test arena with a grid delineated on the floor, in which an animal is placed; a variety of innate behaviors, such as grid crossings and rearing, are scored over time by one or more observers. Other observational techniques use time-lapse photography to record, for example, the huddling behavior of litters in the nest [O'Connor, 1988] or disruptions in a working memory task by a microwave hyperthermia treatment [Mickley et al., 1994]. The film record is scored for the presence of specific innate behaviors by several observers. Because the observational method requires much time for scoring behaviors either directly or from a film record, it can be used with only a few animals and a limited number of experimental treatments.

The alternative approach, involving automated techniques, quantifies innate behaviors with the help of mechanical or electronic devices designed to record certain behavioral components. These devices measure an animal's behavior, either directly with photocells, touch detectors, infrared or ultrasonic detectors, or indirectly by monitoring the animal's living space with tilt cages, stabilimeter platforms, exercise wheels, etc. Each automated device records a particular component of behavior. For example, photocells may measure alley entrances in a maze or shuttle box, while touch detectors may measure an animal's licking rate from a sipper tube. A more complex understanding of specific innate behaviors may combine observation with automated techniques. For example, the lifetime study [Chou et al., 1992] of 200 rats exposed (or sham exposed) in circularly polarized waveguides to 2.45 GHz pulsed RF energy at 0.4–0.15 W/kg periodically assessed open field activity as a measure of RF effects on behavior. The open field test apparatus was equipped with infrared light emitting sensors to measure both activity and location of the animal in the field. On completion of the test, the apparatus was inspected for urine and feces to quantify measures of emotion or stress.

Learned behaviors. Learned behavior, the other class of behavior, involves the strengthening, or conditioning, of particular behavioral responses by scheduled rewards or reinforcements. Two paradigms traditionally have been used to characterize learned behavior, respondent, and operant conditioning. When the response is reflexive or natural such as pupillary constriction and certain stimuli such as a light flashed into the eye can elicit that response, it may be conditioned by pairing a previously neutral stimulus (such as a noise that did not previously elicit the response) with the natural stimulus. Over repeated pairings, the response will occur in the presence of the neutral stimulus alone; that is, the pupil will now constrict when the noise is presented. A hungry dog salivating when presented with food is another famous example. When a tone is repeatedly paired with food, the dog eventually learns, or becomes conditioned, to salivate to the sound of the tone alone. This type of learning is variously called respondent, classical, or Pavlovian conditioning.

Other behaviors that are naturally and voluntarily emitted, but do not require an eliciting stimulus, also are susceptible to conditioning. When a specific stimulus is delivered close in time after the emitted behavior, the probability of a subsequent emission of the behavior may increase. If this occurs, the stimulus is a reinforcer (reinforcement of learning). This type of learning is called operant or instrumental conditioning. Operant conditioning, and the behavior it produces, is established by allowing the animal to alter its environment by emitting a response, called an operant. A large variety of operant behaviors have been conditioned, including lever pressing, chain and rope pulling, key pecking, and breaking a photocell beam with the nose. When emitted at the appropriate time, the operant response changes the animal's environment by producing a reinforcer such as food, water, or absence of electric shock [Honig and Staddon, 1977].

Sometimes visual or auditory stimuli are used to signal upcoming events to the animal; these are called discriminative stimuli. The temporal or numerical sequence of stimuli, relative to responses to produce a reinforcer, establishes a reinforcement schedule that generates schedule-controlled behavior. For example, an FI 10 min schedule refers to delivering a reinforcer for a response that occurs after fixed interval of 10 min has elapsed. A VI 10 min schedule refers to delivering a reinforcer for a response that occurs after a variable amount of time, averaging 10 min, has elapsed. A FR 10 schedule refers to an application of reinforcement after fixed number of 10 responses is emitted. Some schedules may selectively reinforce the timing of responses, such as a differential reinforcement of low rate (DRL) response schedule. In the laboratory, investigators can use well defined and measurable scheduled-controlled behaviors to investigate the effects of agents such as microwave radiation. Changes in schedule-controlled behavior then can serve as an index of microwave bioeffects.

Special kinds of apparatus, such as mazes and shuttle boxes, also are used to generate learned behavior. The paradigms are somewhat different, in that there are multiple choices for the animal to make and the response is usually locomotor, rather than manipulative. Measures of response include response time, correct responses, and errors. The radial arm maze has become popular for studying the effects of electromagnetic energy on learning and memory. This maze consists of a central start box and a set of 8–12 alleys (arms) extending outward from the center. A baited cup is located at the end of each arm; and the test animal, usually a rat, is allowed to explore the maze to acquire the food. An error is scored whenever the rat enters an arm more than once within a prescribed time period. The effects of previous or concurrent RF exposure have been studied in this maze and compared with control tests with RF absent [e.g., Lai et al., 1989].

IMPACT OF RF FIELD CHARACTERISTICS

Radiofrequency radiations (RFRs) occupy the portion of the electromagnetic spectrum between 3 kHz and 300 GHz. Exposure to RFR will induce an internal electric field and associated current density within the exposed biological medium. Stimulation of excitable tissues will occur most readily below 1 MHz, while thermal effects occur at higher frequencies [Reilly, 1998]. Absorption of energy in the range of 1 MHz–300 GHz results primarily in tissue heating by movement of ions and oscillations of dipole molecules, resulting in transfer of energy from the RF field to the biological medium.

A living organism exposed in this frequency range will scatter and absorb energy depending on factors such as wavelength, body size, body shape, and orientation in electric and magnetic field vectors [Gandhi, 1974; Durney et al., 1986]. When exposed to ionizing radiation, absorption is directly related to the cross sectional area of the organism [NCRP, 1986]. In the RFR portion of the spectrum, however, the factors listed above strongly control absorption that occurs independent of cross sectional area and can result in resonant absorption in both man and animal. Generally, the smaller the animal, the higher the resonant frequency and the whole body averaged specific absorption rate (SAR) produced for a given power density (PD). Body shape is important. The rhesus monkey is a very suitable model for human exposure, since the absorption profile is nearly the same as man, but simply shifted to a slightly higher frequency (300 MHz) because the monkey is smaller than man.

Early studies confirmed that whole body resonance occurs when the long axis of the body is parallel to the electric field and is 0.4 times the wavelength [Gandhi, 1974]. Thus, a rat, 20 cm in length, would resonant at 600 MHz, whereas a 172 cm human would resonate at 70 MHz.

Penetration depth of RF energy varies inversely with wavelength where longer wavelengths penetrate deeply and short wave lengths are absorbed nearer the surface. At higher frequencies the penetration of RFR radiation decreases, such that at 300 GHz the penetration into the body is superficial (less than 0.1 mm). Modulation of the RF fields, primarily amplitude modulation, has received some experimental investigation.

While many studies have involved continuous wave (CW) fields, there is little evidence for a difference in behavioral response to pulsed fields (PFs) of equivalent whole body specific absorption rate (SAR, which is expressed as watts per kilogram (W/kg) of absorbed power). This appears to be true even for very high peak powers and ultra wide band fields [Sherry et al., 1995]. However, there is always the possibility that PFs can produce auditory cues [Lin, 1990], so appropriate masking noise and/or positive control procedures should be part of the experimental design. On the other hand, while some believe that modulated fields possess special characteristics that may influence behavior, specific effects of modulated fields are equivocal at this time [Frey and Feld, 1975]. More detailed discussion and reviews of PFs can be found in Lu and de Lorge John [2000] and Pakhomov and Murphy [2000].

LABORATORY INVESTIGATIONS IN ANIMALS

As thresholds of behavioral change have been quantified, many studies have sought to capitalize on the thermogenic nature of the interaction between RF fields and the tissues of the target organism. Behavioral studies have been very useful in pinpointing those characteristics of RF fields that control the SAR, thereby corroborating analytical dosimetric predictions [Schrot and Hawkins, 1976; D'Andrea et al., 1977]. Many thermal effects controlled by frequency dependent energy absorption, animal shape and size, and the presence of local electrical "hot spots" in the animal have been investigated with behavioral tests. In most cases, a simple test protocol has been followed to (1) establish a stable behavioral baseline of performance and then (2) determine the effects of RF exposure on this performance baseline. Generally speaking, the effect of RF exposure and concomitant rise in body temperature has been merely a reduction in behavioral responding. Stern [1980] and others have pointed out that the reduction of responding on a learned task may not necessarily imply an adverse effect, but may simply reflect the animal's attempts to engage in other behaviors, for example, escape or cooling off, which are thermoregulatory in nature and incompatible with learned behaviors such as lever pressing for food pellets on a prescribed schedule.

A short term RF exposure can produce a thermal burden in an organism that may cause behavioral and other effects, some of which may be harmful [Adair, 1983]. Justesen [1979] has described several classes of behavioral effects of such exposure that include perception, aversion, work perturbation, work stoppage, endurance, and convulsions. The product of intensity and duration of exposure is the assumed basis for this classification; as the product increases, the effect advances from the threshold of perception, through intermediate steps, to an extreme thermal insult, grand mal seizures, and finally death. In this respect, exposure to a RF field differs little from exposure to conventional sources of thermal energy or inhospitable thermal environments.

Thermal Tolerance and Lethality

A few studies have been added to the classical literature on thermal tolerance. Modak et al. [1981] showed that the motor activity of mice would decrease immediately after exposure to single, intense pulses of 2450 MHz RF energy and remain at a low level for at least 5 min thereafter. A 25 ms pulse at an energy dose of 18.7 J was more effective than a 15 ms pulse at 14.25 J, and body temperature was elevated more at the longer (+4 °C) than at the shorter (+2 °C) duration. Guy and Chou [1982] reported high brain temperatures, convulsions, and loss of consciousness in rats exposed to high power (2–10 kW) 918 MHz PFs (1 μs). Many early studies had shown repeatedly that RF exposures of sufficient PD and duration to produce a rise in core temperature to 43–44 °C would be lethal to the organism. On the other hand, recent reports [Frei et al., 1996; Ryan et al., 1996] indicate that circulatory collapse and death can occur in anesthetized rats exposed laterally for 30–60 min to 35 GHz at a whole body SAR of 13 W/kg. However, under these conditions, death appears to be associated with rapidly elevated skin temperatures and relatively normal core temperature (40.3 ± 0.3 °C).

Behavioral Performance Disruption (Work Stoppage)

The studies described in this section can be classified technically as behavioral disruption studies because they have determined the PD threshold for RF exposure, at different frequencies, that will change either locomotor behavior or rate of lever pressing for food by the rat and nonhuman primate (Table 1). Performance disruption can be operationally defined as a significant change in behavior from a well defined baseline. Work stoppage is simply the point at which the animal ceases emitting the trained behavior for a predetermined time period. Disruption of learned behavior induced by short term RF exposure has been useful in pinpointing the specific characteristics of the RF field that are effective, while corroborating analytical and dosimetric predictions.

RF frequency has been a primary characteristic for investigation of work stoppage. D'Andrea et al. [1977] extensively examined the effects of 20 mW/cm^2 RF exposure on the lever pressing responses of rats working under a simple variable interval (VI) schedule

TABLE 1. Behavioral Performance Disruption

Organism	Behavioral effect	CW effect	PF effect	Exposure data	References
Albino rat	DRL response timing disrupted	No, 0.2–3.6 W/kg	Yes, 2.5 and 3.6 W/kg	2.8-GHz, 2 s pulse width, 500-pulses/s, 1–15 mW/cm^2	Thomas et al. [1982]
Long-Evans rat	Multicomponent (fixed ratio, timeout (TO)) task	Yes, 5.8 W/kg	Yes, 6.7 W/kg	1.3-GHz, 1 µs pulse width at 600 pulses/s	Lebovitz [1983]
Rhesus monkeys	Disruption of lever pressing	Yes, see Table 2 & Table 3	Yes, see Table 2 & Table 3	225 MHz, 1.3, 2.45, 5.7 GHz	de Lorge [1983]
Squirrel monkeys	Disruption of lever pressing			2.45, 5.7 GHz	
Rats	Disruption of lever pressing			1.3, 2.45, 5.7 GHz	
Rats	Disruption of lever pressing	NA	Yes, 6.0 W/kg, 6.9 W/kg	1.28 GHz, 5.5–15 mW/cm^2 5.60 GHz, 7.5–48.5 mW/cm^2	de Lorge and Ezell [1980]
Rats	Disruption of lever pressing	Yes, 9.5 W/kg	NA	600 MHz	D’Andrea et al. [1977]
Rhesus monkeys	Disruption of lever pressing	NA	Yes, 4 and 6 W/kg	5.6 GHz, 100 pps 2.8 µs and 50 ns PD	D’Andrea et al. [1994]

of reinforcement. Different frequencies were studied on different days, and the primary dependent variable was the exposure duration necessary to meet a criterion of 33% reduction below the control response rate. The authors operationally defined this as time to work stoppage. Of the frequencies studied (400, 500, 600, and 700 MHz), they found the rats to be most sensitive to 600 MHz, a frequency very close to resonance for the standard laboratory rat, for example, 598–623 MHz [Durney et al., 1986]. Longer exposure durations were necessary to meet the behavioral criterion of frequencies above and below resonance. Rats exposed to 600 MHz exhibited the greatest rate of temperature rise and the shortest exposure duration to work stoppage. The other frequencies required longer exposure times and showed lower temperature elevations. These results confirmed previous analytical predictions [Gandhi, 1974] that whole body resonance was an important factor in determining the SAR of microwaves, which governed the rate of heating, and subsequently duration of exposure necessary to disrupt behavior.

de Lorge and Ezell [1980] trained rats to lever press for food during 40 min test sessions. During stable lever pressing performance, the rats were exposed to various PDs of RF at 5.6 GHz (7.5–48.5 mW/cm^2) and 1.28 GHz (5.5–15.0 mW/cm^2). At each frequency, the interference with ongoing behavior exhibited a dose-response relationship, with the higher PDs taking less time than the lower to produce an effect. The results showed that for 5.6 GHz exposure the behavior of all (or most) rats was disrupted by PDs of 26–38.5 mW/cm^2. At 1.28 GHz, which is approximately twice the resonance frequency of the rat, lower PDs disrupted behavior more than was the case at the much higher, supraresonant frequency, 5.6 GHz. Thus, at 1.28 GHz, significant behavioral changes were measured at 15 mW/cm^2 in all rats, with some changes noted as low as 10 mW/cm^2.

The study of de Lorge and Ezell [1980] described above was one of a series of studies by de Lorge [1976, 1979, 1983, 1984] and de Lorge and Ezell [1980] that investigated the disruption of operant behavior, not only in terms of RF frequency, but also in terms of animal species (i.e., different sizes). The conclusion that different PDs affected the animals similarly at different frequencies was based on the thermal consequences of disparate SAR distributions. These SAR distributions were quantified by temperature measurements in RF exposed Styrofoam models filled with muscle-equivalent material or by temperatures obtained from animals during experimental sessions.

The series of studies on the three animal species was summarized by de Lorge [1983, 1984]. The animals included rats (Long Evans and Sprague–Dawley

TABLE 2. Characteristics of Contributing Experiments—Behavioral Disruption

	Microwave frequency			
Subject	225 MHz, CW	1.3 GHz, PF	2.45 GHz, CW	5.8 GHz, PF
Rat	—	B_1, T_{est}, X+Y, lateral	B_2, T_{est}, X+Y, dorsal	B_1, X+Y, lateral
Saimiri	—	—	B_1, T, Z+Y, dorsal	B_3, T, Y, frontal
Macaca	B_1 T, Y, frontal	B_1, T, Y, frontal	B_1, T, Y, frontal	B_1, T, Y, frontal

Symbol identification: B_1, observing response; B_2, fixed interval schedule; B_3, repeated acquisition; X,Y,Z, long axis orientation to E field; T, colonic temperature measured; T_{est}, colonic temperature estimated; PF, pulsed field; CW, continuous wave field.

strains), squirrel monkeys (*Saimiri sciureus*), and rhesus monkeys (*Macaca mulatta*). Only males were used. The average body masses were 300–400 g for rats, 700 g for squirrel monkeys, and 4.7–5.1 kg for rhesus monkeys. All animals were trained to work for food pellets, while being maintained at ~75–90% of their free-feeding body weights. All tests were conducted in climate conditioned anechoic chambers equipped with response levers, food dispensers, sound and light cues, and a 75 dB SPL masking noise to prevent extraneous auditory cues.

Table 2 (adapted from de Lorge, 1983, 1984) gives the basic characteristics of the contributing experiments. The three subject groups are listed at the left side of the table, and the RF frequencies studied are shown across the top. PF and CW fields are indicated. The operant task shown in each cell was either an observing response with two levers (B_1); a fixed interval schedule with one lever (B_2); or a repeated acquisition task with three levers (B_3). Colonic temperature was measured continuously during the test sessions (T) or estimated (T_{est}) from other measurements. The orientation of the subject's long axis to the E-field vector of the plane wave is shown by X, Y, and Z. Also indicated is whether the subject was facing the antenna (frontal), was below the antenna (dorsal), or had the left side toward the antenna (lateral). Note that squirrel monkeys were not exposed to 1.3 GHz and that all exposures were not oriented to the same polarization.

The data were analyzed primarily in terms of the ratios of response rates during RF exposure compared to sham exposure and associated increments in colonic temperature. Figure 1, modified from de Lorge [1983], shows typical changes in the response ratio for five rhesus monkeys exposed to 1.3 GHz fields during 1 h sessions of observing response performance (panel A). The data indicate that a significant decrement in responding occurred at power densities of 63 mW/cm^2 and above. The absolute threshold for behavioral disruption was defined as the PD midway between that at which a decrement was reliably observed and the one where no effect was seen. Under the conditions represented in Figure 1, this threshold was calculated as 8 mW/cm^2 at 225 MHz, as 56 mW/cm^2 at 1.3 GHz, and 140 mW/cm^2 at 5.7 GHz. The associated change in colonic temperature is shown in panel B of the figure.

The calculated values in PD corresponding to behavioral disruption and a 1 °C increment are shown in Table 3, which has the same format as Table 2. Animal size (or species) appeared to determine the effectiveness of RF exposure to disrupt behavior at any given frequency. In general, as animal size increased, higher power densities were required to affect either behavior or colonic temperature. Across all species studied, it appeared that an increase of 1 °C in colonic temperature, produced by RF exposure, would almost certainly disrupt ongoing learned behavior. Table 3 includes

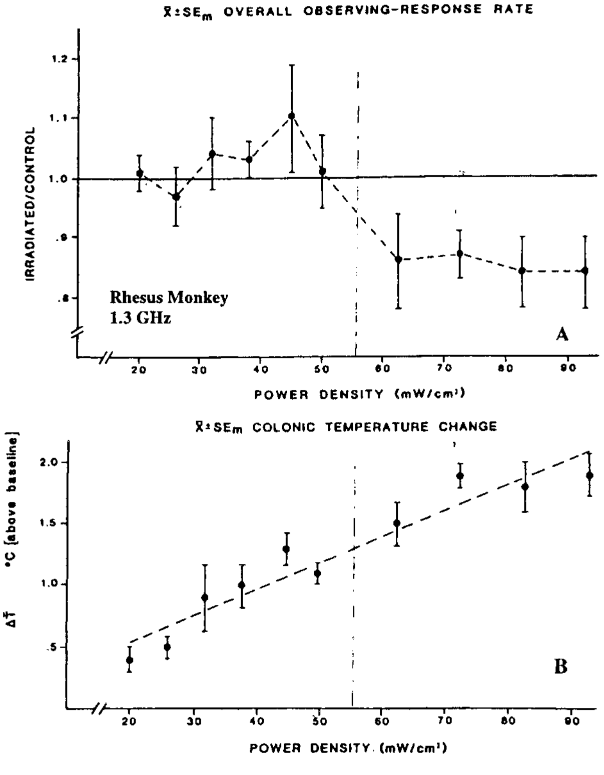

Fig. 1. Mean response ratios (irradiated/sham ± SD) of five Rhesus monkeys exposed to 1.3 GHz pulsed fields (PFs) as a function of power density (PD) (**panel A**) and associated increments in colonic temperature (**panel B**). Modified from de Lorge [1983].

TABLE 3. Power Density (PD) Thresholds (mW/cm^2) for Behavioral Disruption and Temperature Increase

	Microwave frequency			
Subject	225 MHz, CW	1.3 GHz, PF	2.45 GHz, CW	5.8 GHz, PF
Rat	—	$B_1 = 10$ $T_{est} = 10$	$B_2 = 28$ $T_{est} = 32$	$B_1 = 20$
Saimiri	—	—	$B_1 = 45$ $T = 50$	$B_3 = 40$ $T = 40$
Macaca	$B_1 = 7.5$ $T = 7.5$	$B_1 = 53$ $T = 42$	$B_1 = 67$ $T = 67$	$B_1 = 145$ $T = 140$

Symbol identification: B_1, observing response; B_2, fixed interval schedule; B_3, repeated acquisition; T, colonic temperature rise of 1 °C measured; T_{est}, colonic temperature rise of 1 °C estimated; PF, pulsed field; CW, continuous wave field.

certain discrepancies from these general conclusions, but these are believed to relate to the fact that the test animals could alter their orientation to the imposed RF field somewhat: the rats were freely moving in the test environment, while the monkeys were loosely restrained in Styrofoam chairs. Also, the exposure of Macaca at 5.7 GHz was at 60% of the far field distance from the horn in order to achieve high power densities at the animal's head. The resulting nonuniform energy distribution may have led to the exceptionally high power densities required for behavioral and temperature thresholds at this frequency.

Whole body SARs, either calculated or measured in saline filled models, were consistent across species only at the 2.45 GHz frequency, where they averaged between 4 and 5 W/kg. The rat at 5.7 GHz and Macaca at 1.3 GHz also absorbed between 4 and 5 W/kg. However, Saimiri and Macaca at 5.7 GHz had higher whole body SARs and the rat at 1.3 GHz had a lower whole body SAR at the behavioral disruption threshold. These variations caused de Lorge to suggest that whole body SAR may not be the best indicant of behavioral effects across frequencies and that other aspects of RF energy absorption, such as local SAR, might be preferable. He also observed that while the correlation between behavioral change and a 1 °C rise in colonic temperature is very useful in predicting behavioral disruption, the rise in core temperature should not be considered the causal agent. The causal agent could just as well be energy deposition in some brain locus, as yet unknown. Finally, these studies do not address the unique question of resonant exposure, for which a different set of relationships may exist.

High Peak Power

A few recent studies have examined the disrupting effects of PFs, particularly those of high peak power. Akyel et al. [1991] provided additional evidence for work stoppage in the rat that was correlated with an increase in body temperature. The animals were first trained on different reinforcement schedules (FR, VI, and DRL) to work for food pellets. Then each rat was exposed for 10 min to 1.25 GHz PFs at 1 MW peak power (10 μs pulse width) at total doses (SA) of 0.5, 1.5, 4.5, and 14 kJ/kg. Corresponding time averaged whole body SARs were 0.84, 2.5, 7.6, and 23 W/kg. Immediately after exposure, animals were placed in the operant test chamber. Exposures at the highest dose induced an average colonic temperature rise of 2.5 °C and a suppression of lever pressing for ~13 min. The rats did not begin responding again until colonic temperatures had fallen to 1.1 °C or less above their pre exposure temperatures. No behavioral effects were observed at the lower dose levels, leading to the conclusion that behavioral disruption by pulsed microwaves was thermal in nature.

Three studies examined the effects of exposure to high peak power microwaves on learned behavior in the rhesus monkey. D'Andrea et al. [1989a] noted that certain safety guidelines for humans [ANSI/IEEE C95.1-1982, 1982; NCRP, 1986] limited the localized peak tissue SAR to 8 W/kg, but set no limit on the peak power of PFs. In the study, rhesus monkeys were exposed to 1.3 GHz PFs at peak power densities of 131.8 W/cm^2 and low pulse repetition rates (2–32 Hz), while performing a time related behavioral task for food reinforcement. The task consisted of three different behavioral components: interresponse time, time discrimination, and fixed interval. No significant change occurred in any behavior during irradiation, compared with sham irradiation sessions. However, the authors cautioned against generalization of these findings to other experimental conditions, including other behavioral tasks, higher peak powers, other frequencies, etc.

The second study [D'Andrea et al., 1989b] involved exposure of rhesus monkeys to high peak power RF pulses (2375 MHz) produced by a virtual cathode oscillator. Single pulses of short pulse duration (80–100 ns) produced energy densities per pulse of 640–800 μJ/cm^2. Although pressure waves in the monkey brain were probably much higher than the human or monkey threshold of hearing, no effects on the performance of a vigilance task, similar to that used by de Lorge [1976], were observed.

The third study [D'Andrea et al., 1994] was conducted after promulgation of the ANSI/IEEE C95.1-1992, 1992 standard, which set limits (100 kV/m peak E field) on human exposure to high peak power microwave pulses of short duration. Rhesus monkeys were trained on a complex operant task involving color discrimination. A red light was the signal to pull one lever on a VI-25 s schedule; responding on a second lever to a green signal produced a food reward, unless a white signal was presented instead, where upon the lever pull produced a 30 s timeout (TO). Thus monkeys were performing discrimination between green and white lights to earn food and avoid TO and loss of food. The monkeys were exposed to microwave pulses while performing this task. Two types of pulses, radar at 5.62 GHz and radar coupled to a Stanford linear energy doubler (SLED) device were studied. The SLED is a pulse forming device that enhanced the radar peak power by a factor of nine [Farkas, 1986]. Peak field power densities studied were 518, 1270, and 2520 W/cm^2 for SLED pulses and 56, 128, and 277 W/cm^2 for radar pulses. Pulse repetition rate was 100 pps (2.8 μs radar pulse duration; ~50 ns SLED pulse duration) for 20 min. Average whole body SAR was 2, 4, or 6 W/kg.

Responses in the presence of PFs were evaluated against responses during sham exposures. The study showed that significant alterations in lever responding (Fig. 3, top panel), reaction time (Fig. 3, bottom panel), and acquired food pellets occurred during 4 and 6 W/kg exposure but not at 2 W/kg. Further, the high peak power (SLED) pulses and normal radar pulses did not differentially alter behavioral performance, which recovered rapidly after exposure ceased. It is possible that the monkeys could hear the pulses, but the sensation may have been the same for the two types of pulses. Thus, this study, while replicating some of the earlier behavioral disruption thresholds of 4 W/kg, did not find evidence of unique high peak power microwave hazards from fields near the ANSI/IEEE C95.1-1992, 1992 E field limit. Thus, the threshold whole body SAR for behavioral disruption described in many of the studies above is very close to 4 W/kg. This is in spite of very high peak power densities.

Aversive and Escape Behavior

Although RF energy can serve as a positive reinforcement to maintain behavior (see below), it can also have the opposite effect, that of negative reinforcement. While a positive reinforcer results from an operant response, a negative reinforcer is "...an otherwise prevailing stimulus that is subtracted from—eliminated by—the operant response" [Justesen, 1988, p. 236]. Thus, negative reinforcement strengthens a behavior because a negative condition is stopped or avoided as a consequence of the behavior. Punishment, on the other hand, weakens a behavior because a negative condition is introduced or experienced as a consequence of the behavior. For example, Frey and Feld [1975] had demonstrated that rats would avoid PFs but not CW fields. A study by Hjeresen et al. [1979] also showed that PFs were detectable by rats and could control behavior. Thus, rats can perform an operant response to escape PF illumination and on subsequent trials in both studies perform an operant response to avoid PF illumination. However, subsequent studies, designed to demonstrate that PF microwaves can influence behavior differently from comparable CW microwaves, have produced equivocal results when other experimental paradigms are used. Such a paradigm might involve rats trained to lever press on schedules that control the delivery of a positive reinforcement such as food. The study described next did precisely that.

Thomas et al. [1982] compared the effects of PF and CW microwaves on a DRL schedule in four rats exposed to 2.8 GHz at whole body average SARs of 0.2–3.6 W/kg. In a DRL schedule, each reinforcement is presented only after an animal has withheld responding until a specified period of time has elapsed. The investigators reported that the emission rate of appropriately timed responses declined after the animals were exposed to PF at SARs of 2.5 and 3.6 W/kg, whereas CW exposure at the same SARs did not consistently alter response rate. Exposures at the two highest SARs were accompanied by rectal temperature increases of 1.1 and 1.5 °C, respectively; however, the possibility of auditory effects was not ruled out. On the other hand, Lebovitz [1983] reported that the behavior of rats trained to perform on a multicomponent FR and TO reinforcement schedule was not differentially affected by PFs, compared with CW RF exposure, even at whole body average SARs as high as 6.7 W/kg. Based on these data, the relative aversiveness of PF versus CW microwave exposure remains unclear, although the possibility of an aversive microwave auditory effect as accompaniment to PF exposure cannot be ruled out [Stern, 1980].

Electrical Hot Spots

The reports cited above [Schrot and Hawkins, 1976; D'Andrea et al., 1977] give a clear indication of the importance of frequency to the determination of SAR, as well as resulting changes in behavior that are presumably SAR dependent. Dosimetric evidence [Gandhi, 1990] indicates further that electrical hot spots can occur in the body during RF exposure, and these may generate thermal hot spots in regions lacking sufficient local blood flow. D'Andrea et al. [1985], extending the data of Lin et al. [1977], discovered thermal hot spots in the tail and rectum of euthanatized rats during exposure to 360 and 2450 MHz fields. Interestingly, similar hot spots were not seen during exposures at frequencies close to resonance for medium sized rats. The most intense hot spots were found to exceed the whole body average SAR by 50 and 18 times for exposures at 360 and 2450 MHz, respectively. It was important to learn if these hot spots would influence the behavior of live rats significantly. Convective heat transfer through increased blood flow should greatly diminish the importance of localized thermal hot spots, although D'Andrea et al. [1987] had found that this was not completely the case in anesthetized rats.

In conscious rats, the behavioral consequences of RF induced thermal hot spots were studied by D'Andrea et al. [1988] under a novel behavioral paradigm. The rats were tested in a long Plexiglas runway, which they were allowed to explore. Over time, each rat selected one (preferred) end of the runway in which to rest. On subsequent tests, a RF exposure occurred when the rat selected the preferred end of the runway; if the rat moved to the nonpreferred end, the exposure stopped. Three RF frequencies were tested, two (360 and 2450 MHz) that produced localized hot spots and one (700 MHz) that did not. PDs were adjusted for each frequency to yield equivalent whole body SARs of 1, 2, 6, and 10 W/kg. The results showed that the rats vacated the preferred (irradiated) end of the runway much sooner during 360 and 2450 MHz exposures than they did during 700 MHz exposures, thus indicating an aversion to the frequencies that generated hot spots. Unfortunately, it was not possible to measure the local tissue temperature in the location of presumed hot spots during this experiment. A second experiment demonstrated for longer exposures that the whole body SAR threshold for aversion of 2450 MHz was 2.1–2.8 W/kg.

Justesen [1988] has argued, on the basis of studies conducted in his laboratory that the salience of RF fields is inadequate to serve either as a negative reinforcement or a discriminative stimulus for operant behavior. Carroll et al. [1980] had reported that experimentally naïve rats failed to learn an escape response, moving to a safe area marked on the chamber floor, to reduce the SAR of a 918 MHz multipath field from 60 to 2 W/kg. Other rats learned the same response quickly when the negative reinforcer was electric shock to the feet. Several other studies of rats and mice, motivated by intense 918 and 2450 MHz RF fields [Levinson et al., 1982, 1985; Justesen, 1983; Justesen et al., 1985], showed clearly that naïve animals fail to learn an escape response, even at lethal field strengths. All of these studies were conducted in multimode cavities that featured a "safe" area marked on the floor. Cessation of foot shock was always a potent reinforcer, while cessation of either a bright light or intense microwaves alone was not. Pairing the light with an intense microwave field, however, significantly improved escape learning and decreased lethality [Levinson et al., 1982]. These results applied specifically to 2 min periods of irradiation alternated with 2 min TOs (irradiation off). When the period of irradiation was 15 min, all rats and most mice tested at 60 W/kg, as well as all mice tested at 120 W/kg, died of hyperthermia before discovering the safe zone [Justesen, 1983; Justesen et al., 1985]. Once again, foot shock produced rapid escape learning in both species.

Another study [Levinson et al., 1985] attempted to simplify the operant task by dividing the floor of the cavity in half by a black line, thereby creating a shuttle box format. Crossing the line to the safe side in the presence of an intense stimulus represented an escape response; remaining on the safe side constituted an avoidance response. A preliminary experiment determined that both rats and mice would quickly learn to escape foot shock by crossing to the safe side and would avoid shock by remaining there indefinitely. On the other hand, although a RF field of 60 W/kg motivated the animals to spend significantly more time on the safe side, there was no evidence of avoidance; further, there was no evidence of subsequent resistance to extinction. Observations of the animals during the RF exposure tests revealed increased locomotor activity, frequent urination and defecation, and the spreading of saliva over the fur, all indicants of thermal stress.

As a possible interpretation of these results, Justesen [1988] suggested that a delay in timely sensory feedback might explain the inability of experimental animals to learn an escape response in the presence of intense microwave fields. The relatively deep penetration of microwave energy at frequencies below 3 GHz and the large thermal time constants of mammalian tissues conspire to generate a hyperthermic state that can persist long after the field is extinguished. Thus, a hot animal running around in an intense microwave field will not connect transient passage through the safe zone with cessation of irradiation because the contiguous sensory reinforcement is absent. Justesen has offered the further possibility that there may be specific exposure situations, such as are found in industrial or military settings that could pose thermal hazards to unsophisticated humans. If the whole body undergoes exposure to an intense RF field, any diffuse sensations of warming that could lead to serious hyperthermia may not be attributed to a nearby source of RF energy unless the directionality of the energy beam is clearly perceived.

THERMOREGULATORY BEHAVIOR AND THERMAL COMFORT

Introduction

Humans and other endotherms continually seek a comfortable thermal environment. Such an environment provides optimal satisfaction and minimal thermophysiological strain. A need to improve thermal comfort may stimulate a person to reset the thermostat, open a window, or put on more clothing. These strategies are examples of thermoregulatory behavior, i.e., voluntary actions that control the physical characteristics of the air-to-skin interface, thereby facilitating the regulation of the body temperature at a stable level that is characteristic of the species. Ordinarily, temperature sensors in the skin are activated when the environmental (or skin) temperature changes, and information from these sensors, relayed to a central integrator or thermal control center in the brain provides an error signal that initiates appropriate changes in behavior. Responses as diverse as the thermotropisms of unicellular organisms and the complex behavior-plus-technology of an astronaut's lunar walk share a common purpose, that of providing a hospitable microclimate to facilitate thermoregulation.

Organisms may be classified as ectotherms (poikilotherms) or endotherms (homeotherms) in terms of their thermoregulatory capacity. For ectotherms (e.g., lizards), behavioral responses represent most of the thermoregulatory capability of the organism because autonomic mechanisms of heat loss and heat production are absent. For endotherms (e.g., mammals, including humans), thermoregulatory behaviors ensure minimal involvement of the characteristic autonomic mechanisms of heat production and heat loss, thereby helping to conserve the body's stores of energy and water.

Animal Data: Lizards and Rodents

Few experimental data exist, apart from reports of thermal sensations aroused by RF exposure, that relate changes in thermoregulatory behavior of human beings to RF exposure. However, experimental results from animal subjects, including nonhuman primates, are now sufficiently complete that predictions of comparable human behavior can be entertained. The recent animal data stemmed from early observations of locomotor behavior and simple studies of operant responses conditioned with thermal reinforcement. For example, D'Andrea et al. [1978] reported that lizards would orient toward and bask in the radiation from a microwave antenna and thereby regulate their cloacal temperatures efficiently. Gordon [1983] demonstrated that mice select the cooler regions of a thermal gradient, located inside a waveguide, when the imposed RF field becomes more intense. Stern et al. [1979] trained shaved rats in the cold to press a lever for bursts of infrared energy and then measured the reduction of lever pressing when a 2450 MHz RF field was present. The higher the PD of the RF field (range = 5–20 mW/cm^2), the less infrared energy was selected by the rats; these behavioral changes helped the rats to maintain a normal body temperature. Gage and Guyer [1982] conducted experiments that clearly showed the effects of ambient temperature and relative humidity on rodent operant task performance during microwave exposure. Task performance was degraded much sooner at higher ambient temperatures. For many of the performance disruption and work stoppage experiments described earlier in this review, the threshold for effect would occur sooner at higher ambient temperatures [Gage, 1979; Gage et al., 1979].

Studies of Nonhuman Primates

Introduction. A somewhat different approach to the study of behavioral thermoregulation was adopted by Adair and Adams [1980]. Adult male squirrel monkeys were first trained to pull a cord lowered into their test compartment to select between warm (50–55 °C) and cool (10–15 °C) ambient air flowing over their body. Over time, cord pulls at regular intervals yielded an average preferred ambient temperature (T_a) of ~35 °C. Brief (10 min) whole body exposures to 2450 MHz CW microwaves at a threshold field strength of 6–8 mW/cm^2 (whole body SAR = 1.1 W/kg) stimulated the monkeys to select a reliably lower T_a. Exposures to infrared radiation at equivalent incident PD did not produce this effect. Increased RF field strengths up to 2.5 times the threshold level (22 mW/cm^2 or SAR = 3.25 W/kg) provoked an increasingly lower selected T_a. The study demonstrated that skin and deep body temperatures were thereby regulated at stable levels.

Basic phenomenon. The effect of RF exposure duration on thermoregulatory behavior was explored by Adair and Adams [1983]. Squirrel monkeys were first trained to control the temperature of their environment behaviorally, as described above. Then, individual animals were exposed to 2450 MHz CW microwaves for periods from 5 to 150 min. PDs explored were 4, 10, and 20 mW/cm^2, representing a range of whole body SAR from 0.6 to 3.0 W/kg, plus controls (no RF). The 4 mW/cm^2 exposure did not alter thermoregulatory behavior, no matter how long it lasted. The 10 and 20 mW/cm^2 exposures stimulated the monkeys to select T_a that were 1.5 and 3.0 °C cooler than control levels, respectively. Except during the first RF presentation of a series, or during the early minutes of a single long exposure, exposure duration had no significant effect on selection of a preferred T_a or on the body temperatures achieved thereby [Adair, 1985].

Role of the hypothalamus. The role played by the hypothalamic thermoregulatory center in behavioral changes such as those described above has been investigated [Adair et al., 1984]. Squirrel monkeys were chronically implanted, under stereotaxic guidance, with two sealed Teflon tubes in the medial preoptic/anterior hypothalamic area (PO/AH), the brainstem region demonstrated to control normal thermoregulatory processes. A nonperturbing Vitek temperature probe [Bowman, 1976] inserted into one tube measured PO/AH temperature, while changes in thermoregulatory behavior were induced by either brief (10 min) or prolonged (2.5 h) whole body exposures to 2450 MHz CW microwaves. PDs ranged from 4 to 20 mW/cm^2 ($SAR = 0.15$ [W/kg]/[mW/cm^2]). When the PD was high enough to induce a monkey to select a cooler T_a (8 mW/cm^2 and above), PO/AH temperature increased 0.2–0.3 °C, but seldom more. It is of interest that early experiments on squirrel monkeys [Adair, 1970] had demonstrated that an increase in PO/AH temperature of this magnitude, produced by warming an implanted thermode, was necessary and sufficient to initiate changes in thermoregulatory responses, either autonomic or behavioral. In the Adair et al. [1984], report PDs lower than 8 mW/cm^2 produced smaller increases in PO/AH temperature but no reliable change in behavior. During 2.5 h RF exposures at 20 mW/cm^2, colonic temperature remained constant while PO/AH temperature increased 0.2–0.3 °C because the T_a selected was 2–3 °C cooler than normally preferred. Pilot experiments, in which an implanted tube was perfused with temperature controlled silicone oil to alter PO/AH temperature [Adair, 1988], indicated that autonomic thermoregulatory responses, for example, vasodilation, might play a mediating role in the mobilization of thermoregulatory behavior.

Chronic exposure. No changes in thermoregulatory behavior occurred during tests administered periodically during a 15 week chronic exposure (40 h/week) of sixteen squirrel monkeys to 2450 MHz CW microwaves (0, 1, and 5 mW/cm^2) in controlled T_a of 25, 30, or 35 °C [Adair et al., 1985]. The tests assessed the PD threshold for selection of a cooler-than-preferred T_a as well as the actual T_a selected. In this study, a large battery of physiological and behavioral endpoints was recorded, including measures of metabolic heat production, heat loss mechanisms, blood indices, and thermoregulatory behavior. The most robust consequence of chronic microwave exposure was a reduction in body mass, which appeared to be a function of RF field strength and may have been related to food consumption (not measured).

Partial body exposure. Adair [1985] reported that if only part of the body is exposed to the RF field, the change in selected T_a is governed by an integrated energy deposition over the whole body, not by energy deposited in some specific locus such as the brain. Squirrel monkeys, trained to control T_a behaviorally [Adair and Adams, 1980], were tested when either their trunk or head was effectively screened with microwave absorbing material during 10 min exposures to 2450 MHz CW energy. Contour maps, based on measurements of RF field PD, were determined in the vicinity of the animal subject under both conditions [Adair, 1988, 187p]. When the head was irradiated (trunk screened) at local PD from 15 to 60 mW/cm^2, three monkeys did not reliably select a cooler T_a. However, at 45 mW/cm^2 and above considerably increased agitation (observation only) accompanied head exposures. On the other hand, when the trunk was irradiated (head screened) and the experiment was repeated ($PD = 2–12$ mW/cm^2), a reliable reduction in preferred T_a occurred at a field strength only ~2 mW/cm^2 higher than the level determined during whole body exposure [Adair and Adams, 1983]. When the PD was averaged over the total cross sectional area of the body in all cases, the experimentally determined thresholds were the same. These results provide further evidence that the thermoregulatory response depends on the integral of energy absorption by the whole body, not on energy deposited in some specific body part.

A similar relationship was reported by Adair [1988], who measured changes in the metabolic heat production of monkeys undergoing partial body RF exposure in cool environments and compared the results with other data [Adair and Adams, 1983] in which exposure of the body was unrestricted. All the data points fell on a single function when the RF field strength was expressed as an average across the irradiated surface (projected area) of the monkey.

Exposure at the resonant frequency. A special case of whole body RF exposure occurs when the longest body dimension is aligned with the electric field vector (E polarization) and is 0.4 of the free space wavelength. This condition is called resonance and RF energy deposition in the body's tissues is maximal. When squirrel monkeys underwent 10 min whole body exposures at the resonant frequency (450 MHz CW, E polarization), behavioral thermoregulatory responses were mobilized less efficiently than was the case for comparable exposure at 2450 MHz [Adair, 1990]. This conclusion was based on a 40% higher SAR threshold for selection of a cooler T_a and higher levels of skin and deep body temperatures that resulted from this exposure. Studies of four monkeys (five sessions each), undergoing 10 min exposures to RF energy at PD ranging from 0.5 to 6.0 mW/cm^2 during behavioral thermoregulation, provided conclusive data. In contrast, when squirrel monkeys were exposed to 2450 MHz CW fields, thermoregulatory behavior efficiently regulated the skin and deep body temperatures at the normally preferred levels. This general finding includes partial body exposure [Adair, 1985], brief (10 min) exposures at SARs as high as 9 W/kg [Adair, 1987], and prolonged exposure (90–120 min) at SARs as high as 6 W/kg [Adair and Adams, 1983].

Surface vs. deep heating. Thermoregulatory behavior is usually triggered by stimulation of thermosensors in the skin. Because of the deeper penetration of RF energy at resonance, atypical thermal gradients in peripheral tissues and inefficient stimulation of these thermosensors may result. These events may lead in turn to longer latencies for the proximal stimulation of sensory end organs in the skin, delayed signals to the sensory cortex, and abnormal behavior patterns. In the absence of efficient peripheral heat loss, the extra heat generated deep in the body may quickly exceed the convective capabilities of the circulation, leading to a bias or offset in the regulated variable, deep body temperature. This situation is identical to that occurring during exercise, as has been elaborated by Shimada and Stitt [1983] and demonstrated for RF exposure by Nielsen and Nielsen [1965].

Other experiments, involving prolonged RF exposure at resonance, have been conducted to test the hypothesis that there is a significant delay in the mobilization of thermoregulatory behavior when a deeply penetrating RF field first appears [Adair, 1990]. The thermoregulatory behavior of four squirrel monkeys was measured in five tests on each animal that included a 120 min behavior baseline, followed by a 90 min exposure to 450 MHz CW microwaves at a PD = 5 mW/cm^2 (SAR = 3 W/kg). A 30 min period of behavioral thermoregulation (RF absent) terminated the test session. Colonic temperature, four skin temperatures, and the T_a selected by the monkey were measured every minute. For comparison, five tests were conducted on each monkey in a 2450 MHz CW exposure facility under an identical protocol and at a PD = 20 mW/cm^2 (SAR = 3 W/kg). Five 240 min sessions of behavioral thermoregulation, in the absence of RF exposure, constituted control data for each monkey. During the 90 min RF exposures (SAR = 3 W/kg), the patterns of behavioral thermoregulation were very similar at both frequencies. RF irradiation stimulated selection of a cooler environment that had stabilized, within the first 30 min, at levels 1.8 °C below baseline at 450 MHz and 1.9 °C below baseline at 2450 MHz. The selected T_a was such that the skin temperature, on average, was regulated at the level normally preferred. However, the steady state colonic temperature of the animals was regulated at a level 0.5 °C higher at 450 MHz than at 2450 MHz (0.74 °C above baseline at 450 MHz, 0.27 °C above baseline at 2450 MHz). The greater increase in deep body temperature at resonance, while carefully regulated, was evidently due to the deeper penetration of the longer waves into body tissues. As noted above, this stable offset, or bias, is identical to that occurring during exercise.

Thermal comfort. When no RF field is present, many endothermic species, including humans, will select a characteristic T_a that provides a sensation of thermal comfort. In the steady state, the T_a selected by a RF exposed animal is a linear function of the imposed field strength. Figure 2A shows this relationship for trained squirrel monkeys undergoing whole body exposure to a 2450 MHz CW field [Adair, 1990]. When no RF field is present (PD = 0 W/m^2), these animals select a T_a of ~35.5 °C. Berglund [1983] has demonstrated that such a function represents the conditions that provide a constant level of thermal comfort or operative temperature (T_o). Thus, the empirical function plotted in Figure 2A describes the combinations of T_a selected and imposed RF PD that yield a T_o of 35.5 °C.

Because the relationships between T_o, comfort, and thermoregulation are well understood for humans, Berglund [1983] was able to predict the effect of RF energy on human thermal comfort over a wide range of ambient conditions, as shown in Figure 2B. A critical variable in this calculation is that of clothing insulation (clo). Two families of curves are presented, one for nude persons (0 clo) and the other for persons wearing a warm vested suit or equivalent (1.2 clo). The functions describe loci of constant T_o (27.5 and 19.5 °C, respectively) and assume constant thermal comfort. For each clothing level (clo), lines are drawn for both beam (incident from one side) and diffuse RF radiation. The T_o lines are each further divided into two absorption classes ($\alpha = 0.5$ and 0.9) because absorption (α) varies with RF frequency. Figure 2B shows that the differences between beam and diffuse RF radiation are great; much larger T_a reductions are possible, for a given

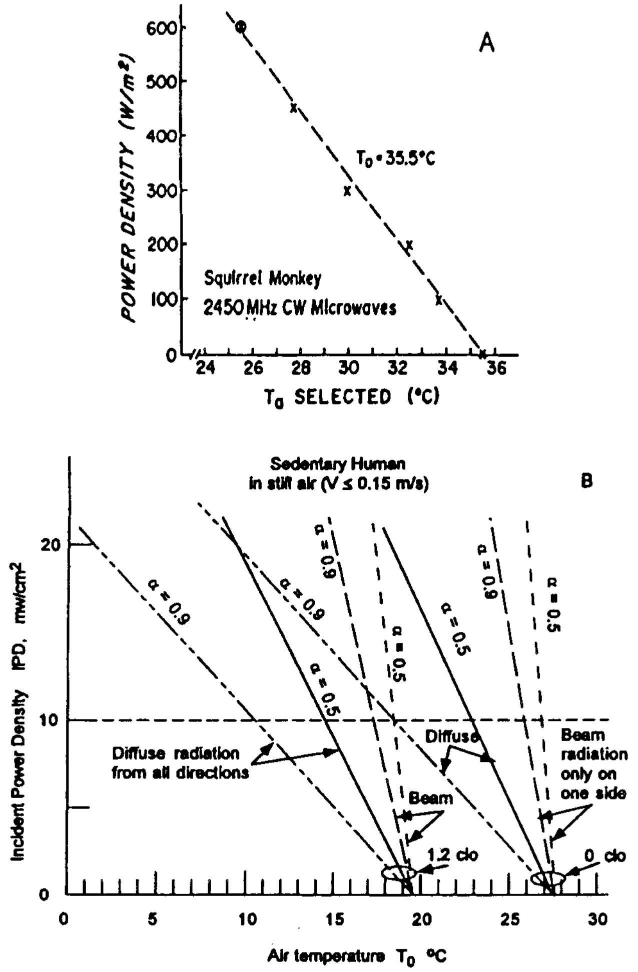

Fig. 2. **Panel A**: Steady-state air temperature (Ta) chosen by sedentary squirrel monkeys exposed to 2450 MHz RF energy at different PDs. To, operative temperature. **Panel B**: Predicted incident PD required for comfort of sedentary humans in various air temperatures at two levels of clothing insulation (clo). The effect of radiation beamed from one side and simultaneously from all directions is shown, as is the effect of 0.5 and 0.9-radiation absorptance (α). [Reproduced from Berglund (1983) with permission.]

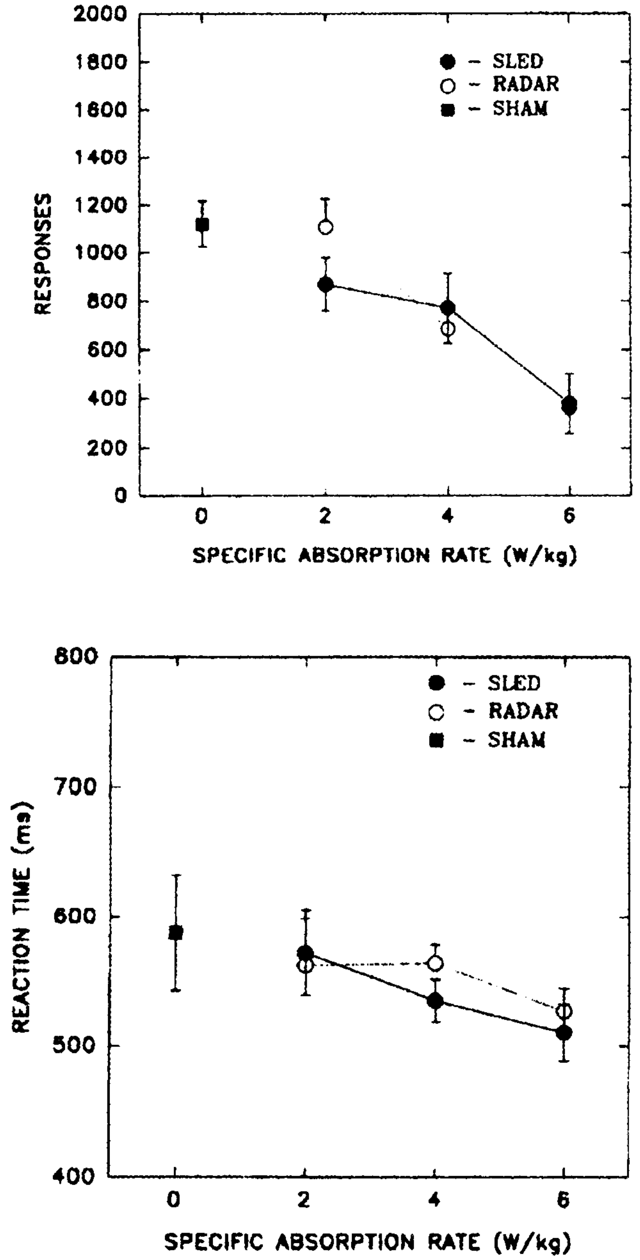

Fig. 3. Threshold for behavioral disruption by pulsed RF absorption at 5.62 GHz. The top panel shows total responses emitted by rhesus monkeys for sham and pulsed conditions. The bottom panel shows reaction time for monkeys responding to a visual stimulus during task performance. [Reproduced from D'Andrea et al., 1994 with permission.]

incident PD, with diffuse than with beam radiation. Also, thermal comfort for sedentary humans, wearing typical winter clothing, should be possible in a 10.5 °C (51 °F) environment with diffuse RF radiation at PD = 10 mW/cm^2, the current ANSI/IEEE C95.1-1999, 1999 safety guideline for frequencies above 3 GHz. Thus, the concept of radiant comfort heating as proposed by Pound [1980] may have the potential for improving the thermal environment in many situations, for example, the space environment, and perhaps for saving energy as well.

RF fields as positive reinforcement for behavior. Although it is abundantly clear that experimental animals will orient around a RF source in order to thermoregulate or will modify their thermal environment behaviorally if a RF source is present, it is not so clear that a RF field can serve as a positive reinforcement for operant behavior. Justesen [1988] observes that the presence of intense RF energy is not, in itself, a salient stimulus to escape behavior imply that the reinforcing power of a RF field might be low. Bruce-Wolfe and Adair [1985] attempted, with limited success, to train squirrel monkeys to work for 2450 MHz RF energy. The monkeys were first trained to select a preferred thermal environment [Adair and Adams, 1980]. Then the stimulus contingencies were changed so that the monkeys alternately selected between a draft of cool (10 °C) air and a 2450 MHz CW RF field accompanied by a draft of thermoneutral (30 °C) air. Three PD were studied (20, 25, and 30 mW/cm^2). Each of four squirrel monkeys underwent three 120 min sessions of behavioral thermoregulation under each test condition. Colonic and four skin temperatures were monitored continuously as were the T_a selected by the monkey and the percentage of time the RF field was activated. The percentage of time the monkeys selected the RF field, paired with thermoneutral air, averaged 90% at 20 and 25 mW/cm^2, but declined reliably to 81% at 30 mW/cm^2. Although the skin temperatures were lower than usually preferred in experiments when the RF field was chosen, the colonic temperature was regulated with precision at the normal level under all stimulus contingencies. Justesen [1988] has pointed out, however, that the stimulus conditions were complex in this study and that a cleaner experiment should be designed in which convective and radiant heat were not confounded.

Two exploratory studies by Vitulli et al. [1986, 1987] investigated the possibility that rats would learn to press a lever for 6 s of RF irradiation in a cold environment in order to maintain thermal homeostasis. A small refrigerator was outfitted as an operant test chamber and a small 437 W microwave oven (2450 MHz) served as the RF source. The two appliances were connected by a 20 in (60 cm) aluminum "waveguide" that was inserted between the doors of the two appliances; thus, RF energy could pass through into the refrigerator. No assessment of field strength dosimetry, or measures of the rats' body temperature(s) was made. T_a in the operant chamber was recorded from a wire thermometer placed in a 4.5 oz (~125 ml) jar of water. Rates of lever pressing for continuous reinforcement (CR) or fixed ratio (FR) schedules from FR2 to FR30 were recorded during 8–9 h sessions. Some rats were pretrained to work for infrared (IR) reinforcement, but response rate deteriorated after a shift to RF reinforcement. Operant response rate generally increased with an increase in FR but no RF PD related trends were evident in either study.

Marr et al. [1988] conducted a better controlled study than those cited above to explore the process of learning to operate a RF source. Four male rhesus monkeys, chair restrained inside an aluminum chamber, were trained to pull a response lever to control a source of 6.4 GHz CW microwaves. The RF energy was launched from a low gain transmission horn located at chest height ~70 cm in front of the animal. A 2 s irradiation at a PD = 50 mW/cm^2 (SAR = 12 W/kg), accompanied by a signal light, served as the reinforcement. Initially, each 60 min test session was preceded by a 15 min "cool-down" to a $T_a = 0 \pm 0.5$ °C to aid the learning process. In early sessions, lever responses were carefully shaped under CR using a method of successive approximations. Later, the schedule was gradually changed to fixed ratios as high as FR 20 if an animal learned to control the RF source behaviorally. One monkey failed to learn the response. Two others learned but their performance was mediocre. The fourth monkey learned to respond rapidly enough to produce frequent reinforcements, but no assessment was made of the T_a produced by this behavior or of any body temperatures. Instead, various extinction conditions were explored for 20 min periods in the middle ofindividual tests; these included no cue light, no RF field, and no light or RF field. Absence of the cue light did not change behavior but absence of the RF reinforcement lowered responding significantly. Marr et al. [1988] seemed to be more interested in the efficiency of the reinforcement schedules employed than in the effects of the resulting behavior on the animals' thermal state. No additional published reports have appeared from this group.

PSYCHOACTIVE DRUG/MICROWAVE INTERACTIONS

Although most of the published papers on the biological effects of drugs in combination with RF exposure have been discussed elsewhere [D'Andrea et al., 2003; Adair and Black, 2003], a few papers with behavioral end points should be mentioned here. Thomas et al. [1979] found that the increase in rat response rate on a fixed interval schedule produced by chlordiazepoxide was potentiated by exposure to 2450 MHz microwaves (1 mW/cm^2) even though the microwaves alone did not alter the trained behavior. They extended their findings to show similar effects with dextroamphetamine [Thomas and Maitland, 1979], and chlorpromazine and diazepam [Thomas et al., 1980].

Lai et al. [1986] investigated the effects of repeated exposure to low level microwaves on amphetamine induced hyperthermia in rats. The study was designed to determine if tolerance to the microwave effect would develop after repeated exposure and if the effect of microwaves could be classically conditioned to the circular waveguide environment. They had earlier reported [Lai et al., 1983] that amphetamine induced a smaller hyperthermia in rats, following a single 45 min exposure to 2450 MHz PFs in a circular waveguide, compared with the hyperthermic response of sham irradiated controls. In the 1986 study, animals were exposed in 10 successive sessions to RF energy (unconditioned stimulus) in waveguides (neutral stimulus). The unconditioned response was attenuation of amphetamine induced hyperthermia; they wondered if the waveguide environment could become a conditioned stimulus for this response. On day 11, the magnitude of amphetamine induced hyperthermia was measured following a session of either RF or sham exposure. The data indicated a potentiation of hyperthermia in rats sham exposed on that day (“conditioned effect”), an attenuation of hyperthermia in rats RF exposed on that day (“unconditioned effect”), both of which could be blocked with naloxone treatment. The conditioned effect was presumed to relate to some aspect of the microwave environment (e.g., waveguide, handling), but potential PF auditory cues were not discussed. In addition, no evidence for the development of tolerance to subchronic RF exposure was found when these data were compared to those from an earlier study, an unusual and perhaps invalid comparison.

A follow-up study examined the potential for classically conditioning the sodium dependent, high affinity choline uptake in frontal cortex and hippocampus of rats following a similar 11 session protocol, but in the absence of induced hyperthermia [Lai et al., 1987]. In this case, the animals were killed immediately following the 11th session in order to measure choline uptake in hippocampus and frontal cortex. They found that tolerance, defined as a decrease in response to microwaves, developed with respect to choline uptake in the hippocampus but not in the frontal cortex. An increase in choline uptake in the hippocampus and a decreased uptake in the frontal cortex were characterized as “classically conditioned” responses.

MICROWAVE EFFECTS ON COGNITIVE BEHAVIOR

Effects on Cognitive Performance

Animal studies. The behavioral disruption and work stoppage paradigms described above have been very useful for standards setting as they have provided a threshold (4 W/kg) for potential hazards of microwave radiation absorption. Some of the tasks used employed cognitive components. For example, cognition can be defined as information processing, which includes a variety of processes such as attention, perception, learning, and memory. The behavioral tasks described by de Lorge [1983] and D'Andrea et al. [1994] are vigilance tasks and involve attention processes by monkeys. The measure of this performance is the reaction time to the change of stimuli, either auditory or visual, to perform the task correctly.

Recently, D'Andrea [1999] pointed out, however, that little concerted effort has been made to evaluate other “cognitive” behaviors during microwave exposure. He postulated that that effects on some aspects of cognitive performance might occur at lower SARs than required for behavioral performance disruption. The whole body and partial body absorption of microwaves is unique at each frequency in the range of 10 MHz–100 GHz. One of the major concerns of occupational toxicity testing is the detection of early functional changes [Williamson, 1990] prior to complete stoppage of behavior. Neurobehavioral testing and evaluation of cognitive performance has proven valuable in identifying early changes produced by other toxicants [Annau, 1990]. However, there are only a few studies that have examined cognitive functions during or subsequent to microwave exposure with animal models.

In a recent study, Dubreuil et al. [2002] used a radial arm maze and a dry land spatial navigation task to evaluate head exposure to a 900 MHz GSM electromagnetic field (pulsed at 217 Hz). There was no difference between rats exposed for 45 min to 3.5 W/kg and sham exposed or cage control rats in performance of these tasks. A similar study using mice [Sienkiewicz et al., 2000] studied the effect of exposure to low intensity 900 MHz RFR pulsed at 217 Hz with a spatial learning and working memory task. Mice were exposed under far field conditions in a GTEM cell for 45 min each day for 10 days at an average whole body specific energy absorption rate (SAR) of 0.05 W/kg. No significant effects on radial maze performance were observed.

Lai et al. [1989, 1994] have explored the effects of RF exposure on learning in the radial arm maze. The earlier study [Lai et al., 1989] found that rats, acutely exposed for 45 min to 2450 MHz PFs (average whole body SAR = 0.6 W/kg), showed a learning deficit when compared with sham exposed controls. The later study [Lai et al., 1994] included drug treatments selected to reveal the role played by central cholinergic systems and endogenous opioids in this RF induced memory deficit in the radial arm maze. The experiment began with 5 days of familiarization with the waveguide exposure system and the maze. Rats then underwent daily RF or sham exposure for 45 min in the waveguide for a total of 10 days. Each animal was injected with one of the three drugs or normal saline (control) prior to being placed in the waveguide. Across the 10 training days, saline injected rats exposed to microwaves made significantly more performance errors in the maze than did their sham exposed counterparts. This behavioral deficit was reversed by pretreatment before RF exposure with the cholinergic agonist physostigmine or the opiate antagonist naltrexone. However, pretreatment with the peripheral opiate antagonist naloxone methiodide did not block the microwave effect, suggesting that peripheral opioid mechanisms are not involved in this learning deficit.

Wang and Lai [2000] trained three groups of rats, microwave exposed, sham exposed, and cage control, to locate a submerged platform in a circular water maze. The microwave group was exposed to 2450 MHz PFs (pulse width 2 μs, 500 pps, average PD 2 mW/cm^2, average whole body SAR 1.2 W/kg) for 1 h in a circular waveguide system immediately before each training session. When tested 1 h after the last training, a probe trial was given in which the platform was removed. Time spent where the platform was located during the probe trial was scored. It took microwave rats longer to locate the platform, implying that exposure to PFs caused a deficit in spatial memory.

Mickley et al. [1994]; Mickley and Cobb [1998] investigated memory deficits in rats exposed to microwaves and determined that the threshold for memory effects was 10 W/kg. In a series of experiments, the "remembering of recently explored objects" was evaluated to determine changes in working memory following exposure to microwave radiation. Rats were allowed 10 min to explore a novel object in a familiar test arena. At a later time (50 min) they were returned to the test arena, which now included the familiar object and a novel object. Memory changes were evaluated over a 3 min period by measuring each rat's exploration time of the familiar and new stimulus object. Memory loss was associated with relatively extensive exploration of the once familiar object. Rats were sham irradiated or exposed to microwave radiation at whole body SARs of 10, 8.5, 5, and 1 W/kg and brain and rectal temperatures were recorded. Rats exposed to 10, 8.5, or 5 W/kg showed a reliable brain hyperthermia. Only the 10 W/kg treatment, however, produced a significant memory disruption.

Luttges [1980] evaluated the effects of microwave exposure on learning and memory in mice and found an enhancement of performance. He exposed mice, following daily training, to 3 GHz PFs at approximately 18 mW/cm^2 average power levels (estimated whole body SAR 13 W/kg) and documented small but reliable increases in performance. The treatments were delivered post-trial for a 15 min period with the sham treated mice handled in the same manner as exposed mice, except that no radiation was delivered. He found that repeated replications with different aged animals produced the same effects. The microwave memory facilitation was found in both automated active avoidance testing and in single trial, passive avoidance test. The small facilitation of memory was observed when the mice were tested 20 days after original training.

Beel [1983] repeated the study by Luttges [1980] and again found significant enhancement of learning and memory following 15 min exposure, both with five consecutive days of multiple trial, active avoidance training, and with single trial, passive avoidance training. The performance changes were evident in tests given 1 week after training and microwave exposure. On repeated daily exposures of 30 min duration, enhanced performance during the first 3 days of training occurred with performance deterioration thereafter. Thus, an increase in total irradiation time appears to produce a detrimental effect.

Nelson [1978] determined the effects of PFs on the learning of new behaviors by male squirrel monkeys in a repeated acquisition task. For 30 min periods, the monkeys were repeatedly exposed to 5.62 GHz microwaves pulsed at a repetition rate of 600 pps. Pulse widths were 0.5 μs at an average incident PD of 11 mW/cm^2 and 2 μs at 43 and 53 mW/cm^2. A standard gain horn was used to irradiate the monkey's ventral surface. Response acquisition was impaired following 30 min of exposure to an incident PD of 53 mW/cm^2, but not to 11 or 43 mW/cm^2. An increase of 1.9 °C in rectal temperature was observed in monkeys irradiated at a PD of 53 mW/cm^2. Effects were not observed without concomitant hyperthermia. The reported effects were transitory, with no evidence of irreversible impairment of learning ability. The threshold PD necessary to significantly disrupt behavior was estimated to be between 45 and 50 mW/cm^2 (estimated whole body SAR range 3.2–3.6 W/kg). The results of this experiment were compatible with the hypothesis that behavioral changes were directly related to hyperthermia in the monkey.

Recently, D'Andrea et al. [2000] reported the effects of a head resonant microwave frequency on time estimation behavior (temporal response differentiation) in rhesus monkeys. It requires the monkey to press a lever for a minimum period of time (10 s) and release the lever before a maximum time (14 s). Releasing the lever too early or too late starts another trial. Food pellets were delivered at the end of each "correct" time interval. Distributions of lever hold durations were compiled and analyzed. Monkeys were exposed for up to 1 h to 500 MHz CW or PFs (1000 pps, 500 ms pd) at whole body SARs of 0.8–6.0 W/kg. The major effect observed was a reduction in the total number of hold times during exposure sessions at 6 W/kg. The distribution of hold times, however, did not appear to change. Thus, in this experiment a measure of "cognitive performance" was not more sensitive to microwave exposure as the effect was not significant until a dose-rate of 6 W/kg.

A unique attempt with operant behavior to assess the effects of RF fields associated with cell phones was that of Bornhausen and Scheingraber [2000]. Pregnant Wistar rat dams were continuously exposed to 0.1 mW/cm^2 of 900 MHz EMF pulse modulated at 217 Hz (GSM digital phones). The offspring of these rats and sham exposed ones were tested in a series of 15 h learning sessions with food reinforcers given for lever responses. Although the tasks were sensitive enough to discriminate between "learners and non-learners" on lever presses and inter-response intervals, no differences were observed between the offspring of exposed and sham exposed dams.

From the few studies that have been done, evaluating cognitive performance during or subsequent to microwave exposure, conclusions cannot easily be drawn. Some deficits are observed at whole body SARs less than 4 W/kg, while an enhancement of performance was observed at approximately 13 W/kg. The different cognitive tasks, different exposure systems used, modulation parameters employed, frequency discrepancies between studies, differences in test species, and exposure duration all conspire to make easy interpretation of this sparse literature difficult.

Human studies. The popularity of the mobile phone has resulted in concerns over alleged effects from exposure of the head to microwave radiation from the phone antenna. Several studies have sought to evaluate the effects of mobile phone irradiation on cognitive processes in humans.

Preece et al. [1999] used a simulated analogue mobile phone to irradiate the left temple of 32 human subjects while they performed a series of cognitive tests over a 25–30 min period. A subset of tests from a cognitive test battery (Cognitive Drug Research computerized assessment system) was used. The exposures used 915 MHz as either CW (1 W power), pulse modulated (217 Hz, 12.5% duty cycle), or a sham exposure with no irradiation. A three-way crossover design was used with subjects serving under all conditions. The only test affected was a choice reaction time as an increase in speed (a decrease in reaction time). The change in choice reaction time was actually an improvement in performance during irradiation. This experiment showed no changes on many other response variables, for example, word recall, simple reaction time, spatial working memory, etc., implying a very selective effect and not a general malaise as might be expected with hyperthermia.

Edelstyn and Oldershaw [2002] also found performance enhancements. They investigated the effects of acute mobile phone exposure on tasks that tested functioning of the attention system of 38 human volunteers. One group was exposed to emissions from a 900 MHz mobile phone for 30 min. Cognitive performance was assessed before and after exposures with neuropsychological tests that revealed no deficits but rather performance improvement following mobile phone exposure. Another evaluation by Hladky et al. [1999] using human volunteers did not find significant effects from microwave exposure during mobile phone use. Twenty volunteers participated in two experiments exploring the acute effects of using the Motorola GSM 8700 mobile phone on CNS function. Visual evoked potentials and memory were unaffected by mobile phone exposure.

Koivisto et al. [2000] tested cell phone frequency RFR at 902 MHz (pulsed 217 Hz) on cognitive performance in human subjects. A cognitive test battery was used to evaluate subject's performance with and without field exposure. The results on simple and complex tasks showed that RFR exposures speeded up response times in simple reaction time, vigilance tasks and that the cognitive time needed in a mental arithmetic task was decreased. However, this study suffered from several methodological problems. In a replication and extension of their previous work, Haarala et al. [2003] made methodological improvements (double blind procedure, counterbalanced order of testing, and SAR measurements) and performed a battery of similar cognitive tasks. Although the reaction times and the accuracy of answers were very similar to the previous study, the previous results were not replicated.

Koivisto et al. [2001] evaluated the effects of the pulsed GSM mobile phone signal (902 MHz, pulsed 217 Hz) on subjective symptoms in subjects in two single-blind experiments. The RFR exposure lasted about 60 min in Experiment 1 and 30 min in Experiment 2. The results showed that there were no differences between exposure and nonexposure conditions, suggesting that a 30–60 min exposure to this RF field does not produce subjective symptoms in humans. Thus the effect on cognitive behaviors in their two previous experiments (above) would not be confounded by subjective sensations from the mobile phone exposure.

Krause et al. [2000] studied the effects of 902 MHz microwaves emitted by a mobile phone while subjects performed a memory task both with and without exposure (217 Hz, 2 W peak power, 0.25 W average power) in a counterbalanced order. The electroencephalogram (EEG) was recorded during the performance of the memory task and exposures. The exposure to microwaves significantly increased EEG power in the 8–10 Hz frequency band, but only during the memory task (N-Back task of previously presented digits). Memory task performance itself was not altered during the exposures.

At the present time, the evidence that RFR exposure from mobile phone use can influence cognitive performance is very weak. Only a few studies have been performed and firm conclusions cannot be drawn until more studies are conducted with improved methodology and standardized protocols. In a recent review, Cook et al. [2002] pointed out that a common problem in bioelectromagnetics research is the lack of reproducibility of reported effects. If variables are not carefully controlled, then the variance within the experimental data will be tremendous and have a negative impact on any experiment. Conclusions regarding health and safety cannot be drawn from the few human cognitive studies until additional research is done.

SUMMARY

Research conducted during the past three decades has shown that exposure of laboratory animals to RFR can cause a variety of behavioral changes. These changes range from subtle effects such as perception of microwave pulse-induced sound to behavioral disruption and complete cessation of behavioral performance due to hyperthermia. Thermoregulatory behaviors have been investigated. Cognitive performance evaluations during RF exposure have begun in animal models and in human studies. A central theme of this research has been to determine a relationship between SAR and other field characteristics and adverse consequences of exposure to microwave radiation.

Studies that have evaluated the effects of microwave exposure on the performance of well learned operant tasks have been the primary avenue for determining this relationship. In such studies, performance disruption (or complete work stoppage) was evaluated by first establishing a stable behavioral performance and then determining the effects of RF exposure on the baseline performance. Typically, the effect is a decreased rate of responding or decreased reaction time, although occasional increased rates of responding and reaction time have been observed. The key factor, adding to the value of this protocol, is that the laboratory animals and human subjects are exposed to RF while performing the behavioral task. One of the first demonstrations of behavioral disruption during microwave exposure was conducted by de Lorge [1976], as described above, with rhesus monkeys trained on an observing task, which is similar to vigilance behavior in humans. This experiment demonstrated that disruption of observing behavior was associated with a rectal temperature increase, during microwave exposure, by 1 °C or more. This temperature increase was highly correlated with a whole body SAR near 4 W/kg. This protocol, measuring behavioral disruption, has proven to be one of the most sensitive and repeatable measures of potentially harmful biological effects.

In all cases, the disruption of ongoing behavior during acute RF exposure is associated with a 1 °C increase of body temperature. The disruption of a highly demanding operant task is a statistically reliable endpoint that is associated with whole body SARs in a narrow range between 3.2 and 8.4 W/kg, despite considerable differences in carrier frequency (225 MHz–5.8 GHz), species (rodents to rhesus monkeys), and exposure parameters (near and far field, CW and pulse modulated). The time averaged power densities associated with these thresholds of disruption ranged (by calculation or measurement) from 8 to 140 mW/cm^2. Thermal changes seem to account for nearly all of the reported behavioral effects of absorbed RF energy across the limited frequency range explored.

Those studies that report disruption of behavioral performance (or work stoppage) during acute RF exposure also involve tissue heating, mild heat stress, and alternate behaviors that are thermoregulatory in nature. As Stern [1980] and others have pointed out, the reduction of responding on a learned task may simply reflect the animal's attempts to engage in other behaviors (e.g., escape), which are thermoregulatory in nature and incompatible with learned behaviors such as lever pressing for food pellets on a prescribed schedule. Because the threshold for disruption of ongoing behavior in rats and nonhuman primates always exceeded a whole body SAR of 3.2–4 W/kg [de Lorge, 1976, 1979; D'Andrea et al., 1977, 1994; de Lorge and Ezell, 1980; D'Andrea and de Lorge, 1990], the latter value has again been adopted as the working threshold for unfavorable biological effects in human beings in the frequency range from 100 kHz to 300 GHz. RF fields can serve as either positive or negative reinforcers and can disrupt simple as well as more complex behaviors associated with cognitive capabilities. Thermal changes seem to account for all of the reported behavioral disruption effects of absorbed RF energy across the limited frequency range explored. Those studies that report changes in behavioral performance during acute RF exposure also involve some level of tissue heating, perhaps mild heat stress, and alternate behaviors that are thermoregulatory in nature. This information provides a scientific database from which safe exposure standards can be derived.

Alteration of behaviors that suggest changes in cognitive performance, both learning and memory, have also been reported for exposures that result in overt heating of the animal subject [Nelson, 1978; Luttges, 1980; Beel, 1983; Mickley et al., 1994]. The human studies utilize partial body exposures at low power densities and cannot be easily explained by overt heating of the body. It is difficult to draw any conclusions at this time because there are too few studies with human subjects. Additional studies that expand the experimental parameter space and evaluate variables such as frequency, modulation, PD, and task complexities are needed to begin to have an understanding of mechanisms involved. Once this is accomplished, then models can be developed that may predict cognitive disruptive or enhancing effects.

Other behavioral changes have been reported following low level chronic microwave exposure, as described above. Many reports from Eastern European countries and the former Soviet Union have reported that long term exposure of animals to low level RF energy can produce assorted effects of a deleterious nature. Although the preponderance of studies has involved short term RF exposure to high level fields (>10 mW/cm^2), many have argued that the effects of low level RF exposure (<10 mW/cm^2) should be the focus of extensive further investigation by the research community. The conduct of superior long term, low level RF research is easier said than done. Large numbers of laboratory animals must be exposed to highly controlled RF energy, in highly controlled environments, and for long periods of time. A great many animals must be studied, including a control group (RF absent) that is otherwise treated identically to the RF exposed group. The animals' living environment must be conducive to good health and the RF exposure of individual animals must be the same in terms of field strength and uniformity. Some studies have met these requirements while many have not.

Often intermittent low level exposures have produced results yet failed the test of replication or given entirely different results than the original study. For example, D'Andrea et al. [1986a] exposed rats intermittently to 0.5 mW/cm^2 2450 MHz microwaves for 90 days and reported changes in time-related lever pressing behavior. However, a replication experiment reported different effects and failed to replicate the lever pressing findings reported by the D'Andrea et al., study [DeWitt et al., 1987]. Both of these experiments failed to replicate earlier findings reported by Rudnev et al. [1978] and Shandala et al. [1979]. One can only conclude that these experiments were below the threshold for reliable effects and cannot be used for safety standard setting.

A following study at 2.5 mW/cm^2 reported additional effects that were statistically reliable, but this study was never replicated [D'Andrea et al., 1986b]. The few biological effects reported subsequent to chronic microwave exposures [Lovely et al., 1983] such as reduced food intake in exposed rats, cannot be viewed as adverse to the health of the exposed laboratory animal. Moreover, none of the reported biological effects during or subsequent to chronic, low level exposure has ever been independently replicated. For these reasons, it is implausible to use the low level exposure studies to define thresholds for hazards to man from microwave exposure.

RESEARCH NEEDS

Over at least the last 20 years, behavioral tests have been widely used to assess diverse consequences of microwave exposure on assorted mammals. The threshold of ~4 W/kg for the disruption of complex behavioral performance in several animal species and under diverse exposure conditions has formed the basis for the setting of human exposure guidelines since 1982. The fact that this threshold is often accompanied by an increase in body temperature of ~1.0 °C is fortuitous, but does not necessarily mean that the behavioral disruption is thermally mediated. Other kinds of studies have quantified RF thresholds for alteration, but not necessarily stoppage, of a variety of learned and unlearned behaviors. In general, these thresholds are lower than those mentioned above, lying between 1.0 and 4.0 W/kg depending on the frequency, and may or may not involve changes in body temperature. Essentially, all of the behavioral changes in these categories are reversible upon extinction of the RF field and appear to leave no residual effects. Whether there may be underlying permanent changes of a biochemical or neurological nature is unknown; there seems to be no experimental evidence for long term changes in the basic functioning of the organism.

However, all of the published research on behavioral alteration and work stoppage has been conducted on laboratory animals; none has been conducted on human beings. Somehow, equivalent behavioral experiments must be conducted on human volunteers to (1) confirm the purported "hazardous" nature of RF exposure on performance and (2) to gain some insights into the changes in body temperatures that may be expected to occur. Extrapolation to human beings of thresholds of reversible changes in animal behavior, while useful as interim bases for standard setting, must be superceded by hard data on the species in question, homosapiens.

Thermoregulatory behavior in the presence of RF fields has been well studied in several species, including nonhuman primates, and appears to be quite efficient under most conditions, including exposure SARs equivalent to twice the resting metabolic rate. An exception may be irradiation at the resonant frequency of the organism under study. More data on this question would be helpful. Rodent species appear to have difficulty using intense RF fields as discriminative stimuli for escape or avoidance behaviors and perhaps this difficulty in attribution may impact the accidental exposure of humans, as suggested by Justesen [1988]. For example, strong fields from commercial RF heat sealers and dielectric heaters have the potential to heat the operators without their knowledge; service engineers who climb AM and FM broadcast towers may not be aware of the symptoms of accidental overexposure [Adair et al., 2003]. Further research on human perception of RF fields, at a variety of frequencies and exposure configurations, is urgently needed.

Thermal changes seem to account for most of the reported behavioral effects of absorbed RF energy across the limited frequency range explored. Those studies that report changes in behavioral performance during acute RF exposure also involve tissue heating, mild heat stress, and alternate behaviors that are thermoregulatory in nature. Certainly the demonstrated reinforcing and aversive properties of RF energy are derived from tissue heating. Whether low level RF exposure, which characterizes the chronic studies, also involves tissue heating is unknown, but acclimation would surely ameliorate the impact of such heating in a short time [Goldman, 1983]. Studies that evaluate cognitive performance, in more detail, may discover a hierarchy in task sensitivity to RF exposure and heating. Hancock and Vasmatzidis [1998] evaluated human literature on performance in thermally challenging environments and discovered that indeed some cognitive tasks were quite sensitive to small increases in body temperature. Further evaluation of cognitive performance in humans, while under RF irradiation, with different tests of performance would add greatly to our understanding of RF biological effects.

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