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# Behavioral Effects of Microwave Radiation Absorption

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HHS Publication FDA 85-8238

# Behavioral Effects of Microwave Radiation Absorption

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CENTER FOR DEVICES AND RADIOLOGICAL HEALTH

WHO Collaborating Centers for:
- Standardization of Protection Against Nonionizing Radiations
- Training and General Tasks in Radiation Medicine
- Nuclear Medicine

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## FOREWORD

In October 1982, the Food and Drug Administration established the Center for Devices and Radiological Health (CDRH) by merging the Bureau of Medical Devices and the Bureau of Radiological Health.

The Center develops and implements national programs to protect the public health in the fields of medical devices and radiological health. These programs are intended to assure the safety, effectiveness and proper labeling of medical devices, to control unnecessary human exposure to potentially hazardous ionizing and nonionizing radiation, and to ensure the safe, efficacious use of such radiation.

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Also, CDRH technical reports in radiological health are made available to the World Health Organization (WHO) under a memorandum of agreement between WHO and the Department of Health and Human Services. Three WHO Collaborating Centers, established under the Bureau of Radiological Health, continue to function under CDRH:

WHO Collaborating Center for Standardization of Protection Against Nonionizing Radiations;

WHO Collaborating Center for Training and General Tasks in Radiation Medicine; and

WHO Collaborating Center for Nuclear Medicine.

We welcome your comments and requests for further information.

John C. Villforth
Director
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## PREFACE

Within the Center for Devices and Radiological Health (CDRH), the Office of Science and Technology (OST) is responsible for developing programs to protect the public health. An important aspect of this work is the dissemination of scientific information to public health professionals, the medical and scientific community, and the general public.

During the last 40 years there has been an increasing use of radiofrequency and microwave equipment in a variety of important consumer and industrial applications including communications, radar, food processing, and medical applications. At the same time reports of subtle biological effects from this form of nonionizing radiation have generated concerns about potential human health hazards from incidental exposure. Inconsistencies in the research results have further complicated the interpretation and usefulness of these reports for predicting effects in humans.

This publication examines one specific area of microwave-biological effects research, i.e., behavioral effects. It attempts to provide a critical assessment of the available information and to resolve some of the apparent discrepancies in the research data. In addition, it defines some areas where more information is needed. It represents the work of leading experts in the areas of microwave induced behavioral effects and also that of microwave engineers intimately involved in the engineeering aspects of this work.

We recognize that no report will meet the needs of all readers but every effort was made to address the major areas in this field in a comprehensive manner.

Kshitij Mohan

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The enthusiastic exchange of ideas and information by all the workshop participants which ultimately resulted in this report is gratefully acknowledged. Many others, too numerous to mention, have also made substantial contributions and helpful suggestions during the preparation of this volume. Special thanks are offered to the many anonymous reviewers who took the time and effort to critically review and comment on each manuscript. Their comments have contributed greatly to the overall quality of this report. The efforts of Alyce Neff and Alice Rohan are especially appreciated for the preparation of the final copy for this report.

ABSTRACT

Monahan, John C. and John A. D'Andrea, Editors. Behavioral Effects of Microwave Radiation Absorption. HHS Publication FDA 85-8238 (August 1985) (pp. 159).

The need for an understanding of the biological effects induced by exposure to microwave radiation has increased in recent years because of increased usage and applications and also concerns about potential adverse health effects. Although many research studies have been conducted to examine the question of biological effects, the information is scattered in many diverse sources. This publication brings together in a single source the major research findings related to the behavioral consequences of microwave exposure. In addition it attempts to provide a critical assessment of this information and to provide a perspective upon which the reader can interpret the findings.

This publication begins with a review of behavioral-microwave research in the Soviet Union and then proceeds to examine the work of researchers in the Western countries. Both learned and unlearned behaviors are examined in the context of microwave induced effects. Other important areas which are covered include: selecting appropriate animal models, extrapolation of animal data to humans, dose considerations, and problems inherent in this type of research.

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# SOVIET RESEARCH on MICROWAVE-BEHAVIOR INTERACTIONS

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## ABSTRACT

Soviet researchers generally consider that microwave exposure results in an initial increase in excitability of the nervous system. This is followed by a period of adaptation with subsequent depression; an excitability "rebound" is then seen during the post-exposure period. The extent and character of the effects depend on the wavelength, intensity, and nature of the field as well as the duration of the exposure. Most important, however, is the duration of the exposure. In animals, effects have been reported down to 10 $\mu W/cm^2$ if the exposure is long enough (7-8 hours/day for 3-4 months). Tasks most commonly used for "standard setting" research, using rats, are: spontaneous motor activity, threshold for jerking of paws from an electrified metal bar, measure of food intake over a 20-minute period, measure of "work performance," and shuttle box avoidance. Tasks in which the animals are highly trained or very familiar with are considered to be insensitive to microwave effects. The Soviet (and Eastern European) literature continues to be the major source of information on microwave effects in humans. Although these studies still suffer from a lack of data on the circumstances of irradiation and the simultaneous presence or absence of other factors, there is evidence of a greater awareness that these factors are important considerations.

## INTRODUCTION

The Soviet and Eastern European literature on the biological effects of microwaves have been previously reviewed by Dodge (1969) and Dodge & Glaser (1977). These articles provide excellent overviews of the reported effects. In addition, the references cited provide other sources (in English) where one can probe the subject in more detail.

My familiarity with the subject, aside from the aforementioned reviews and their accompanying references, arises primarily from my involvement in the US/USSR cooperative agreement in the field of environmental health. This agreement, signed in 1973, initially dealt only with chemical agents. A new problem area, "Study of the Biological Effects of Physical Factors in the Environment," was added in 1975 with D.I. McRee of the National Institute of Environmental Health Sciences as the U.S. topic leader and M.G. Shandala of the A.N. Marzeev Institute of General and Communal Hygiene (Kiev) as the USSR topic leader. The first topic under this problem area was the study of the biological effects of microwave radiation and a program was developed which emphasized effects of microwaves on the central nervous system and behavior. Workshops on the subject have been held in Kiev in 1977 and 1981 and in Seattle in 1979. Proceedings of the Seattle workshop were recently published (1981). In addition, a workshop on the nervous system effects of electromagnetic waves (0-300 GHz) was held in May 1982 in the United States. In preparation for this workshop, both sides exchanged literature surveys on the subject (Lovely, 1981; Shandala et al., 1981). The surveys focused on the methods used for studying nervous system effects with special emphasis on their relative sensitivities.

This article will summarize that portion of the USSR survey dealing with microwave radiation, with emphasis on behavioral effects. In addition, some material from the workshops will be included.

## BACKGROUND

The Soviet philosophy toward setting exposure standards (irrespective of the substance or factor) has been that functional, not pathological, changes should serve as criteria in setting those standards. An obvious problem with this philosophy is ascertaining whether or not an observed change is, in fact, "harmful." Until recently, it appeared that any observed change was considered detrimental. Indeed in the overview, it is stated that "...in order to guarantee complete assurance in the safety of permissible levels, sub-threshold levels which do not cause detectable functional changes in the organism of animals and man have been adopted as maximum permissible levels for the population in our country up to the present time."

There is now evidence, however, of a growing concern about significance for the organism of observed changes. They state, "working out adequate methods for assessing the functional condition of the organism under the influence of physical environmental factors is one of a number of the pressing problems faced by experimental medicine. The solution to these problems can be accomplished only by applying complexes of tests and integrating the merits of different methods based on a reliable mechaninsm for showing the biological effect of physical environmental factors."

In contrast to much of the work in the United States, Soviet investigators have emphasized effects discovered in conditions of prolonged exposure (up to 4 months) of animals to microwaves. Moreover, they attach considerable importance to evaluating the ability of the functional systems to return to normal after exposure has been discontinued. Typically, animals are examined 1 to 3 months post-exposure.

In discussing the effects of microwaves, they state that "single exposures show quite varied effects. Under the influence of different levels and durations of exposures, a certain phasing of these effects is observed. The diversity of methodology, however, often complicates evaluation of the results." Clearly, this last statement applies to the U.S. literature also.

As already mentioned, conditions of prolonged exposure to microwaves are considered more significant. In their opinion, very thorough studies have been performed on the behavioral effects in animals exposed to incident power levels of 1-10 $mW/cm^2$. In general, at least two phases are seen: an increase in the excitability of the central nervous system followed by depression. Sometimes a period of adaptation is observed between the two phases. They state that there is some argument as to whether the first phase (excitability) is "harmful" (again, evidence for concern about significance for the organism of observed changes). The second phase (depression) is, however, considered to be an "absolutely harmful" one. The magnitude of the effect varies with wavelength and duration of exposure. They emphasize, however, that both phases will be seen at all power density levels between 1-10 $mW/cm^2$, if the duration of exposure is long enough.

It is conceded that behavioral effects, in animals, below 1 $mW/cm^2$ are more controversial. Levels below 5 $\mu W/cm^2$, CW, are considered to be without effect. Effects down to 5 $\mu W/cm^2$ have been reported. They state, however, that "the variety of exposure conditions, experimental designs, and species of animals tested often makes it impossible to compare results directly." They go on to state that a definite conclusion can, nevertheless, be made; vis-a vis, "the novelty of a test plays an important part in its sensitivity."

## BEHAVIORAL METHODS USED IN THE USSR

Commonly used behavioral methods are listed in Table 1. The Kotlyarevsky one-cage method consists of a long, two compartment box. The larger compartment is brightly lit and the smaller compartment is relatively dark. The end of the brightly lit compartment contains a food trough. A small light over the trap door separating the two compartments, when lit, signals that food is being put into the trough. The trap door opens when the investigator raises the lid to the box. On the underside of the lid is a mirror for the experimenter to observe the rat. Endpoints measured are the time it takes (1) until the rat crosses the trap door (latency) and (2) to run to the trough and take the food (see Silverman, 1978, for a more complete description and drawing of the chamber). The Yakovleva method consists of measuring respiratory and cardiac responses conditioned using a 15 percent ammonia solution as the unconditioned stimulus. The conditioned stimulus was not specified.

Table 1. Behavioral methods used in the USSR

I. Conditioned Reflex
- A. Aversive
  1. T-shaped maze - animal receives electric shock if enters wrong arm of maze
  2. Shuttle box
  3. Passive Avoidance (not common)
- B. Appetitive - Kotlyarevsky one-cage method
- C. Autonomic - Yakovleva method

II. Unconditioned Reflexes and Naturally Occurring Behaviors
- A. Spontaneous Motor Activity
- B. Orienting Reflexes
- C. Threshold for Motor Response to Electrical Stimulation
  1. Paws
  2. Different Brain Structures

The most sensitive methods for demonstrating effects of microwaves were reported to be the Kotlyarevsky chamber and the shuttle box, methods of registering spontaneous motor activity, and thresholds to responses elicted by electrical stimulation of the skin.

The authors again point out that the sensitivity of the method for studying conditioned reflexes depends to a significant degree on the novelty factor; "therefore it makes sense to study unstable conditioned reflexes." Different approaches have been taken in this regard. In one approach, conditioned reflexes are developed before the beginning of the experiment but not to any significant degree of stability. Another approach is not to begin conditioning until exposure is initiated. The third approach (and stated to be the most useful) is to obtain a (relatively) stable conditioned reflex to one conditioned stimulus (CS) before exposure, then use a different CS 3 to 4 months after the beginning of exposure and still another CS during the post-exposure period.

Soviet toxicological work on chemicals, at least, commonly utilizes so-called "functional stress tests" (Pavlenko, 1975) to uncover subtle effects on compensatory and adaptive mechanisms in the nervous system. Examples are exposure to drugs, to cold, to noise, and work to exhaustion. The extent to which this approach has been taken with microwaves is not entirely clear. However, statements about measuring the "functional load" or examining the "functional burden" occur throughout the overview. At the A.N. Marzeev Institute in Kiev, examination of the so-called working capacity in rats is a common procedure. Two approaches are taken: measurement of "dynamic working capacity" and "static working capacity." In the former, rats are placed on a rotorod rotating at 14 rpm; the time the animals remain on the rod is measured. In the latter, the time rats will cling to a cloth covered plank at an angle of 30° (from vertical) is measured.

## SPECIAL STUDY ON COMPARATIVE VALUE OF BEHAVIORAL INDICATORS

At a US-USSR Workshop on "Improvement of Methods for the Study of the Effect of Environmental Factors on the Central Nervous System and Behavior," held in Suzdal, USSR, Shandala et al. (1978) presented the results of a study designed to evaluate the procedure which revealed effects at the earliest possible time or at the minimum incident power. The exposure was 7 hours/day for 1 month (500 μW/cm$^2$) or 3 months (all other exposure levels). The methods used are listed in Table 2 and the results are summarized in Table 3.

Table 2. Special study on comparative value of behavioral indicators

*Purpose:* Determine those indicators which revealed differences at the earliest possible time or at the minimum incident power

*Methods:* Non-conditioned reflexes only

1. Open field - three 1 minute samples at 15-20 second intervals
   a. Number of squares crossed
      (1) First day - exploratory activity
      (2) Second day - motor activity
   b. Number of times the 9 central squares were crossed
   c. Latent period to exit from the 9 central squares
   d. Number of times rat stood on its hind paws.
2. Threshold for jerking forepaws from metal rod (100 Hz, 1 ms pulse width)
3. Food consumption
   a. Latency to begin
   b. Amount eaten in 20 minutes
5. "Working capacity"
   a. Dynamic - rotorod rotating at 14 rpm
   b. Static - clinging to cloth covered plank at 30° angle from verticle

*Exposure:* CW, 2375 MHz; 500, 50, 5, or 1 μW/cm$^2$; 7 h/day; 1-3 months

*Measurements:* 10 to 30 day intervals

Table 3

*Most Sensitive Indicators for Measuring Depression of CNS:*

| | |
|---|---|
| 1. Exploratory activity<br>2. Number of times central squares crossed<br>3. Vertical activity | 1st day only |

*Most Sensitive Indicators for Measuring Stimulation of the CNS:*

1. Electrical stimulation of paws
2. Latent period to begin eating
3. Exploratory activity

*Insensitive Indicators*

1. Latency for leaving 9 central squares
2. Motor activity

The authors concluded that measurement of exploratory activity and threshold for a response to electrical stimulation of the paws should be included in any microwave study. The fact that exploratory activity was sensitive to microwave exposure whereas motor activity was not (see Table 2 for definitions) is taken by the authors as further confirmation of the role of novelty in the sensitivity of tests.

## SPECIFIC STUDIES ON THE EFFECTS OF MICROWAVES AT THE MICROWATT/cm² LEVEL

Two studies reported at the US-USSR Workshop in Seattle and one at the 1981 US-USSR Workshop in Kiev are of interest. Rudnev & Navakatikyan (1981) reported behavioral effects of microwaves using the same exposure conditions as those given above for the study on the comparative value of behavioral indicators. In fact it may actually be from the same animals since all experimental conditions were the same except that shuttle box avoidance was included along with the other tests listed in Table 2. The rats were 4 to 5 months old at the beginning of the experiment, exposures were 1 to 3 months following exposure. There were 8 to 15 animals/group. At 500 μW/cm² incident power, signs indicative of central nervous system depression were apparent by the 20th day of irradiation as measured by a decrease in exploratory activity, increase latency for alimentary behavior, elevation in threshold for electrodermal stimulation, and decrease in work efficiency. Apparent excitation was observed 30 to 90 days following exposure. At 10 and 50 μW/cm², signs interpreted as indicative of central nervous system stimulation were present early (10 to 20 days after initiation of exposure) followed by depression with some tests. However, in others they report only stimulation. Results following exposure were also mixed, i.e., recovery was seen in some tests but not others. With some, changes in the opposite direction occurred. Effects at 1 and 5 μW/cm² were reported to be slight. They do state, however, that post-irradiation excitation of the central nervous system is a consistent finding at all exposure levels examined.

Dumanskii et al. (1981) examined the behavioral effects of 9400 MHz, PW, at 5, 25, 40, 60, and 115 μW/cm² for 12 hours per day for 4 months. The parameters for the PW were not given. The rats were also examined for 2 months following irradiation. Tests used were open field, threshold for paw jerk, static work (clinging to inclined plank), and the Kotlyarevsky chamber. They reported no effects at 5 and 25 μW/$cm^2$. At all other levels, an increase in the threshold for paw jerk was observed. At 40 μW/$cm^2$, this was not seen until after 90 days of exposure. A decrease in "static work capacity" was seen at 60 and 115 μW/$cm^2$. Again, at 60 μW/$cm^2$ this was not observed until 90 days of exposure. They reported the effects generally lasted 30 days post-irradiation but not 60 days.

Rudnev (1981) reported the effect on the offspring of exposing pregnant rats 7 hours/day for 20 days of pregnancy with 2375 MHz, CW, at 10, 50, or 500 μW/$cm^2$. Behavioral responses measured were threshold for paw shock, motor activity, and performance in a shuttle box. The latter was measured 4 months post-exposure. The other two parameters were measured at 1, 2, and 4 months post-irradiation. No significant effects were seen at 10 and 50 μW/$cm^2$. Depression of motor activity was observed at 1 (but not 4) month following exposure to 500 μW/$cm^2$. This, to my knowledge,represents one of the few Soviet behavioral studies utilizing gestational exposure to microwaves.

## MICROWAVE EFFECTS ON HUMANS

Dodge (1969) states "an often disappointing facet of the Soviet and East European literature on the subject of clinical manifestations of microwave exposure is the lack of pertinent data on the circumstances of irradiation; frequency, effective area of irradiation, orientation of the body with respect to the source, waveform (continuous or pulsed, modulation factors), exposure schedule and duration, natural shielding factors, and a whole plethora of important environmental factors (heat, humidity, light, etc.). In addition, the physiological and psychological status of human subjects such as health, previous or concomitant medication, and mental status is also more often than not omitted."

This statement most probably applies to the literature up to the present time. There is, however, evidence in the USSR National Literature Survey of an increased awareness of these problems. For example, it is stated that "study of the effect of microwaves on the state of health of a person encounters considerable difficulties connected mainly with separation of this factor from many others acting simultaneously with it, and also the necessity of measuring the active factor (dosimetry.)" Further, they point out that some authors have argued for specific effects of microwaves without taking into consideration the state of health, physical and social indices, and other conditions such as temperature, humidity, noise, light conditions, etc., acting simultaneously with microwaves.

Nonetheless, they consider it "proven" that long-term exposure to low levels of microwaves with an energy down to 1 mW/$cm^2$, either alone or in consort with other factors, gives rise to "a symptom complex in which disorders of a neurological character occupy a leading place." Dodge (1969) details the Soviet classification of syndromes reported. The USSR National Literature Survey states "originally, a separate nosological form, the so-called 'radiowave illness' was given to this complex of symptoms. In present times, however, such a division of symptoms into a separate nosology for microwaves is considered unjustified inasmuch as a similar symptom-complex may arise in response to a series of other exposures" (e.g., extremely low frequency electromagnetic waves and noise).

Two specific points are made about the frequency, distinctiveness, and character of the symptomatology observed. First, while the wavelength, intensity and character of the field (impulse or steady) are important, the duration of exposure is most important. Second, there is considerable variation in individual sensitivity to microwave effects with extended manifestations of these dysfunctions noted usually in persons with "weakened nervous systems." What this entails is not clear but coping poorly with stressful situations appears to be implicated as an important indicator.

Currently, studies on humans are being conducted primarily along two lines: (1) epidemiological studies on child and adult populations living in zones of known exposure to industrial frequency microwaves and (2) experimental studies on volunteers using electroencephalography, evoked potentials to visual and auditory stimuli, reaction times to various stimulus modalities, cardiovascular and respiratory responses to stressors, and various psychophysiological tests.

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# THRESHOLD EFFECT: LIMITS of BEHAVIORAL ASSESSMENT of MICROWAVE DETECTION

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## INTRODUCTION

The possible role of a microwave field as a stimulus is explored. The nature of such a stimulus and the procedures necessary to measure its perceptual properties are examined. The paper focuses on the demonstration of a sensory continuum produced by a microwave field of varying intensity, then on the absolute sensitivity threshold (RL, *Reiz Limen*), the lower end of the putative sensory continuum associated with microwave intensity. It then considers a course for future research on microwaves as stimuli.

In this discussion putative behavioral effects of microwaves are viewed from an orientation that is almost orthogonal to that of the other papers presented in this Publication. The research approach described takes its inspiration and finds its roots, not in behavioral toxicology or in the study of ionizing radiation, but rather in the earliest days of experimental psychology, which had its modern origin in the work of the German psychophysicists and sensory physiologists during the last century.

## BEHAVIORAL THRESHOLDS FOR MICROWAVE FIELDS

There are several types of behavioral thresholds that may be operationally defined, each unique because of the manner in which the stimulus interacts with behavior. Each type of threshold is associated with a different amount of energy deposition and each demonstrates a different type of biological potency. Listing them in descending order of energy deposition they are: lethal threshold, pain threshold, escape-avoidance threshold, and detection threshold. The interpretation of these thresholds is reasonably clear. Another type of threshold is the differential threshold. The differential threshold is the smallest separation between two stimuli that can be detected.

The RL's discussed here are distinct from these other thresholds that have been of principal concern elsewhere in this Publication. The detection threshold is a complex event which has been adequately described in the general sense by Signal Detection Theory (SDT), which is a branch of information processing theory, games theory and communications theory (Green & Swets, 1966). SDT was developed to describe and specify the performance of an ideal observer. An ideal observer may be either an artificial system or a natural system. SDT recognizes several parameters as significant in determining detection performance. These parameters include the inherent noise in the detection system, the noise in the signal, the difference between the noise and signal +noise distributions (the relative strength of the signal against a background of noise), the *a priori* and estimated probabilities of the occurrence of a signal or a nonsignal in a

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given point in time, the costs of incorrect rejections and of false alarms; the rewards of correct detections and correct rejections. The final factor is the establishment of a criterion for detection.

The RL and the conditions under which it can be measured are very well understood for all continua that have been studied. It typically corresponds to the smallest quantity of energy that when deposited in an organism can be associated with a well defined behavioral response. Thus the RL is the smallest quantity that can be shown to have biological potency over short intervals of time. Determination of the RL is thus of special significance in setting exposure standards.

## CONDITIONS FOR MEASURING AN RL

An RL cannot be measured for every sensory continuum. There is only one condition where it is well defined, that is when there is a transduction mechanism in the organism that scales the physical magnitude of the stimulus to psychological magnitude. A necessary step preliminary to the measurement of the RL, therefore, is the demonstration that as stimulus magnitude varies, sensation magnitude varies (a prothetic continuum exists; see Stevens, 1975). There are two alternatives to the existence of this relationship. First, changes in stimulus intensity lead to changes in sensation quality (a metathetic continuum exists). Second, there is no change in sensation related to changes in stimulus magnitude (no sensory continuum).

Demonstration of this relation is based on the production of a psychometric function (poikilitic function). A psychometric function relates stimulus magnitude, the independent variable, to a response measure that due to training will be proportional to stimulus magnitude. If this relationship cannot be demonstrated the RL is not defined and cannot be measured. It is therefore necessary to develop an adequate measurement procedure, a behavioral testing procedure, to evaluate the subject's performance while manipulating stimulus intensity. This procedure may be directly compared to the process of developing an electronic microwave detector, except that in this case a living organism serves as the detector element. The design goals are the same in building any kind of detection instrument: the instrument must be stable under all sorts of variability, except variability on the particular dimension one is interested in measuring. On that dimension variability of behavior of the detector system must be relatively great so that there will be adequate amplification by the system as the signal to be detected varies.

## MICROWAVE FIELDS AS UNIQUE STIMULI

As microwave fields of fixed frequency are varied in intensity two different types of thresholds have been measured, each associated with a different sensory modality. The microwave field may act as a heating agent, activating a normal sensory system in a normal manner (Adair & Adams, 1980). The microwave field may also activate a normal sensory system as a nonoptimal stimulus (Muller's Law: producing a normal sensation by abnormal means), the "microwave hearing" phenomenon (Lin, 1978).

Here we consider the possibility that the microwave field can act as a unique stimulus. Operationally this means that the microwave field will be considered to be a unique stimulus only if it is not confused with nor is masked by a conventional thermal and/or acoustic and/or other stimulus. Successful use of a thermal and/or auditory and/or other stimulus as a masker of a microwave stimulus, or the confusion of one of these stimuli with a microwave stimulus would tend to disprove the possibility that a microwave field can possess unique sensory properties. This proof of uniqueness based on masking and confusion can be applied to any putative unique stimulus regardless of its nature, including all regions or the nonionizing region of the electromagnetic radiation spectrum.

When microwave fields are viewed as (unique) stimuli principles developed through the study of the psychophysics of many sensory continua, including vision, are applied to an as yet unexplored region of the electromagnetic spectrum. There are several advantages to this approach. For the experimental psychologist it provides a unique opportunity to extend the principles derived from the study of behavior to a new class of putative stimuli with which the experimenter presumably has no personal experience. For those concerned with the study of the mechanisms of physical interaction of microwave fields with biological systems a number of unique possibilities exist using this approach. This is the case since behavioral experiments are uniquely capable of revealing functional changes in vital brain structures that are too small to evaluate by standard dosimetric techniques or which would be damaged by the application of these techniques. For those concerned with health and safety related issues, the exploration of microwave fields as sensory stimuli and, in particular the determination of absolute sensory thresholds, provides one of the most relevant and experimentally most well defined means for determining the biological potency of microwave fields.

Microwave fields as unique sensory stimuli have not received extensive consideration, but a small body of research on unique sensory properties of ELF fields is emerging. Therefore, an experiment from our laboratory that examined the sensory properties of 60 Hz electric fields will be described as paradigmatic of the microwave field experiments that will ultimately be performed. This experiment is discussed in the following paragraphs.

## METHODS, RESULTS AND DISCUSSION OF A PARADIGMATIC EXPERIMENT

The goal of the experiment (Sagan et al., 1981) was to determine whether variations in a vertical 60 Hz electric field, a putative discriminative stimulus along a prothetic continuum, led to changes in sensation in the manner expected on such a continuum. With the demonstration of the existence of a prothetic continuum. The goal was then to measure the RL for the 60 Hz field.

Essentially the same steps would have to be followed with a microwave field. Modifications in the apparatus described would be required to ensure uniform microwave field distributions. The procedure described here minimizes the exposure duration and allows the subject to control the onset of exposure, so at all power levels the impact of microwave heating will also be minimized.

*Subjects.* The subjects were adult male Sprague-Dawley (Simonsen) rats, 22.5 h water deprived.

*Apparatus.* The subjects were tested in four identical test chambers housed in isolation cubicles. The experiment was controlled by a PDP-11/70 computer located outside of the laboratory.

In Figure 1 a subject can be seen in position in the test chamber between the two parallel plates, which were energized with the 60 Hz field. Three response levers (illuminated discs) were located in the test panel for the subject to work on. Extending out to the right of the test chamber were fiber optic guides which were used to illuminate the response levers. Other fiber optic guides sensed the levers' operation. Drops of deionized water, the reinforcers, were delivered through a tube also extending to the right of the test chamber.

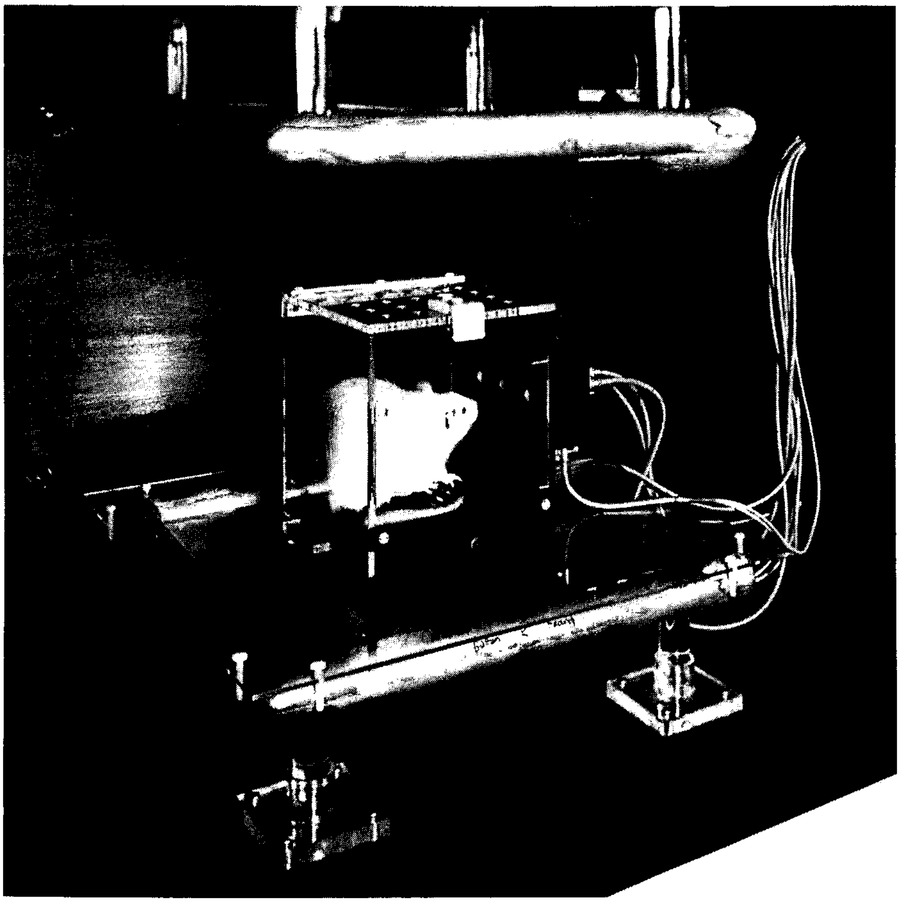


Figure 1. One of the four test chambers that was used in the paradigmatic 60 Hz experiment is illustrated. The fields are established between the aluminum plates positioned on Plexiglas posts above and below the test chamber. Seen above the subject's head are the three lights indicating the positions of each of the three response levers. Extending to the right of the test chamber are the plastic fiber optic guides used for illumination and sensing of presses and the water delivery tube.

*Procedure.* Training the subjects to make the field discrimination proceeded through a number of stages chosen to maximize the chances of successful performance. An added benefit of this training procedure was that it obtained sufficient data for each subject to allow that subject to serve as its own control: an extensive performance history on a well studied sensory continuum, loudness of a tone, was obtained for comparison with performance on the field discrimination. This procedure incorporated features of explicit discrimination training on the relevant stimulus dimension (Lashley & Wade, 1946), training on an irrelevant continuum (Honig, 1969), stimulus shaping (Lawrence, 1949, 1950) and errorless discrimination learning (Terrace, 1966).

Figure 2 shows a flow chart for the test procedure. Each 90 minute session was comprised of a number of extended trials separated by inter-trial intervals (ITI's). The number of trials received by a subject was determined jointly by the particular test parameters selected by the experimenter and by the subject's behavior.

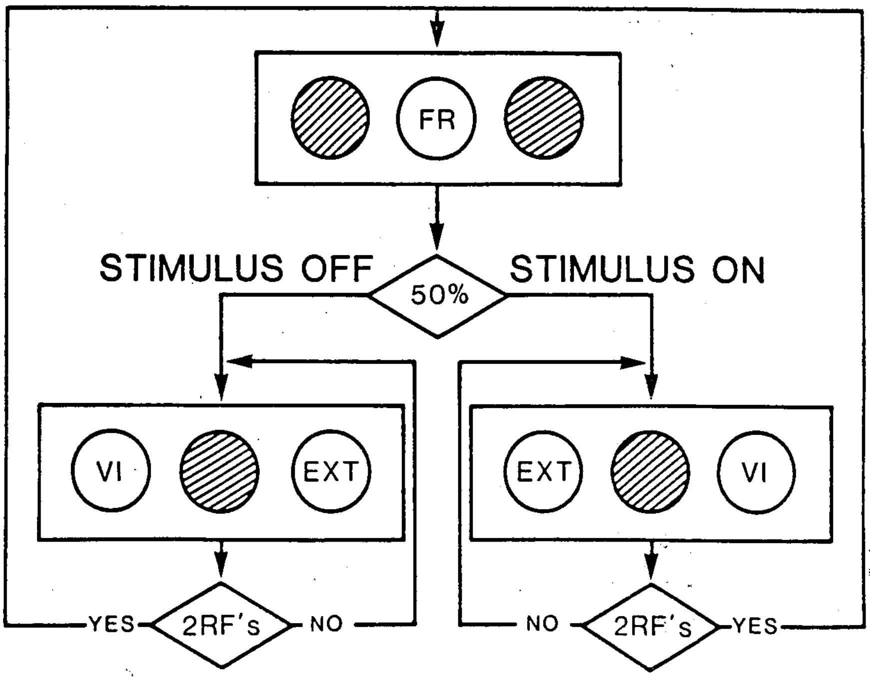



Figure 2. The course of a single trial is charted. The ITI conditions are shown at the top while the two trial conditions are shown at the bottom. The flow of the trial is indicated by the arrows. Each box represents one of the 3 states of the experiment. The circles located in the boxes symbolize the three response levers and their associated stimuli: the diagonal lines symbolize a darkened lever while the open circles symbolize an illuminated lever. The letters on the illuminated levers indicate the schedules imposed; FR for Fixed Ratio, VI for Variable Interval and Ext for Extinction. These schedules are explained in the text. RF stands for Reinforcement.

The subject had three response levers (Fig. 1). During ITI's, the center lever was illuminated and the outer levers were dark while during the trials the center lever was dark and the outer levers were illuminated. Presses had programmed consequences only when they occurred on illuminated levers. A trial was initiated when the center lever was being pressed a predetermined number of times (Fixed Ratio, FR3, requirement). The imposition of the FR requirement ensured that the subject was ready to work on the trial and was not engaged in some other activity, such as grooming, when the trial began.

In the determination of the psychometric function (and if possible the RL) stimuli of varying intensity were discriminated from a zero stimulus condition. Half the trials were stimulus trials while the remainder of the trials were no stimulus trials. The stimuli were never turned on during ITI's.

The stimulus levels were varied according to a staircase procedure (see Blough & Blough, 1977 for a discussion of techniques commonly used in selecting stimulus level). The intensity of the stimulus on any trial was jointly determined by the initial stimulus intensity selected by the experimenter and by the performance of the subject over the last three trials. Each session began with a stimulus that could easily be discriminated from the no stimulus condition by the subjects. The stimulus was then reduced by a fixed increment over a number of trials until over the last three trials it was not reliably discriminated from the no stimulus condition. Failure to reliably discriminate was indicated by a discrimination ratio (see below) of less than 0.45 for those three trials. On the next trial the stimulus was increased by an amount three times larger than the amount by which it had been decremented. The stimulus was increased by this amount on each succeeding trial until the stimulus had been successfully discriminated again, using the same three trial standard. The intensity was now decreased on the next stimulus trial. This down-up-down cycle was repeated over and over throughout a number of test sessions.

The subject's task was to indicate whether a stimulus was or was not present on each trial. For a given subject one of the two outer levers was designated the "stimulus lever" and the other outer lever was designated the "no stimulus lever." This assignment was fixed over the course of the subject's participation in the experiment. Since one lever was correct for each sort of trial, it was possible to compute a simple discrimination ratio of correct presses divided by total (correct+incorrect) presses. Defined this way chance performance is indicated by a score of 0.5 while perfect discrimination is indicated by a score of 1.0.

On stimulus trials presses on the lever designated as correct were reinforced with drops of water according to a Variable Interval 20sec (VI20) schedule. Presses on the other illuminated lever were never reinforced. On a no stimulus trial the conditions were reversed. A trial lasted (with the previously noted exception) until two reinforcers were obtained. When the second reinforcement was delivered, the stimulus was turned off, the outer lights turned off and the center light turned back on. Note that only data obtained during the first VI were used in calculating the RL's.

To ensure that the subjects did not simply alternate between the two illuminated levers during the trial (a likely tactic if the discrimination was difficult), a Change-Over Delay (COD), essentially a penalty for guessing, was imposed. The COD required that when the subject changed from the stimulus lever to the no stimulus lever during a trial, or vice-versa, no press would be reinforced until the designated delay period, 6 seconds had passed. Each change-over started another COD.

The following stages of training were employed:

1. *Training on Procedure*: A tone 20 dB above noise (64 dB SPL) was the discriminative stimulus while the subjects were trained to respond on the discrimination procedure. Training continued until performance was fully stabilized.

2. *Control Psychometric Function and RL*: A psychometric function and RL were obtained for the loudness of the tone.

3. *Addition of Field, Fading of Tone*: The field was introduced for the first time; it was presented along with the tone and co-varied along with the tone as the procedure for measurement of the psychometric function and RL continued. During this stage the

tone was faded out: its maximum intensity was cut by 5 dB in each of 2 steps and then set to 0.

4. *Field Psychometric Function and RL:* The field alone served as the discriminative stimulus; the psychometric function and RL for the field alone was obtained.

Figure 3 shows for a single subject (R80021) the course of acquisition of the pattern of discriminated responding required by the training procedure. Two response measures are compared to illustrate the high degree of behavioral control achieved by the discriminative stimulus, a tone 20 dB above ambient noise level in the test chamber. The upper two panels show the response rate, in presses/min, produced on each of the two levers depending on the stimulus condition. The rate of responding on each lever starts at a low level, with the non-tone lever preferred independent of the stimulus condition. Over the first five sessions (7.5 hours of training), the response rates separate. The rate of responding on the correct lever slowly increases, but the rate on the incorrect lever stays essentially unchanged from that observed in the first training session. The bottom panel shows the discrimination ratios associated with the rates of responding shown in the upper panels. The discrimination ratio starts out at chance, shows little change for the next four sessions, then shows a largely continuous increase for the remaining 29 sessions shown. The drop in performance seen in test session 25 resulted from an apparatus failure during the course of the session. The performance of this subject is typical of that for the other 15 subjects in this group.

Figure 4 shows for a single subject (R80033) a psychometric function relating discrimination ratio to tone intensity, measured in dB above the average noise level in the test chambers, 64 dB SPL. This figure is based on descending threshold determination runs from the second 3 tone-only RL measurement sessions made over a 5d period. The form of this function is as expected for stimulus dimensions where the sensation magnitude is proportionate to the stimulus magnitude: discrimination ratio is a monotonic function of stimulus intensity. The curve presented here is typical of that for the other 15 subjects. It is also typical of individual session curves as well as individual threshold determination curves.

Figure 5 shows psychometric functions for four subjects (R80021, R80023, R80029 and R80031) relating discrimination ratio to 60 Hz electric field level, measured in kV/m. This figure, based on descending threshold determination, runs from 3 field-only RL measurement sessions made over a 5d period. The form of these functions is the same as that seen in Figure 4, when a tone, alone, served as the discriminative stimulus.

Figure 6 shows the RL's obtained during the various stages of the experiment. Data are from 16 subjects collected over 5 sessions. The standard errors reflect the variability between subjects. The stages shown in this figure correspond, from left to right, to the stages of training previously described. Two pairs of bars are shown for Stage 3 during which a biasing procedure was applied to lower the sensitivity of the test procedure. The result can be seen in a doubling of the tone RL obtained for each group of 5 sessions. Note that while the mean was increased, the standard error was not affected. When there was a joint tone and field discriminative stimulus both the tone and field thresholds are shown; these values are, of course, not independent. It would be safe to assume that even as the starting value of the tone was reduced over these stages, the tone alone would determine the threshold level until it was removed in the final stage of training.

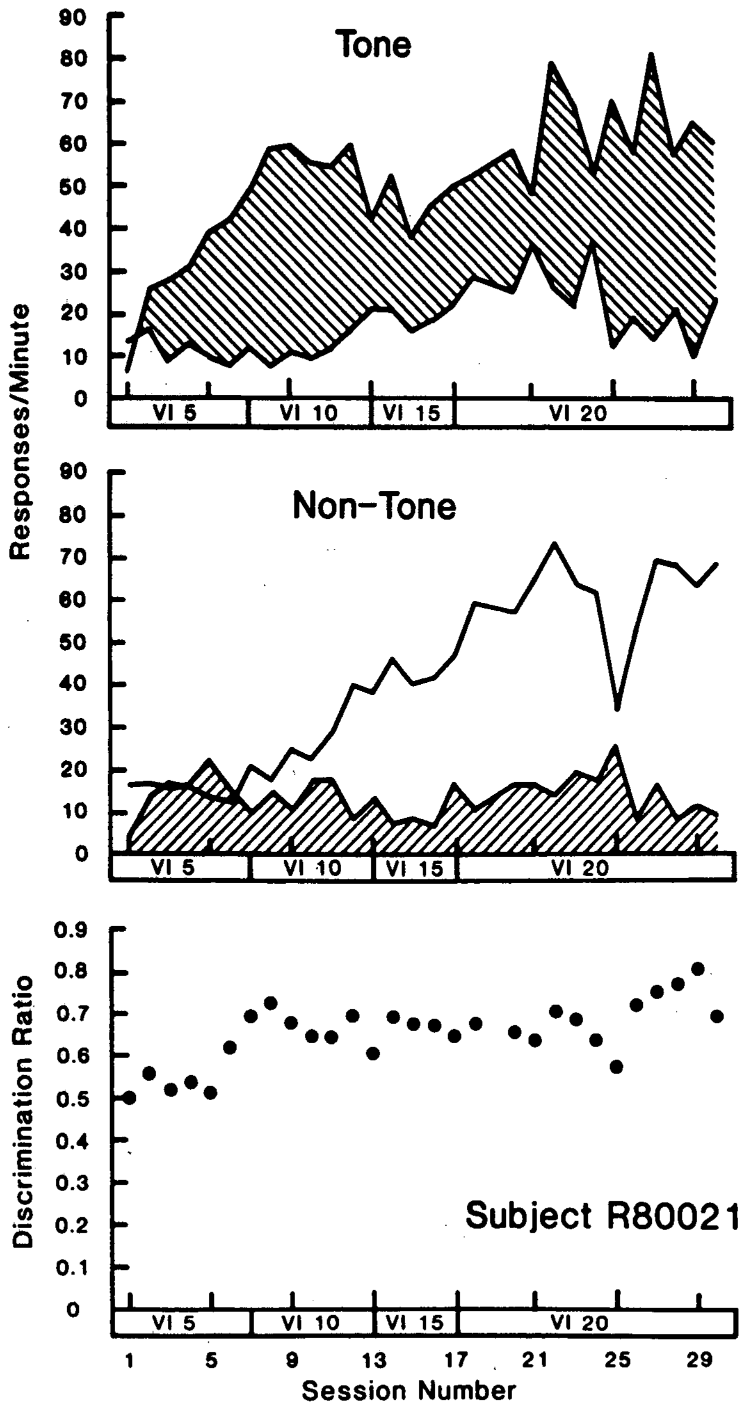
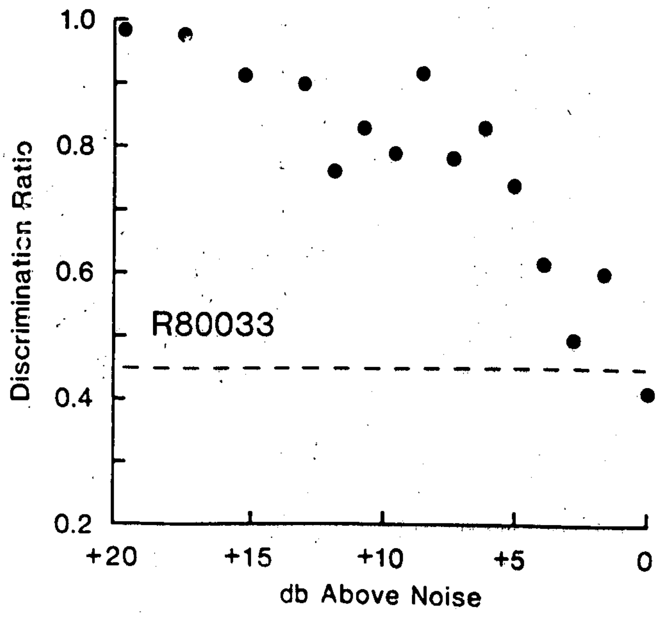



Figure 3. This figure shows the course of typical development of stimulus control in a naive subject using the testing procedure. The top two panels show the stimulus dependent changes in response rate on the two levers during the first 30d, 45h, of training conducted over a period of 6 wks. The bottom panel shows the corresponding discrimination ratio for each 1.5h session.

Figure 4. This figure shows the psychometric function relating discrimination ratio for the auditory (training) discrimination to the stimulus magnitude expressed in dB above noise, 64 dB SPL for a single subject. These data come from three threshold measurement sessions.



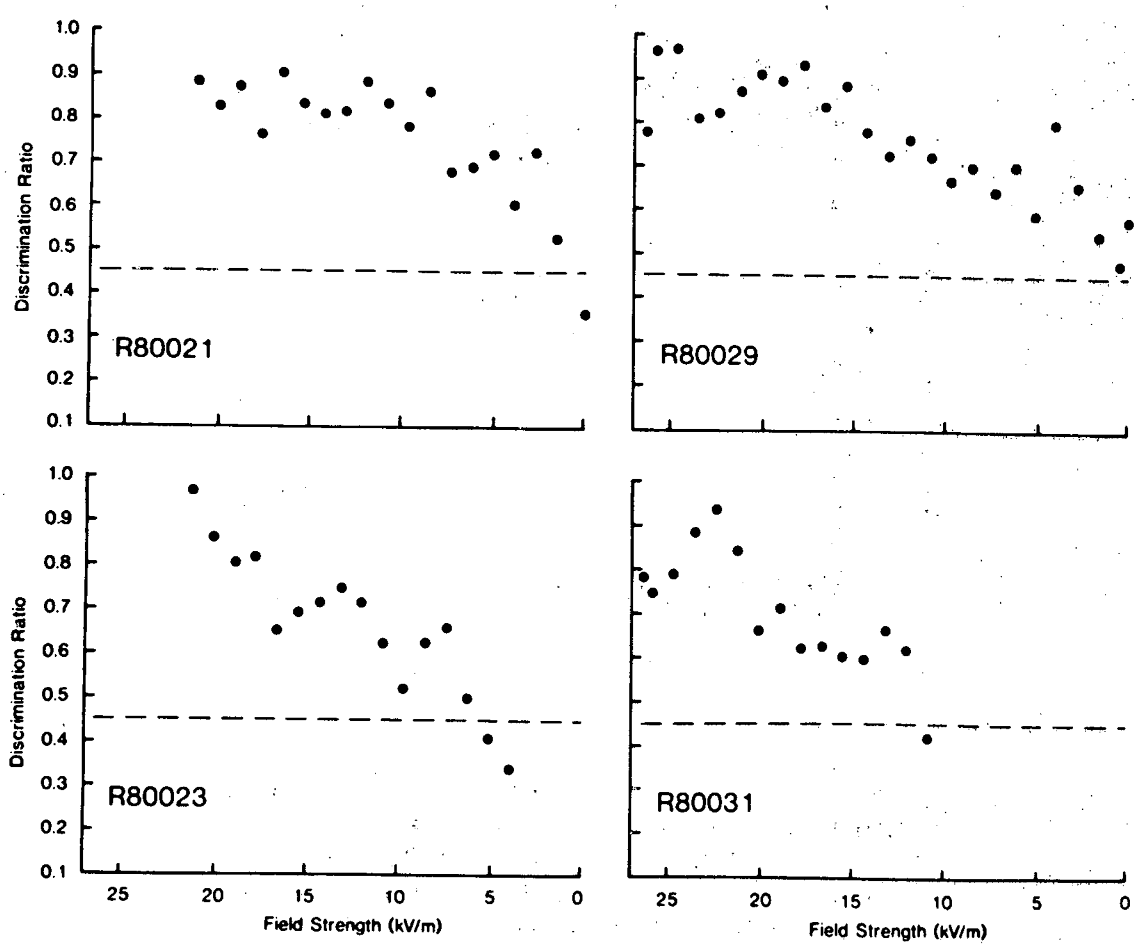




Figure 5. This figure shows the psychometric function relating discrimination ratio for the 60 Hz (test) discrimination to the stimulus magnitude expressed in kV/m for four subjects. These data come from three threshold measurement sessions.

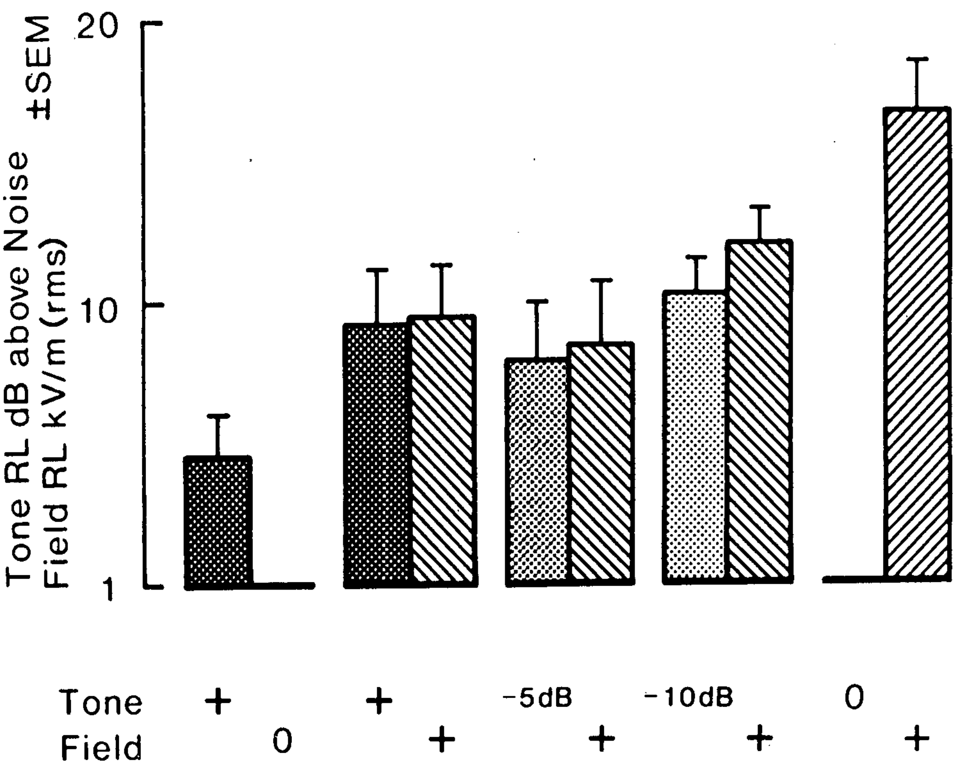
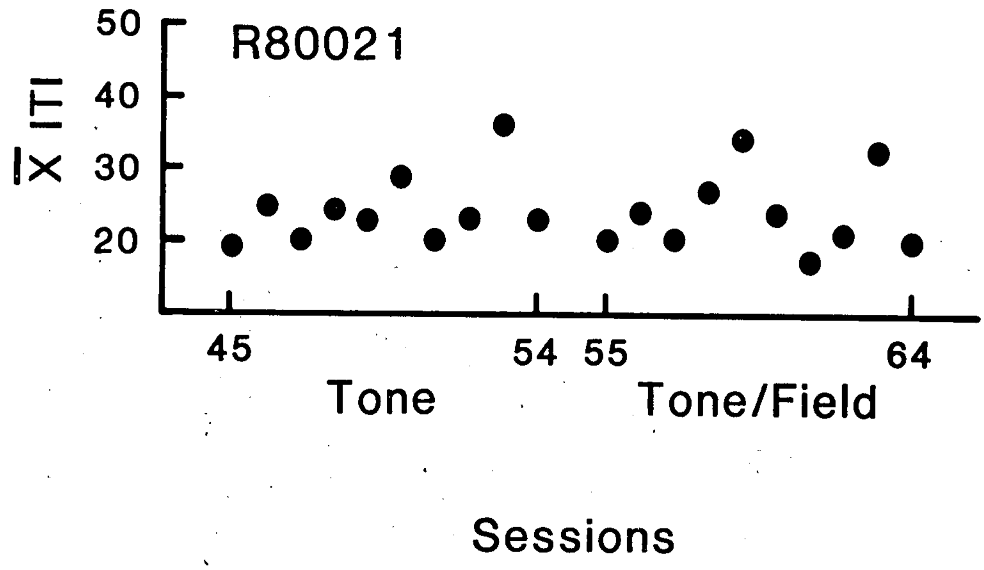



Figure 6. This figure summarizes the threshold estimates obtained at various stages of the training and testing of the subjects in the experiment. Each bar (or pair of bars) represents the data of 16 subjects collected over 5d of threshold measurements. The error bars (SEM) reflect variability between subjects.

None of the subjects was observed making orienting or startle responses during field presentations at any field level tested. The overt behavior of all subjects was consistent between tone, field+tone, field and no stimulus trials: the subjects remained oriented toward the response panel end of the test chamber with either all legs on the floor or in a slightly rearing position, with fore paws on or in the vicinity of the response levers. No changes in amount of grooming or area groomed during field exposure were observed.

Figure 7 shows the mean ITI during the 10 sessions preceding the first introduction of the 20 kV/m and the 10 sessions following its introduction. This figure shows that there was no measureable aversiveness associated with the introduction of a 20 kV/m field. It would be expected that if turning on the 20 kV/m field on half of the trials had an aversive effect there would be an increase ITI, but this was not the case.




Matched Pairs t-Test for 15 Subjects

Mean Difference = 2.22 seconds

$\hat{s}$ of Difference = ±6.74

t = 0.33

Figure 7. This figure shows the mean ITI over the 10 sessions prior to introduction of the 20 kV/m 60 Hz field as compared to the 10 sessions following introduction of the field.

## RELEVANT EXPERIMENTS AT MICROWAVE FREQUENCIES

The 60 Hz ELF experiment demonstrated the feasibility of the approach advocated here. By successfully demonstrating that it is possible to conduct a psychophysics experiment using electromagnetic fields outside of the visible range as discriminative stimuli, and by demonstrating the psychological relevance of the procedures employed, it encourages similar experiments at microwave frequencies.

Many experiments using basically similar procedures are possible at microwave frequencies. These experiments can form some of the first steps in a series of experiments that will determine those parameters of microwave fields that are biologically significant and which when manipulated, therefore, change the biological potency of microwave fields. These parameters are: (1) field frequency, (2) field intensity, and (3) modulation characteristics. The following is a list of some of these experiments. They have obvious relevance to the primary concerns of those who have an interest in evaluating the interaction of microwaves with animals and in determining the nature of the interaction:

1. Determine if different microwave fields have equal biological potency by obtaining RL's for different field frequencies.

2. Determine if modulation of a microwave field changes its biological potency by obtaining RL's with a fixed carrier while varying modulation frequency.

3. Determine the minimum amount that a modulation frequency must be changed to affect its biological potency as indicated by means of a differential threshold technique.

4. Assess the significance of carrier frequency as an agent of biological potency by obtaining equal sensitivity contours for different microwave fields. This would be done by adjusting the power level of fields of different frequency. A similar experiment could be performed by manipulating modulation frequency, or the two experiments could be combined.

This list of experiments is by no means exhaustive, nor is it intended to be programmatic. This list is simply a collection of obvious experiments that are immediately suggested when one takes classical psychophysics as a model of microwave behavior interactions and repeats classic experiments using appropriate microwave fields as stimuli.

In spite of its many advantages, there are a number of restrictions on what can be done and what can be known that need to be taken into account. Among these are that:

1. These procedures would not by themselves identify a particular receptor organ, though they might indicate the point of transduction.

2. There is no known fully adequate scaling procedure available for animal psychophysics experiments. Therefore some of the best psychophysics available for human psychophysics cannot be duplicated in any branch of animal psychophysics.

3. There are many different techniques that may be used in performing these experiments. There is thus a problem relating data obtained using different psychophysical techniques. In principal this can be done using SDT and looking at the data in terms of ROC curves, but this would be an extremely laborious technique.

## CONCLUSIONS

This paper presents an approach to behavioral effects of microwaves that is derived from animal psychophysics. In effect it simply extends the principles derived from vision research to a new region of the electromagnetic spectrum. A paradigmatic experiment performed at 60 Hz shows the utility of this approach and encourages its extension to the microwave region of the electromagnetic spectrum. On the basis of experience with other sensory continua it can be concluded that measurement of the absolute threshold (RL), in turn, is apt to be one of the most sensitive measures of the biological potency of microwave fields. The limits imposed by this approach are primarily those of animal psychophysics and are not uniquely associated with the study of the behavioral effects of microwaves.

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# EFFECTS of MICROWAVES on SCHEDULE-CONTROLLED BEHAVIOR

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A review of experiments in the microwave area in which operant behavior is controlled by various schedules of reinforcement will be presented by describing scheduled-controlled behavior and then continuing by emphasizing problems of interpretation, control, and confounding that one ordinarily encounters when using schedule-controlled behavior as an index of the effect of physical agents. Specific instances of these problems in microwave research will be described where appropriate. These problems have frequently been observed in the broad area of behavioral pharmacology and toxicology; in most cases methods have been devised for their solution (Weiss & Laties, 1972).

Schedule-controlled behavior refers to procedures for delivering reinforcing stimuli in relation to time and responses. The effect on behavior of a reinforcement schedule is, in general, stronger than more traditional and broadly defined variables such as motivation (Morse & Kelleher, 1970). When behavior is reinforced on a schedule it is said to be controlled by that schedule.

Research utilizing schedule-controlled behavior typically calls for only a few subjects, each serving as his own statistical control, and schedule-controlled behavior implies that consistent behavior will occur from session to session as long as the same schedule is imposed. Following the development of this consistent behavior, the physical agent is introduced. The investigator then searches for changes in the baseline behavior as a function of variables associated with the physical agent. Statistical analyses become less important since group averages are not sought and one generally analyzes for intersubject differences. These intersubject differences tend to be associated with the physical agent and not session to session variability which is controlled for by the schedule of reinforcement.

The presence or absence of a microwave effect is dependent on much more than merely a transduction of energy. It depends on the state of the organism including the type and frequency of its past experiences, the present ongoing behavior, and the total milieu in which the animal is located. I will concentrate on schedule-controlled behavior as merely one of the ways of limiting the variability introduced by such varied dependabilities. Variability inherent in experimental procedures such as placement of manipulanda, direction of irradiation, exposure prior to a session versus exposure during a session and the myriad other parameters associated with microwaves will be addressed by other contributors to these proceedings.

A variety of reinforcement schedules has been employed in the search for behavioral effects of microwaves. Most of these schedules can be encompassed in the framework of standard, relatively simple, schedules such as the fixed-ratio (Hawkins et al., 1973; Gage, 1979c; Lin et al., 1977), fixed-interval (Lundstrom et al., 1979; Sessions, 1981; Sanza & de Lorge, 1977; Thomas et al., 1979; 1980) and variable-interval (Gage, 1979b; Gage & Guyer, 1982; Sessions, 1981; de Lorge, 1976; 1979) schedules. For those unfamiliar with this terminology, Catania (1968) is an excellent source of information. Another frequently used schedule is the differential reinforcement of low rates schedule (Maitland, 1979; Maitland & Thomas 1980; Diachenko & Milroy, 1975; Thomas & Maitland, 1979). Table 1 contains most of the reported research using scheduled controlled behavior and illustrates that half of the listed research involved these four schedules or their combinations. The remainder of investigations have resorted to more complicated reinforcement schedules and in many instances the schedules have been so unique that a simple description will not suffice (Gage, 1981; Thomas & Banvard, 1980; Cunitz et al., 1975; Galloway & Waxler, 1977; Thomas et al., 1976).

Table 1 summarizes known investigations wherein schedules of reinforcement were utilized in the study of microwave effects. The initial column defines the specific schedule e.g., fixed time (FT) means reinforcement is scheduled every fixed period of time regardless of the animal's behavior; fixed ratio (FR) indicates a fixed number of responses has to occur prior to a reinforced response; a multiple (MULT) schedule indicates that more than one schedule occurs consecutively and each schedule is signalled by a specific stimulus; extinction (EXT) means that regardless of an animal's behavior no reinforcement is scheduled; alternating (Alt) indicates that an animal has to alternate between two manipulanda; fixed interval (FI) means that responding is reinforced after the passage of a fixed duration; variable interval (VI) denotes a variable duration of time with the mean interval shown, typically in minutes; random interval (RI) is a special case of the variable interval with the intervals randomly determined; Sidman avoidance schedule (SIDMAN AVD) requires an animal to respond within a specified time period to avoid a noxious stimulus otherwise the stimulus is delivered repeatedly during another specified time period; differential reinforcement of low response rates (DRL) means that responding is not reinforced until a fixed period of no responding passes; limited hold (LH) is a period of time immediately following the period during which the animal has a fixed time in which to respond (these times are in seconds). The other schedule designations are rather unique and a clear description is best obtained from the specific referenced article.

The second column denotes the animals used. Rh stands for rhesus monkeys, *Macaca mulatta*, and SS is for squirrel monkeys, *Saimiri sciureus*. The response column is self-explanatory and the index column refers to the major variable measured, e.g., act. indicates locomotor activity; wk. stop lat. indicates the time to stop responding; IRT is the interresponse time interval and disc. ratio is the discrimination ratio. The result column indicates no differences observed (ND) increases (inc) and (dec) in the dependent variable. Frequencies are shown in MHz and power densities are shown in $mW/cm^2$ except where an asterisk shows otherwise. The effective PD column indicates the approximate power density where a behavioral effect was observed. The exposure time shows the exposure duration and whether exposure occurred prior to an assessment of the effects on behavior (PRE). Rep. means repeated exposures. Var means a variable exposure time. RF refers to exposure time being determined by the delivery of a fixed number of reinforcers or in certain cases (60 rf/2h) either the delivery of a number of reinforcers or 2 hours. Citations are listed in the Reference section.

A common problem in much of this research is that some particular schedules were chosen as if behavior generated by the schedule would allow the investigator to make an analysis of underlying behavioral processes. For example, repeated acquisition tasks (Knepton & de Lorge, 1983; Galloway, 1975; Nelson, 1978; Schrot et al., 1980) have generally been used in an attempt to assess effects on "learning." The relationship of repeated acquisition performance to learning in general has not yet been demonstrated. This type of broad relationship has seldom been confirmed since the behavioral processes are not independent of the schedules from which specific functional analyses are derived.

A more common problem associated with schedule-controlled behavior is that colleagues in other scientific areas frequently make an assumption that behavior generated by a specific schedule directly reveals underlying physiological processes controlling a class of behavior within which the schedule-generated-response may or may not be subsumed (Gavalas-Medici, 1977). For example, performance on a fixed-interval schedule of reinforcement may not be related to the physiological process that underlie an organism's ability to perceive duration. Also fixed-ratio performance is probably not related to the physiological processes that are associated with an animal's ability to count, at least this investigator is unfamiliar with research demonstrating such a relationship.

I will now discuss some specific aspects of schedule-controlled behavior as they relate to microwave irradiation beginning with the major consequence of exposure. The primary effect of microwaves on operant behavior is to reduce response rate (see column 5 in Table 1) although exceptions have occurred. The consequences of a reduced response rate are schedule dependent. On ratio schedules even small reductions in response rate will result in fewer reinforcing events per unit of time. Hence, the microwave effect becomes confounded with an effect caused by a decreased reinforcement density. On time-based schedules, such as fixed- or variable-interval, changes in reinforcement density as a consequence of variations in response rate are less likely because of the nature of the schedule and one sees reinforcement frequency reductions only with relatively large decrements in response rate.

Another higher-order effect produced by decreased reinforcement frequency is the possibility of two different outcomes when the animal is next exposed to microwaves. The animal might fail to respond because of the previous association of microwaves with fewer reinforcers or, and this tends to be the most likely outcome, the animal may become tolerant of the microwaves and not lose reinforcers. Tolerance in this case is similar to drug tolerance observed in psychopharmacological studies (Weiss & Laties, 1972). Tolerance to microwaves should be more likely seen on ratio schedules than on interval schedules, although it's only been reported on variable-interval schedules (de Lorge, 1976; 1979).

It is highly possible that the unique loss of reinforcement with reduced response rates on ratio schedules is responsible for the differences in microwave effects on fixed-interval and fixed-ratio schedules. Studies in which fixed-interval schedules have been used have failed to find microwave effects on response rate with one exception (Sanza & de Lorge, 1977), whereas studies examining fixed-ratio behavior have, in almost all cases, found either a reduced response rate or decreased time to work stoppage (Hawkins et al., 1973). However, no direct comparisons of these two schedules under microwave exposure have been attempted, and the power densities in the FI studies were generally very low.

The one exception just mentioned was a study in which the animals, responding at high response rates on a fixed-interval schedule, displayed a microwave-induced reduction in responses; whereas, those animals responding at low rates failed to show an effect (Sanza & de Lorge, 1977). The reason for this contrast could be that the differential response rates produced different amounts of metabolic heat in rats which acted in a cumulative fashion with microwave induced heat to reduce responding. This interaction will be addressed later.

Another problem that may also be related to differences in reinforcement density is that associated with the behavioral context of a specific schedule or reinforcement. For example, behavior generated by a differential reinforcement of low rates schedule (DRL) when scheduled singularly might be very different from that produced by the same schedule associated with an FR schedule (D'Andrea et al., 1983; Thomas et al., 1975). For example, the "Journal of the Experimental Analysis of Behavior" is replete with references to "contrast" and the effects of context on response rates. Such being the case one should not be surprised to see different effects of microwaves on the same schedule in multiple versus single arrangements.

A somewhat different problem occurs when schedules are modified by including relatively simple contingencies in the original schedule. A case frequently observed in the microwave literature is the addition of a limited time duration wherein a reinforcement can be obtained on a DRL schedule. This is referred to as a DRL with a limited hold (LH). Thomas & Banvard (1979) found a microwave effect on a DRL 8 LH 4 but did not observe the same effect on a DRL 14. Shifting to and from the original and second schedule allowed the phenomenon to be repeated illustrating that the effect was schedule dependent. In this case one is not sure that the effect was dependent on the smaller DRL or on the limited hold. One must assume that a DRL LH has stronger schedule control over performance than does a DRL alone because of the added contingency that a response must occur within a fixed period of time. However, strong schedule control does not imply less vulnerability to other independent variables. In this case, as in others, the more strongly schedule-controlled behavior may be more sensitive to physical agents. For example, Fischman and Schuster recently demonstrated that self initiated DRL behavior (strong schedule control) was more easily disrupted by amphetamines than traditional DRL scheduled behavior (Fischman & Schuster, 1972).

Behavior generated by schedules of reinforcement is frequently under stimulus control. That is, exteroceptive stimuli become the occasion for differential responding. Behavioral pharmacology has demonstrated that drugs will produce different effects dependent upon the presence or absence of external stimulus control. Similar studies are missing from the microwave literature. The operant literature in general seems to support the contention that stimulus control is frequently more powerful than schedule control (Rilling, 1977). For example, several microwave experiments summarized in Table 1 used multiple schedules (multiple schedules are often used to illustrate stimulus control) wherein the appropriate behavior was occasioned by the multiple stimuli, yet the behavior within a unit of the multiple schedule tended to deteriorate in the presence of microwaves (D'Andrea et al., 1983; Lebovitz, 1981; Mitchell et al., 1977).

Some confusion evident in the literature regarding schedule control and stimulus control is a result of poor experimental design. When one uses a two-component multiple schedule (Johnson et al., 1976) and considers the presence or absence of microwaves as one of the discriminative stimuli, SD, the discriminative properties of the schedule itself are often ignored. That is, on a mult FR10 EXT the animal can frequently learn to discriminate the two components because of the presence or absence of reinforcement following 10 responses. If microwaves were the SD for one component and it was reported that the animals learned the discrimination there is no way to easily eliminate the stimulus aspects of the reinforcement.

In general if one uses multiple schedules to measure a differential effect of microwaves it is best that all components of the schedule produce responding at greater than a zero rate, but not at extremely high rates. When extinction components are used, there is always the danger of the response rate in extinction being zero and an analysis concluding that there was no effect during the extinction. Rate enhancement effects can be missed if baseline response rate is too high. A popular theme in behavioral pharmacology is the rate-dependency effect of drugs. That is, certain drugs will increase behavior emitted at low rates, yet decrease behavior emitted at high rates (Dews, 1981). A phenomenon similar to this has been observed in the microwave literature. Recent work however, has indicated that rate-dependency effects may actually be due to "novelty effects" or the disinhibiting effects of extra stimuli (McKim, 1981).

In some of our own work with monkeys performing high effort responses during exposure to moderately high power densities we've found that there is an interaction between microwaves and the amount of work required on a task (Knepton et al., 1983). The more work required, the more susceptible an animal's behavior is to microwaves. Another way of looking at this is that a power density not normally perturbing an animal's response rate will decrease that rate when the work is increased. A different aspect of the same situation is that a specific task performed at a specific power density will not be disrupted in the inital quarter of a session of continuous radiation, yet during the last quarter of a session disruption will occur. A similar task, requiring less effort will not show the same effect (Knepton et al., 1983). Although these experiments showing an interaction of work and microwaves utilized highly effortful responses, it is possible that the same interaction might exist with less effortful bar presses and could be demonstrated in multiple schedules wherein both very high and moderate response rates are purposively generated.

Some studies have shown that the existence of a microwave effect might depend upon the nature of the reinforcing event and the animals previous experience with that event. For example, fixed-interval behavior can be generated with both food, water, and shock as reinforcers (Morse & Kelleher, 1970). Will microwaves produce the same effect on the same schedule in each of these cases? It's difficult to tell since most microwave studies have been conducted with food as a reinforcer. Another aspect of this question is to what extent a reinforcing event will be effective when different animals are used. For example, Medici and her colleagues found that chicks did not significantly change their water reinforced activity whereas ducklings did (Medici, 1981; Sagan & Medici, 1979). Obviously, the stimulus control exerted by a reinforcer differs between different species, but one is faced with the problem of strong stimulus control producing behavior that is invulnerable to the imposition of physical agents versus weak stimulus control that is vulnerable to any physical agent.

One of the strongest reinforcing stimuli used in microwave studies has been electric shock. In only one of the studies, with which I am familiar, wherein behavior was maintained by electric shock was there an effect of microwaves. In this study by Young et al. (1973) microwaves used as a probe produced conditioned increases in response rate on a Sidman Avoidance Task. This effect may be caused by the "novelty effect" mentioned earlier. Microwaves have also been shown to be effective cues for shock in a conditioned emotional response paradigm (King et al., 1971), and microwaves have been used as aversive stimuli in a Sidman Avoidance paradigm (Monahan & Henton, 1979). Mice learned to both avoid and escape irradiation. However, in these microwave avoidance studies the microwaves were cued with sound and there is still some debate as to the discriminative properties of microwaves per se in this paradigm.

The results of several studies may be dependent on the nature of the response. Virtually all of the schedule-controlled studies in the microwave arena have utilized a simple operant, a bar or lever depression. Often, presses on two levers are required (de Lorge, 1983). Other operants have been tongue licks (Justesen & King, 1970) and head insertions (Johnson et al., 1976). Each operant has unique properties such as natural emission rates, rhythms, and saliency to manipulanda and environment (Millenson & Leslie, 1979). Certain animal species will display interresponse time intervals that differ substantially from those of other species. Pigeons, for example, tend to produce bursts of key pecks on DRL schedules whereas monkeys do not. Some animals tend to persevere on a manipulandum, that is continue responding after reinforcement. Special training techniques are called for to eliminate such responding. The interaction of microwaves and a specific operant might be extraordinarily strong in the case of the tongue-lick operant, particularly if high power densities are imposed. The thermal nature of microwaves may increase the difficulty of making a tongue lick if the animal's tongue is not sufficiently lubricated. Hence, experiments utilizing tongue-licks may be more sensitive indicators of microwave effects than other operant experiments (Justesen & King, 1970; King et al., 1971).

Although most of us are familiar with the notion that the best assessment of changes in operant response rates occurs after response rates have stabilized, only a few of us have gone to the trouble to specify stabilization criteria (D'Andrea et al., 1976; 1977). Merely allowing the animal several sessions on a specific schedule is not sufficient. As Weiss (1970) has shown in the case of DRL schedules, behavior tends to continually change as a consequence of increased experience and average response rates fail to illustrate this change as well as interresponse time (IRT) distributions do. Because of a lack of rigor in regard to stabilized behavior it is possible that some operant experiments have reported the effects of microwaves on transitional behavior. Such effects may differ when assessed with stable behavior and it is virtually impossible to repeat such an experiment because of the inability to assess in what transitional stage an animal's behavior might have been at the time of exposure.

Interresponse time distributions are not the only alternative to response rate measurements. Several investigators have assessed microwave effects by examining length of consecutive response runs (Thomas et al., 1975b), frequency of incompatible responses (de Lorge, 1979), and other aspects of single lever responding such as post-reinforcement pause time (de Lorge & Ezell, 1980). Some of these other measures tend to occur with rather unique schedules wherein response rate and IRT distributions are less applicable.

One way of assessing a schedule's interaction with microwaves is to compare the microwave effect with the effect of other physical agents. Most of the schedules previously employed in microwave experiments have been shown to be sensitive to various pharmacological agents, and only because of this previously shown drug sensitivity were the schedules selected for use in microwave studies. In fact, several studies have shown that the drug sensitivity of a schedule can be enhanced by the presence of microwaves (Maitland, 1979; Monahan & Henton, 1979; Thomas et al., 1979; Thomas & Maitland, 1979). Conversely, I know of no studies that illustrate the enhancement of a microwave effect on operant behavior with drugs.

In terms of sensitivity to similar agents such as convective heat, few comparisons have been made. Those that have, show that the schedules used were more sensitive to a microwave effect (Gage, 1979a; 1982).

A major problem we face as behaviorists interested in microwave effects is the failure to standardize techniques particularly regarding replicating experiments. We have been so concerned about standardized microwave dosimetry that our behavioral experiments were taken for granted. When we have replicated experiments, even our own, we have tended to make minor changes that go unchallanged. Several investigators speak of replications that are not replications at all, merely similar experiments. It is time that those investigators reporting the work summarized in Table 1 collaborate in an effort to provide an answer to the question, "What are the effects of microwaves on schedule-controlled behavior?"

Table 1. Operant behavior experiments with microwave irradiation

| Schedule | Animal | Response | Index | Result | Frequency MHz | Power density mW/cm² *mW/g | Effective PD mW/cm² *mW/g | Exposure time | Session time | Citation | Date |
|---|---|---|---|---|---|---|---|---|---|---|---|
| FT 30s | chick | act. | act. rate | ND | 450@3 + 16 Hz | 1,5 | | 23′ | 69′ | 40 | 79 |
| FT 30s | duckling | act. | act. lat. | change | 450@3 + 16 Hz | 1 | 1@16.Hz | 20′ | 60′ | 33 | 81 |
| FR 10 | rat | bar press | wk. stop lat. | dec | 750-3000 | 25-150 | 50 + > | 13′ | 15′ | 21 | 73 |
| FR 30 | rat | head insert | resp. rate | dec | 918 | 10-40 | 32 + 40 | 30′ | 30′ | 28 | 77 |
| MULT: FR 25, EXT | rat | bar press | resp. rate | ND dec EXT | 1300 | 1.5,3.2,6.8* | 6.8* | 3h | 2.5h | 27 | 81 |
| MULT: FR 5, EXT | rat | bar press | resp. rate | ND inc EXT | 2450 | 2.3* | 2.3* | 5h PRE | 30′ | 34 | 77 |
| MULT: FR 40, EXT | rat | tongue lick | resp. rate | dec | 2450 | 1.5,3.1,4.7* | 3.1* | 5′ rep | 60′ | 23 | 70 |
| Alt: FR 33 or FR 11 | rat | 2 bar alt. press | alt. rate | dec | 2450 | .5-30 | 5 + > | 55′,15h PRE | 30′ | 15 | 79 |
| FI 1 | rat | bar press | resp. rate | ND | 2450 | 1 | | 30′ PRE | 60′ | 46 | 79 |
| FI 50s | rat | bar press | resp. rate | ND low dec hi rate | 2450 | 8.8-37.5 | 37.5 | 60′ | 60′ | 41 | 77 |
| FI 1 | rat | bar press | resp. rate | ND | 2880 | 1,8 | | 30′ | 30′ | 29 | 79 |
| FI 1 | rat | bar press | resp. rate | ND | 2450 | 1,7* | | 30′ PRE | 50′ | 43 | 81 |
| FI 1 | rat | bar press | resp. rate | ND | 2800 | 1 | | 30′ PRE | 60′,60 rf | 49 | 80 |
| VI 1 | rat | head insert | resp. rate | dec | 2450 | 8,14 (22,26,30°) | all PD | 15.5h PRE | 30′ | 17 | 82 |
| VI 1 | rat | head insert | resp. rate | ND | 100 | 50 | | 4hx114D PRE | 30′ | 14 | 79 |
| VI 1 | rat | bar press | resp. rate | ND | 2450 | 1.7* | | 30′ PRE | 50′ | 43 | 81 |
| VI 20s | rat | 2 bar obs. resp. | resp. rate | dec | 1280,5600 | 0-50 | 10,26 | 40′ | 40′ | 9 | 80 |
| VI 1 | rh | 2 bar obs. resp. | resp. rate | dec | 2450 | 0-72 | 67 | 30-120′ | 2h | 6 | 76 |

Table 1. Operant behavior experiments with microwave irradiation (continued)

| Schedule | Animal | Response | Index | Result | Frequency MHz | Power density $mW/cm^2$ *mW/g | Effective PD $mW/cm^2$ *mW/g | Exposure time | Session time | Citation | Date |
|---|---|---|---|---|---|---|---|---|---|---|---|
| VI 1 | ss | 2 bar<br>obs. resp. | resp. rate<br>2 | dec | 2450 | 0-80 | 47 | 30-60′ | 30-60′ | 7 | 79 |
| DRL 18 | rat | bar press | resp. rate<br>IRT | dec<br>inc | 2450 | 1 | 1 | 30′ PRE<br>90 days | 60′ | 31 | 80 |
| DRL 18 | rat | bar press | resp. rate | ND | 2450 | 1 | | 30′ PRE | 60′ | 48 | 79 |
| DRL 14 | rat | bar press | resp. rate | ND | 2800 | 4-16 | | 30′ PRE | 60′ | 44 | 79 |
| DRL 8,<br>LH4 | rat | bar press | resp. rate | disrupt | 2800 | 4-16 | 4 + > | 30′ PRE | 60′ | 44 | 79 |
| DRH 18,<br>LH6 | rat | bar press | resp. rate<br>IRT | -<br>- | 2450 | 1,5 | | 30′ PRE | 60′ | 30 | 79 |
| DRL 12,<br>LH 6 | rat | bar press | resp. rate<br>IRT | dec<br>dec | 2450 | 1-15 | 15 (5th day) | 60′ PRE | 60′ | 11 | 75 |
| MULT: DRL<br>18, LH 6,<br>FR 20 | rat | bar press | resp. rate | inc<br>(drl + TO)<br>(dec FR) | 2450<br>2800<br>9600 | 5-20 | 5 | 30′ PRE | 60′ | 47 | 75 |
| MULT: DRL<br>12, LH 6,<br>FR 20 | rat | bar press | IRT +<br>resp. | inc (drl)<br>ND (FR+TO) | 2450 | 5 | | 8h | 60′ | 5 | 83 |
| MULT:<br>SRW EXT | rat | nose<br>insert | IRT +<br>resp. | dec | 2450 | 8,15 (22+28°) | 8 | 15h | 36′ | 16 | 81 |
| SPACED<br>RESP | rat | bar press | resp. | dec | 2800 | 1-15 P+CW | 10,15P | | | 45 | 80 |
| SERIAL<br>REACTION | rh | bar press<br>(FR 4) | correct<br>resp. | dec | 383 | .001-23* | 23* | 180′ | 120′ | 2 | 75 |
| FIXED<br>CONSECUTIVE<br>NUMBER | rats | 2 bar<br>press | switch<br>rate | inc | 2450 | 5-15 | 5 | 30′ PRE | 60 rf | 50 | 76 |
| MATCH-TO-<br>SAMPLE | rh | bar press<br>(VI 1) | correct<br>resp. | ND | 2450 | 1-15 W | | | | 19 | 77 |
| REPEATED<br>ACQUISITION | ss | bar press<br>(FR 4) | errors<br>correct<br>resp. | inc<br><br>dec | 5600 | 11-53 | 53 | 30′ PRE | 30′ | 38 | 78 |

Table 1. Operant behavior experiments with microwave irradiation (continued)

| Schedule | Animal | Response | Index | Result | Frequency MHz | Power density mW/cm² *mW/g | Effective PD mW/cm² *mW/g | Exposure time | Session time | Citation | Date |
|---|---|---|---|---|---|---|---|---|---|---|---|
| REPEATED ACQUISITION | ss | bar press (FR 3) | errors<br>correct resp. | inc<br>dec | 5620 | 17-46 | 42 | 60′ | 60′ | 25 | 83 |
| REPEATED ACQUISITION | rh | bar press (VR & FR) | errors | VR-inc | 2450 | 0-25 W *20-30 (brain wt) | 25W | 2′ PRE | 60 rf/ 2h | 18 | 75 |
| REPEATED ACQUISITION | rat | bar press | errors | inc | 2800 | .25-10 | 5 + > | 30′ PRE | | 42 | 80 |
| MULT: VI 1, VI 1, DRO | rh | bar press | errors | ND | 2450 | 0-25W *20-30 (brain wt) | | 40′ | 60 rf/ 2h | 18 | 75 |
| MULT: RR 5, EXT | rat | nose insert | disc. ratio | learned | 918 | 15 | 15 | 5′ | 60-90′ | 22 | 76 |
| MULT: FR 40, EXT | rat | tongue lick | disc. ratio | ND | 2450 | .4, .8 W | | 5′ | 60′ | 23 | 70 |
| CER (VI 8s) | rat | tongue lick | resp. rate | dec | 2450 | 0-6.4* | 2.4 + >* | 1′ | 2h | 24 | 71 |
| CER (Sid. Avd) | rh | bar press | resp. rate | inc | 2450 (10 Hz) | 2 | 2 | 1′ | | 53 | 73 |
| RI 1 | rh | 2 bar obs. resp. | resp. rate | dec | 225,1300,5800 | 5-150 | 8.1,57,140 | 60′ | 60 | 8 | 81 |
| RI 30s | rat | bar press | wk. stop lat. | dec | 360-500 | 25 | [500 MHz] E/L | 25′ | 30′ | 3 | 76 |
| RI 30s | rat | bar press | wk. stop lat. | dec | 400-700 | 5-20 | [600 MHz] 10 + > | 20′ | 55′ | 4 | 77 |
| RI 80s | rat | nose insert | resp. rate | dec | 2450 | 5-15 (22 + 28°) | 28° all PD | 15.5h PRE | 30′ | 13 | 79 |
| SIDMAN AVD. | rat | bar press | resp. rate | ND | 2450 | 2.3* | | 5h | 30′ | 34 | 77 |
| SIDMAN AVD. TO MW | mouse | nose insert | resp. rate | learned | 2450 | 45* | 45* | var | 30′ | 36 | 79 |

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# EXPERIMENTAL ANALYSIS of AVERSIVE BEHAVIOR: MICE and RATS in INTENSE MICROWAVE FIELDS

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## ABSTRACT

In Experiment I, experimentally naive mice and rats (ns = 64) were observed for escape from an intense microwave (MW) field or faradic shock (FS) in a 918- or 2450-MHz multimode cavity. Escape was contingent on entry to a "safe" area that comprised 25 or 50 percent of the surface of a false Plexiglas floor. MWs at 60 mW/g or a 2900-Hz sonic stimulus at 80 dBA (or both in combination) or FS (150-300 µA rms) were continuously available for a 10-minute period per day during each of 4, once-daily sessions. Ten-minute baseline sessions were conducted during the 1st and 6th days. FS animals learned rapidly to escape, and most learned to avoid FS. MW animals did not avoid but, compared with day-1 baselines, did exhibit highly reliable increases of times spent in safe areas. Concomitant symptoms of thermal stress may indicate that thermokinetic artifact, not a discriminated escape response, was responsible for the increases. Neither sonic stimulation nor MW frequency was a reliable source of variation. Experiment II on 24 mice and 14 rats was conducted to clarify findings of Experiment I. A MW field at 60 or 120 mW/g, or faradic shock, was continuously available for 15 minutes during each of 4, once-daily sessions. The safe area (25%) was a circle *centered* on the false floor of the 2450-MHz cavity. Once again, FS animals rapidly acquired the escape response, most demonstrating avoidance, but MW animals failed to associate entry to the safe area with cessation of irradiation. All of 10 rats and 2 of 10 mice expired under energy dosing at 60 mW/g. All of 10 mice expired under energy dosing at 120 mW/g. In sum, the data of both experiments in the context of published findings indicate that the naive rodent will not learn adventitiously to escape from a MW field unless cued by visible light. The authors speculate that, as such, non-localized cutaneous warming by radiant energy is proprioceptive in nature, and that light in synchrony endows the sensation of warming with exteroceptive properties.

## INTRODUCTION

We report original data and review published findings on behavior of mammals exposed to microwave radiation. The affective properties of the microwave field— motivational potential and efficacy as a negative reinforcer—are the constructs of interest.

The literature bearing on sensory and motivational properties of microwaves is sizeable; in the collective it has been reviewed and discussed in breadth and depth by many investigators, including Adair (1983), Carroll et al. (1980), Chou et al. (1982), D'Andrea et al. (1977), de Lorge (1983, 1984a, b), Frey (1965), Frey & Feld (1975), Guy et al. (1975), Hendler (1968), Hjeresen et al. (1979), Justesen (1975a, 1979, 1983a, 1983b, 1984), Justesen & King (1970), Justesen et al. (1982), King et al. (1971), Levinson et al.

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(1982), Lin (1978), Lovely et al. (1983), Michaelson (1972), Monahan & Ho (1977), Thomas et al. (1979), Schwan et al. (1966), and Stern et al. (1979). From the experimental work reported or reviewed by these and other investigators, a number of confirmed findings has emerged:

1. Mammals of several species, including human beings, can *hear* repetitively pulsed microwaves at high peaks of field strength, although the rms-averaged power density may be quite low (<1 $mW/cm^2$); the whole-body-averaged energy dose (D) per pulse at the threshold of detection is on the order of 10 to 20 μJ/g (cf. Frey, 1965; Justesen, 1975b, 1979; Lin, 1978; and Chou et al., 1982). At least in the case of the rat, the affective sign of the pulsed field appears to be negative. Frey & Feld (1975) and Hjeresen et al. (1979) subjected rats to location-preference tests and, even though the rats did not *avoid* the pulsed fields, they spent about 50 percent more time in the electrically quiet area of a shuttlebox than in the area exposing them to the field. In contrast, control experiments in which rats were exposed to a non-pulsed, continuous-wave (CW) field at a power density of 2 $mW/cm^2$ revealed no effect on preference (Frey & Feld, 1975). The implication that this CW field (by estimate, the whole-body-averaged dose rate, $\dot{D}$, approximated 300 μW/g) was below the rat's threshold of detection is consistent with an earlier finding: A highly sensitive measure of the absolute threshold in a non-pulsed microwave field revealed that irradiation of rats at power densities in excess of 5 $mW/cm^2$ was required for detection (King et al., 1971). The $\dot{D}$ at the threshold of detection differed among individual rats, ranging from 600 μW/g to 2.4 mW/g.

2. At power densities from 5 to 20 $mW/cm^2$ and at frequencies associated with $\dot{D}$s ranging from 1 to 5 mW/g, the affective sign of a CW microwave field is positive, at least in a cold environment. Rats (Stern et al., 1979) and squirrel monkeys (Adair & Adams, 1980, 1982) that warmed themselves in a cold environment via operant control of an infrared source responded reliably less often when a microwave field was applied continuously as a background source of thermalizing energy. This indirect evidence of positive affect comports with the direct evidence reported by a psychologist that donned a Bikini, entered a cool-for-an-unclothed-person environment (~25 °C), then instructed her assistant to activate a 12-cm microwave field that exposed her at a power density near 50 $mW/cm^2$ (estimated $\dot{D}$, ~5 mW/g). Covered with goose flesh before the field was activated, the psychologist had one word to describe the sensation induced by the field: "Delightful!" Nearly half an hour of irradiation elapsed before the psychologist reported mild discomfort in association with sensible sweating. (Personal communication, 1984, from Eleanor Adair of the John B. Pierce Foundation, New Haven, Connecticut.)

3. At power densities well above 50 $mW/cm^2$, if microwave irradiation resulted in energy dosing circa 60 mW/g, the field would be toxic to the mesothermal organism if the duration of exposure persisted for 10 to 20 minutes in environments at normal ambient temperatures ($T_a$s). At rest, the mouse's specific metabolic rate (SMR) approximates 10 mW/g, and that of the rat is much lower, ~2 to 4 mW/g (Durney et al., 1978, 1980). In spite of the allometric advantage possessed by the mouse—its higher surface-area to body-mass ratio permits its thermal energy at moderate $T_a$s to be dissipated much more rapidly to the environment—both the mouse and the rat soon would be overwhelmed by continuous energy dosing at 60 mW/g. However, the seemingly plausible assumption that the adverse sensory properties of the physiologically toxic field would spur adaptive attempts by the rodent to evade it is not supported by the available evidence. We turn to this evidence because it set the stage for the experiments reported in this paper.

Work in our laboratories (Carroll et al., 1980) revealed that experimentally naive rats, which were subjected to highly intense 918-MHz irradiation ($\dot{D}$ = 60 mW/g) in a multimode cavity (Fig. 1), failed during repeated attempts to acquire an escape response that produced moderate (~30 percent) to large reductions (~97 percent) of field intensity. The same, simple locomotor-escape response, entry to a large "safe" area on the floor of the cavity, was rapidly acquired by naive rats under motivation by faradic shock to the feet. The irradiated rats exhibited a marked increase of exploratory activity during periodic activation of the field, and thus they frequently entered and departed from the safe area, but they exhibited no indications that reduction of field intensity negatively reinforced the adventitious escape responses.

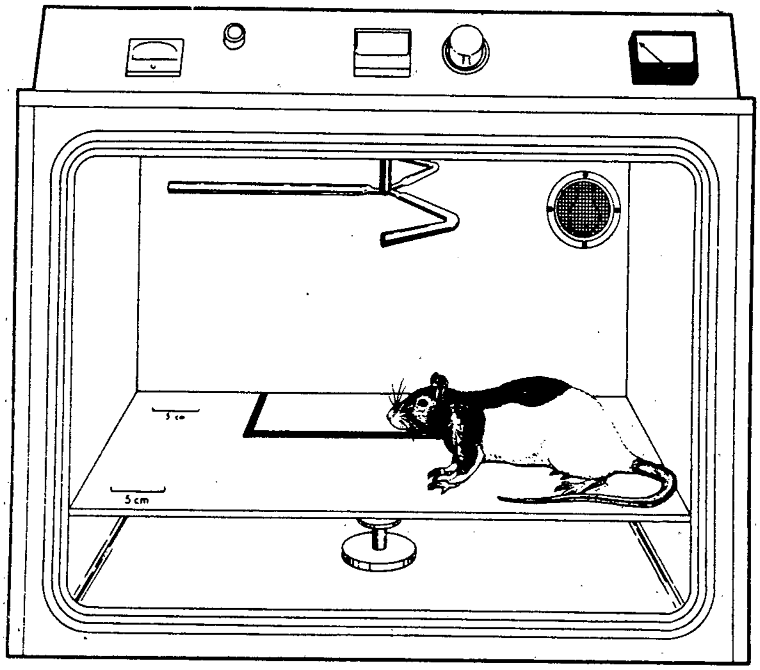


Figure 1. Artist's drawing of a rat on the false Plexiglas floor of a 918-MHz multimode cavity. The black-bordered rectangle that abutted the distal wall of the cavity defined the "safe" area in earlier studies in the authors' laboratory. A mode stirrer is shown near the overhead of the cavity; the antenna for introducing microwaves, just below the false floor. A small incandescent lamp for illuminating the interior of the cavity was mounted behind a radiopaque grille on the distal wall. Entry by an animal into the safe area resulted in immediate reduction of the intensity of the microwave field. An exit from the area led to an immediate restoration of the field to a high intensity. None of 30 rats tested learned to associate entry to the safe area with a reduction of energy dosing from 60 mW/g to a level that ranged from 40 to 0 mW/g. Rats *did* learn to enter the safe area, however, when the incandescent lamp was used to cue the presence of the intense field. (From Carroll et al., 1980, and Levinson et al., 1982; published with permission.)

We confirmed the findings of Carroll et al. in studies in which an absolute reduction in energy dosing (i.e., 60 to 0 mW/g) was used, without success, as a candidate negative reinforcer, but we found also that the addition of a discriminative stimulus—presentation of light to the rat in synchrony with each period of irradiation—led to acquisition of the escape response (Levinson et al., 1982). Because photic stimulation in the absence of irradiation failed to result in a discriminated escape response, we conclude that the intense microwave field as such was a strong motivational stimulus but that, paradoxically, its cessation was ineffective as a negative reinforcer. Presumably, inactivation of photic stimulation in concert with inactivation of the field provided the animal with salient *temporal* information on the contingency between the escape response and cessation of irradiation. Comporting with this interpretation are the large thermal time constants of mammalian tissues: An animal discomfited by a sizeable, microwave-induced elevation of body temperature might not undergo a detectable decline of temperature for several seconds after executing an operant response that extinguished the field (cf. Carroll et al., 1980; Schwan et al., 1966; Hendler, 1968; Justesen et al., 1982). Physical contingency without sensory contiguity—an adaptive response without rapid informative feedback—would almost certainly retard or preclude the associative conditioning that underlies an organism's successful retreat from noxious stimulation.

In the first of two sets of studies reported herein, we sought to determine whether our earlier findings (Levinson et al., 1982) would generalize to another species (the mouse), to irradiation at a different frequency (2450 MHz), to discriminative stimulation of a different modality (auditory), and to different escape responses. Specifically, naive mice and rats were observed for evidence of escape from and avoidance of irradiation in multimode cavities that were excited by 918- or 2450-MHz fields. Subsets of animals of both species received discriminative "cueing" by an intense auditory stimulus in synchrony with periods of irradiation. Animals of other subsets received the auditory stimulation without irradiation—to control for possible adverse sensory properties. Termination of sonic stimulation, of irradiation, or of both in combination was contingent on one of two locomotor responses. In one task, the floor of a cavity was partitioned into equal areas to form a shuttlebox. To escape from a field, an animal simply had to cross a line that divided the floor into "unsafe" and "safe" areas. To avoid the field, the animal needed only to remain in the safe area. A second task, presumptively the more difficult of the two, involved a floor with a hemicircle that abutted the distal wall of a cavity, and that covered 25 percent of the floor's surface. Entry to the hemicircle constituted the escape response; remaining in the hemicircle, avoidance. To provide comparative data, mice and rats as active controls were observed for the same escape responses under motivation by faradic shock.

To complement, qualify, and extend the findings of the first set of studies, a second set was performed in which mice and rats were observed for aversion of microwaves or faradic shock under more demanding contitions.

## EXPERIMENT I. METHODS, MATERIALS, AND PROCEDURE

### SUBJECTS AND EXPERIMENTAL DESIGN

A total of 128 animals, 64 female rats of the Long-Evans strain, and 64 female mice of the CF1 strain, served as subjects. The rats and mice were purchased, respectively, from the Blue Spruce Farms (Altamont, New York) and from the Harlen Company (Madison, Wisconsin). After 2 weeks or more of habituation to rodent vivaria at the

Kansas City Veterans Administration Medical Center, during which they had unrestricted access in their home cages to Purina Lab Chow and water, 96 animals were randomly but equally assigned in independent groups of four to one of 24, factorially defined conditions: The two species (mice versus rats), two frequencies of irradiation (918 versus 2450 MHz), the two escape responses, and three modes of motivation (microwave irradiation alone, acoustic stimulation alone, and both in combination) formed a 2x2x2x3 factorial design. The remaining animals (16 mice and 16 rats) served as active controls. Each motivated by faradic shock to the feet, the 32 animals were randomly but equally assigned in groups of four to one of eight conditions formed by a 2x2x2 factorial: the two species, the two escape tasks, and performance in one of two cavities, each of which could be fitted with a false floor that was equipped with a shock grid. At the inception of experimentation the body mass of the mice averaged 34.5 grams (range: 29-36 g); that of the rats, 289.4 g (range: 261-319 g).

## ENVIRONMENT

During the period of experimentation, the $T_a$ in both rodent vivaria and in the neighboring laboratories averaged 25.0 and ranged variably between 23.3 and 27.0 °C. The light/dark cycle in both vivaria was 12/12 h (lights on at 0600). The spatially averaged flux of air in the 2450-MHz cavity, as measured by a Kurz Model-441M air-velocity meter, was 0.2 m/s; that in the 918-MHz cavity, 0.1 m/s. Relative humidity ranged variably between 40 and 70 percent. All studies were conducted between 0800 and 1800.

## EXPOSURE FACILITIES AND DOSIMETRY

*2450-MHz cavity.* The 2450-MHz multimode cavity and associated apparatus are described in Justesen et al. (1971a). In brief, the 2450-MHz system was a modified Tappan Model-R3L cavity with a magnetron source the output power of which was continuously controllable from 0 to 200 watts. The carrier wave was doubly modulated at 60 Hz (half-wave sinusoid) and 12 Hz (by mode stirring). Microwave energy was coupled to the cavity from a waveguide in the overhead. Directly below the waveguide was a four-blade mode stirrer that rotated at 3 R/s. The interior dimensions of the cavity in cm: 26 (H) x 37(W) x 24(D). Two 15-W incandescent lamps above radiopaque grilles in the overhead of the cavity provided continuous illumination of the interior.

*918-MHz cavity.* The 918-MHz cavity and associated apparatus are described in Carroll et al. (1980). In brief, the 918-MHz system was a modified General Electric Model-J845 cavity with a magnetron source the output power of which was continuously controllable from 0 to 400 watts. The carrier was doubly modulated at 120 Hz (full-wave-rectified sinusoid) and 3 Hz (by mode stirring). Microwave energy was coupled to the cavity by a coaxially fed antenna located on the base of the cavity. A three-element mode stirrer that rotated at 1 R/s was located just below the overhead of the cavity. The interior dimensions of the cavity in cm: 39(H) x 59(W) x 44(D). Illumination of the cavity's interior was provided by a thermally sheltered, 40-W lamp located behind a radiopaque grille in the upper back wall of the cavity.

*Faradic shock and sonic stimulus.* Faradic electrical shock was generated by the apparatus described in Justesen et al. (1971b). Composed of a mix of radiofrequency currents to 10 kHz, the shock stimulus is unavoidable because of its immunity to the presence of fecal boli or urine across electrically opposed elements of a floor grid. The rms-averaged current through the grid when loaded by an animal subject approximated 550 μA, the current through the animal, 150 to 300 μA rms.

When programmed to activate, a sonic source (Sonalert Model SNP 428) that was mounted on the exterior skin of each cavity produced a 2900-Hz signal in the interior at ~80 dBA.

*Dosimetry.* The power level of available energy in each cavity was determined calorimetrically by mass-equivalent saline models of the mouse and rat according to the rationale of Justesen et al. (1971a). Specifically, the $\dot{D}$ for all animals subjected to irradiation in either cavity was set at an average value of 60 mW/g (±5 percent in the 2450-MHz cavity; ±15 percent in the 918-MHz cavity).

## BEHAVIORAL MEASURES

*Escape task.* Removable false floors of 0.95-cm sheet Plexiglas, white in color, were mounted in each cavity 7 cm above the base (Fig. 2). Safe and unsafe areas of all floors were demarcated by black plastic tape, 0.75-cm wide. The floors used during observation of shock-motivated behavior were inscribed with a grid of conductive (silver) paint. Whether under motivation by microwaves, by sonic stimulation (or by both in synchrony), or by faradic shock, the contingency was the same: Stimulation was applied whenever an animal's head crossed the black-line boundary to enter the unsafe area. Stimulation was continuous unless the animal's head moved into the safe area, at which time stimulation was immediately terminated.

*Mediation of motivational stimuli.* Stimulation was applied and inactivated by an observer by respective depression and release of a hand-held microswitch. The on-off state of stimulation—and hence data on an animal's location across time with respect to safe and unsafe areas—was tracked by an event recorder (Esterline-Angus Model AW-20). The on-off state of a second microswitch that was held by a second observer was also tracked by the event recorder, to provide data for quantitative estimates of inter-observer reliability (Pearson product-moment coefficients were calculated for durations of time spent by animals in safe and unsafe areas, yielding rs >.98 and P values <.01). From the printout of the event recorder, the primary datum on each animal was derived: percentage of time per session spent in the safe area.

## APPARATUS SUPPORT

Activation and inactivation of the microwave sources, of sonic stimulation, and of faradic shock were controlled by solid-state and electromechanical modules (Lehigh Valley Electronics), as was automatic timing of each animal's session duration.

## PROCEDURE

Each of the 128 animals was observed during a series of six 10-minute sessions across consecutive days. Athough short in duration if compared with typical periods of operant scheduling, longer sessions would have increased the probability of a lethal exposure of an animal that spent most of its time in an unsafe area. The inter-session interval averaged 24 h. During the first and sixth sessions, stimulation was not applied: Data were obtained on baselines of time spent in the safe area. The initial baseline measure provided data on the basal time of occupancy of the safe area; the terminal baseline measure, on resistance to extinction. For mice and rats that performed the shuttle response, the unsafe area was arbitrarily defined as that in which an animal had spent the greater amount of time during its initial baseline measure. Irrespective of experimental condition, each animal was placed in an unsafe area at commencement of sessions 2 through 6.

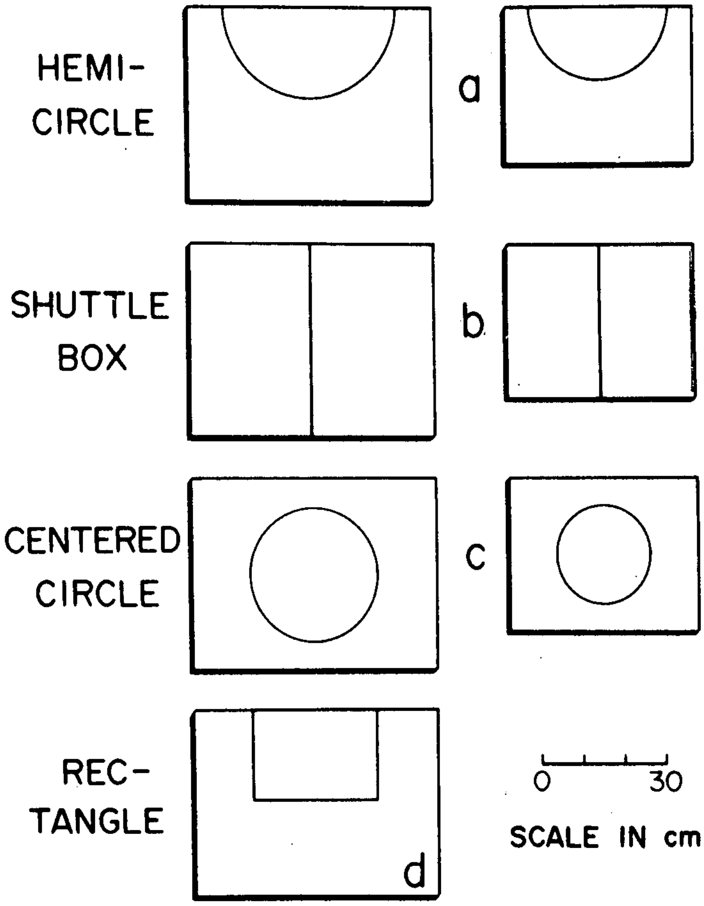


Figure 2. Scale drawings are shown of layouts of the false Plexiglas floors used in Experiment I (a and b), in Experiment II (c), and, to provide comparison, in the studies of Carroll et al., 1980, and Levinson et al., 1982 (d). The larger floors shown to the reader's left were used in a 918-MHz cavity; those to the right, in a 2450-MHz cavity. All floor plans except b utilized a safe area that encompassed 25 percent of the floor's surface. In the shuttle-box format (b), either half of the floor was arbitrarily designated as the safe area, i.e., a given animal's preference during the initial baseline measure was selected to be its unsafe area during experimental treatment. The floors used to apply faradic shock were identical in layout but also were inscribed with a bipolar grid of conductive silver paint.

## RESULTS, EXPERIMENT I

The results are presented graphically in Figures 3 and 4. By inspection it is obvious that mice and rats learned rapidly to escape from and then, in general, to avoid faradic shock. Shocked animals were singular in exhibiting avoidance and in presenting evidence of resistance to extinction, as indexed by their remaining in the safe area during the baseline measure of the sixth and final session. It is also evident from the graphic data that sonic stimulation in isolation failed to motivate escape.

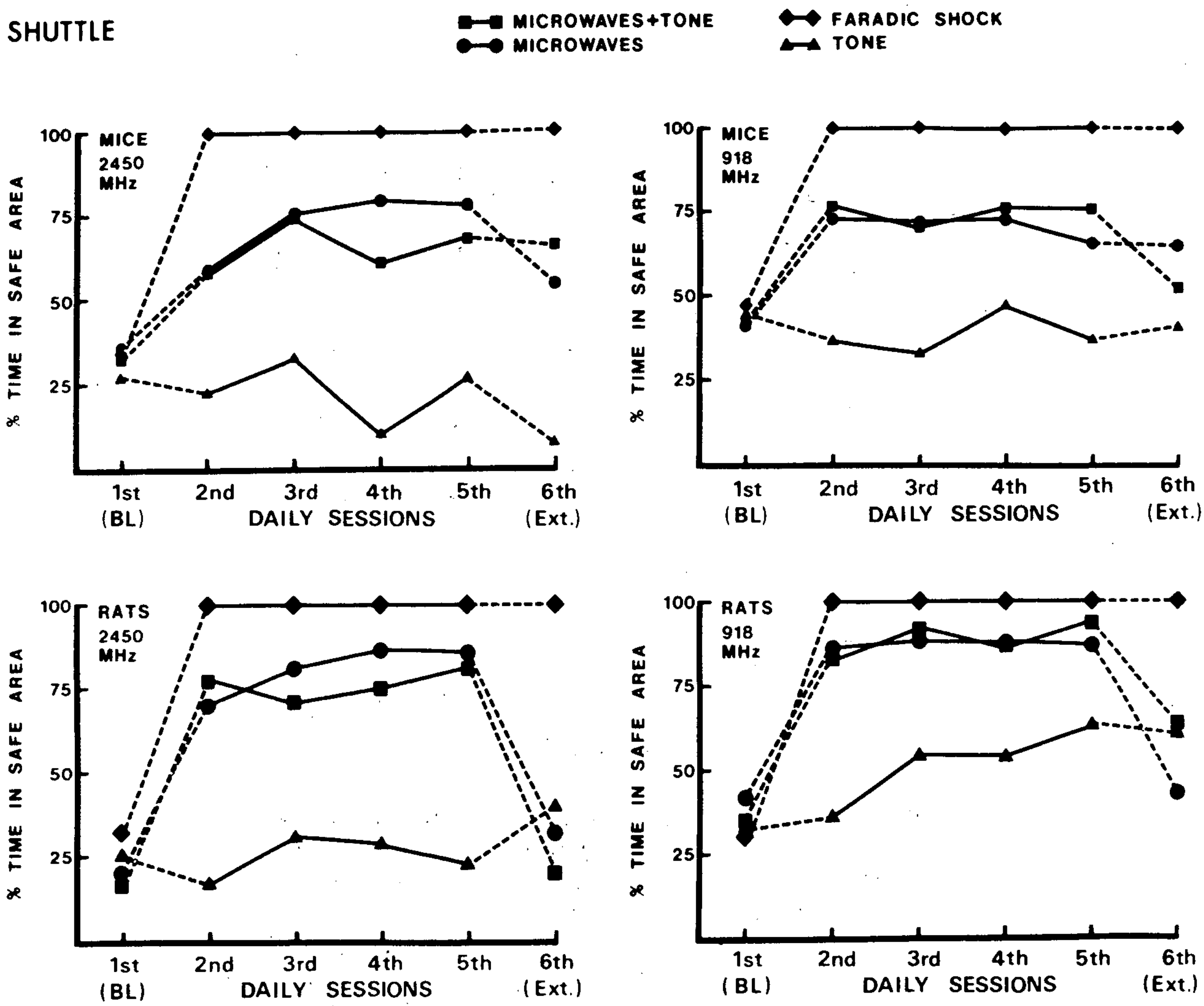


Figure 3. Experiment I: Means of percentage of time that mice and rats occupied the safe side of a shuttle area during a succession of six, once-daily sessions of 10 minutes each per animal. During the 1st and 6th sessions, no stimuli were available. During the sessions of the 2d through 5th day, microwave irradiation at 60 mW/g, or sonic stimulation at 2900 Hz, or both stimuli in synchrony, or faradic shock to the feet was applied whenever an animal's head passed into the unsafe area, and was inactivated whenever the head passed into the safe area. There were four mice and four rats in each of the four groups under each experimental condition.

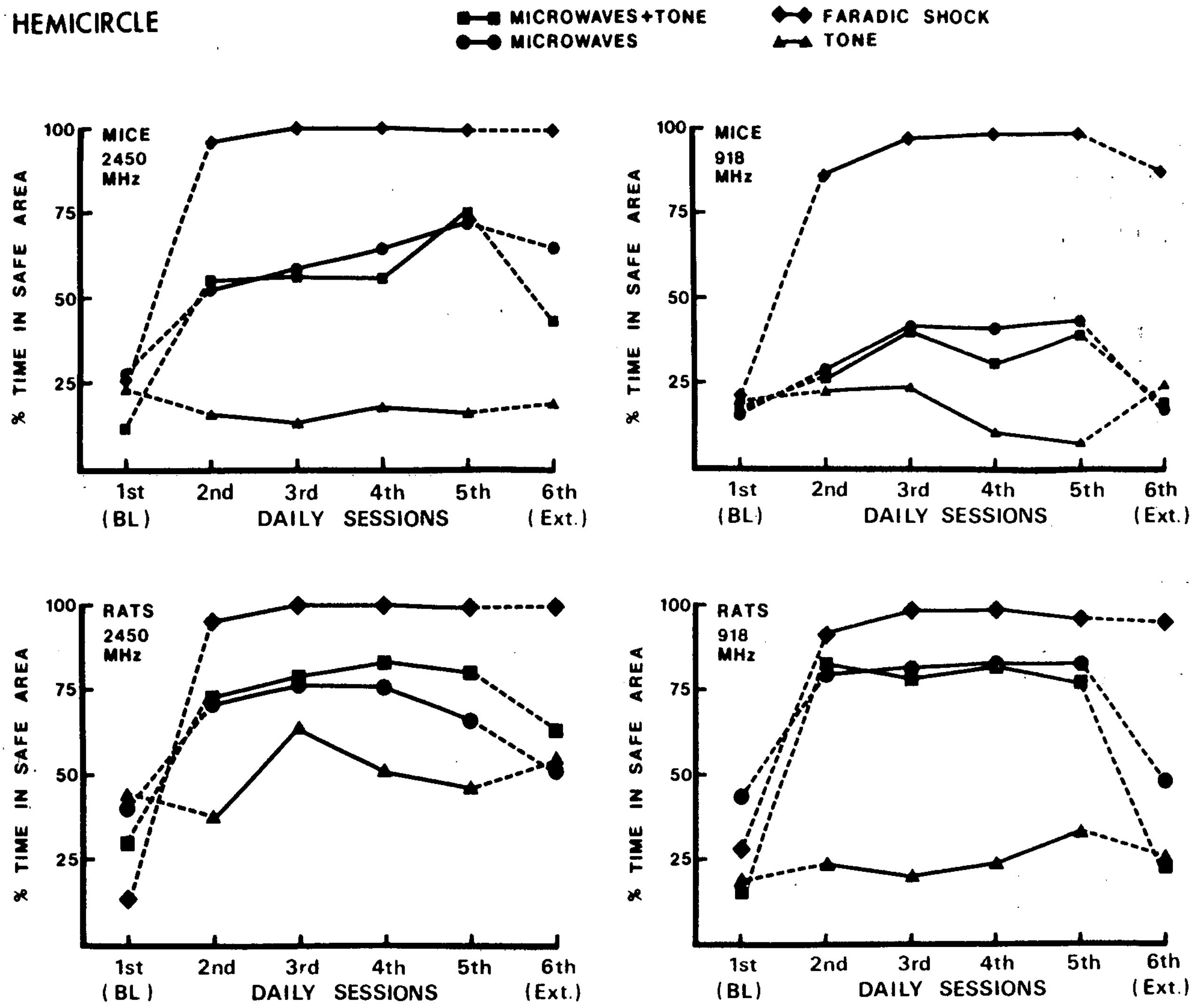


Figure 4. Experiment I: Means of percentage of time that mice and rats occupied a hemicircle during a succession of six, once-daily sessions of 10 minutes each. Except for differing layouts of safe and unsafe areas, conditions are the same as those described in the caption to Figure 3.

To provide quantitative estimates on the reliability of differences during the four sessions of training under microwave and/or sonic stimulation, a five-way analysis of variance (ANOVA) was performed on the primary factors of escape task (shuttle versus hemicircle), species (mice versus rats), field frequency (918 versus 2450 MHz), and motivating stimulus (shocked animals' data excluded), and on the repeated-measures factor (listed as "Days" in Table 1 and based on the second through fifth daily sessions).

The Table 1 summary of the ANOVA reveals that:

1. The times spent by mice and rats in the safe areas differed reliably by task ($P < 10^{-3}$); less time was spent in the safe areas of the hemicircles than in those of the shuttles.

2. Species is a highly reliable factor ($P < 10^{-5}$), the mice generally having spent more time in the unsafe areas. A reliable task-by-species' interaction ($P \sim .02$) results from differences in safe-area occupancy times by mice and rats as a function of task. Note, e.g., that mice spent considerably less time in the hemicircle of the 918-MHz cavity than they did in the hemicircle of the 2450-MHz cavity. In contrast, times of safe-area occupancy by rats were slightly higher in the 918-MHz cavity than they were in the 2450-MHz cavity.

3. Frequency of the field as such is a negligible source of variation ($P > .30$), but does interact strongly ($P < 10^{-3}$) with task. Means of times spent in the safe area of the hemicircles differ more widely in association with the 918-MHz cavity than with the 2450-MHz cavity. In contrast, means of times spent in the safe areas of the shuttles of the two cavities range more narrowly.

4. Motivating stimulus is highly reliable as a source of variation ($P < 10^{-6}$), which reflects the invariably longer times spent in the unsafe area by nonirradiated animals under sonic stimulation. Safe-area occupancy by irradiated mice and rats differed negligibly, however, when sonic stimulation was presented as a discriminative cue.

5. Performances across daily trials differ reliably ($P \sim .02$), possibly reflecting a weak upward trend in times spent in the safe areas by irradiated animals.

Table 1.

Summary of analysis of variance of mean times spent in safe areas during the 2d through 5th daily sessions by 48 mice and 48 rats under motivation by 2450-MHz microwave irradiation, by 2900-Hz sonic stimulation, or by both in combination. F ratios and associated P values are shown for all primary sources of variation. Only F ratios yielding probability estimates at or below .05 are shown for interactions. Interpretation of all P values is based on n and 24 degrees of freedom (df.).

| Source of variation | df. | Est. variance | F ratio | P |
|---|---|---|---|---|
| Primary Source | | | | |
| Escape task (E) | 1 | 12,558.4 | 14.10 | <.01 |
| Species (S) | 1 | 36,387.1 | 40.85 | <<.01 |
| Field freq. (F) | 1 | 61.8 | 0.07 | >.30 |
| Motivating stim. (M) | 2 | 66,689.6 | 74.88 | <<.01 |
| Days (D) | 3 | 713.1 | 3.78 | ~.02 |
| Interactions[1] | | | | |
| E x S | 1 | 5,295.5 | 5.95 | ~.02 |
| E x F | 1 | 12,127.5 | 13.62 | <.01 |

[1]A total of 28 interactions was assessed for reliability.

Because the data of sonically stimulated animals were entered in the ANOVA, and because they differ so markedly from those of animals that underwent irradiation, another round of ANOVAs was performed to obtain a clearer purchase on the effects of radiation as such. A 2 (species) x 2 (frequencies) x 2 (conditions: microwaves versus microwaves + sonic stimulus) x 4 (days of treatment) ANOVA was performed on the shuttle data; another on the data based on the hemicircle. The outcomes of both ANOVAs are generally in close agreement with that presented above: There is no indication that sonic stimulation altered escape performances (both $F$s $<1$); and mean times spent in the safe areas are larger for rats than for mice [both $F$s $>20$ (1/24), $P$s $<.01$]. The major import of the two ANOVAs, which is suggested by the graphic data of Figures 3 and 4, is that means of time spent in safe areas do increase reliably across the four days of microwave treatments [both $F$s $>3.47$ (1/24), $P$ $<.05$], most of the variation of upward trend being accounted for by the rats.

## DISCUSSION, EXPERIMENT I

Whether an escape response was acquired by microwave-irradiated animals is open to question. The times spent in safe areas during the four training sessions did increase appreciably over those of the initial baseline measures, which could be taken as evidence of acquisition. On the other hand, the generally poor resistance to extinction and the complete failure to avoid the field may signal, not learning, but a *thermokinetic* artifact. That is, if the rate of exploration of a cavity by an experimentally naive animal were increased during intense irradiation, presumably in association with elevated body temperature, movement from an unsafe area would occur more rapidly than movement from a safe area. The net result would be a relative increase in time in the safe area quite unrelated to a discriminated escape response.

We are inclined to an explanation based on a thermokinetically inspired, nonrandom walk, but we envision yet another possibility: Given $T_a$s that averaged 25 and never exceeded 27 °C, which are considerably below the rodent's thermoneutral ("preferred") $T_a$, it is possible that the intense fields were *both* positively and negatively reinforcing—that the animals were thermoregulating by alternately moving into the field to warm themselves, and then leaving the field to cool themselves (cf. Cabanac, 1971, 1983; Durney et al., 1978; Adair & Adams, 1980, 1982). The generally longer times spent in the safe areas by irradiated rats as compared with those of irradiated mice might simply reflect the latter species' greater ability to dissipate thermal energy to a cooler environment.

If discriminated acquisition of an escape response and/or if behavioral thermoregulation was the basis of the performances of our mice and rats, how does one reconcile the data with those obtained earlier in our laboratory (Carroll et al., 1980; Levinson et al., 1982), which revealed no evidence of escape learning by rats in a 918-MHz field? We note two differences between the earlier studies and those reported here. First, the safe area of the earlier studies, although displacing 25 percent of the floor's surface, was a rectangle with a smaller linear extent along the far wall of the cavity than that of the hemicircle (Fig. 2). Both the mouse and the rat are positively thigmotactic—are "wall huggers." Movement along the periphery of the cavity would be associated with a lower probability of random entry into the rectangular safe area. And second, the earlier studies included a 2-minute time-out between each of five 2-minute periods of available irradiation during each session. These time-outs, which were incorporated to preclude lethality to an animal that sustained continuous irradiation, also might have precluded the elevations of body temperature required to induce discomfort and thus to motivate escape or avoidance.

Although an explanation based on attempts to thermoregulate behaviorally must be entertained as a possibility, the gross behavior of the irradiated animals, especially that of the rats, leads us to take a skeptical stance: At conclusion of the 10-minute sessions, nearly all irradiated animals, but not animals subjected solely to sonic stimulation, presented evidence of thermal stress. More frequent defecation and urination, and selective lathering of the pelt with saliva, were the rule. Consider the case of a rat that spent 25 percent of its time in the unsafe area—a typical percentage in our present study. If the session-averaged $\dot{D}$ were 15 mW/g, a 10-minute exposure would translate to a D of 9 J/g. Assuming minimal dissipation of energy, a mean elevation of core temperature by as much as 2.5 °C would result (Durney, et al., 1978), an elevation inconsistent with the technical definition of behavioral thermoregulation (see, e.g., Hardy, 1970).

The question of *avoidance* of the intense, potentially lethal microwave field by the experimentally naive mice and rats was answered unequivocally by our data: They did not avoid. Whether they exhibited a field-discriminated escape response that was negatively reinforced by cessation of irradiation is an open question.

## EXPERIMENT II. INTRODUCTORY COMMENT

In our earlier studies of escape behavior of rats (Carroll et al., 1980; Levinson et al., 1982), we employed a 2-minute time-out between each of five 2-minute periods of available irradiation at 60 mW/g during a once-daily experimental session. Our use of time-outs, as noted above, was to preclude lethality borne of an excessive elevation of body temperature. Given a $T_a$ near 25 °C, a rat failing to escape from a field at a $\dot{D}$ of 60 mW/g during a 10-minute exposure (D = 36 J/g) would probably expire because of an elevation of core temperature to 44 °C or higher (cf. Justesen et al., 1971a; Justesen, 1975b; Phillips et al., 1975). Whether the same dose of energy would prove lethal to a mouse at the same $T_a$ is less certain, because its allometric advantage would augur for a smaller $\Delta$ T. Ho and Edwards(1979) exposed individual mice for 20-minute durations in a 2450-MHz waveguide at $\dot{D}$s approximating 60 mW/g (D ~72 J/g) and did not encounter lethality, but 20-°C air circulated through the waveguide at high velocity (>4 m/s). In contrast, Phillips et al. (1975), observed *grand-mal* convulsions and a high incidence of lethality in mice that were exposed to a 12-cm microwave field in a still-air environment at 25 °C; the Ds associated with convulsions ranged between 25 and 30 J/g.

In Experiment I, we dispensed with time-outs and made irradiation continuously available during a 10-minute period. Although symptoms of thermal stress were presented by the animals, the rats more so than the mice, none of the animals sustained the maximal D (36 J/g) because they were spending from 25 to 80 percent of their time in the safe areas of the shuttles and the hemicircles. Moreover, the times of safe-area occupancy invariably exceeded baseline values, thus indicating a powerful influence of the microwave field on behavior (by conservative sign test, the P is less than $10^{-6}$). But are these highly reliable increases indicative of acquisition of an escape response? of efforts by animals to thermoregulate? or do they simply reflect an indiscriminate thermokinesis?

In designing Experiment II, the data of which have been reported in part elsewhere (Justesen, 1983a), we realized that only with a longer period of *continuously* available irradiation—and only with a behavioral task that militates against thermokinetic artifact—can the question of adventitious acquisition of escape or avoidance be resolved. Accordingly, we installed in the 2450-MHz cavity a false Plexiglas floor inscribed with a circular safe area *in its center*, then we observed individual mice and rats for evidence of escape and avoidance during a succession of 15-minute periods of available irradiation. Because entry to the centered circle might have demanded more of the thigmotactic rodent than it is disposed to perform, we also obtained comparative data from other mice and rats under motivation by faradic shock, cessation of which is a demonstrably powerful negative reinforcer (cf. Justesen et al., 1971b; King et al., 1971; Carroll et al., 1980; Levinson et al., 1982). We decided, too, not to provide sonic cueing or any other form of discriminative stimulation. Our intent was to give naive mice and rats the option to "learn or burn" in consequence solely of microwave irradiation as the motivating and reinforcing stimulus.

## METHODS, MATERIALS, AND PROCEDURES, EXPERIMENT II

Experimentally naive rats and mice of the same strains and from the same suppliers as those of Experiment I were assorted into one of two primary conditions: behaviorally contingent inactivation of an intense microwave field, or behaviorally contingent inactivation of faradic shock. The body masses of rats averaged 246 g, those of mice, 39 g, at inception of the experiment. Housing and feeding conditions were the same as those of Experiment I, and $T_a$ ranged variably between 22 and 25 °C. The 2450-MHz cavity used earlier was fitted with one or the other of two, nearly identical, white, Plexiglas floors (see scale drawing in Figure 2). Both floors were inscribed about their centers with a black-bordered circle encompassing 25 percent of the horizontal surface; one also was inscribed with a grid of silver paint by which faradic shock was delivered to active-control animals.

Each of 14 mice and 14 rats underwent a total of six, once-daily, 15-minute sessions at 24-h intervals. During the first and sixth session, irradiation and faradic shock were withheld to provide, respectively, baseline data on times of occupancy in the circle, and post-treatment occupancy times by which to index resistance to extinction. During sessions two through five, 2450-MHz irradiation at 60 (±10%) mW/g or faradic shock (150-300 μA rms) were presented whenever an animal's head was in the unsafe area. Upon each crossing by an animal of the circle's 1-cm black border to enter the safe area, irradiation or shock was immediately terminated. Conversely, each departure from the safe area led to immediate activation of irradiation or shock. Entries to and exits from the safe area were independently observed by two investigators, and durations of occupancy of the safe area were automatically recorded. Ten mice and as many rats were motivated by microwaves; four animals of each species, by faradic shock. Given the mouse's allometric advantage over the rat in dissipating thermalized energy, a second set of six sessions was scheduled, as before, but 10 additional mice, all experimentally naive, were motivated by irradiation at 120 mW/g.

## RESULTS, EXPERIMENT II

### BEHAVIORAL DATA

*Gross behavior.* Each of the four sessions of available irradiation began while an animal was in the unsafe area. Our informal but consensual observations are these: There was a noticeable delay between onset of irradiation and subsequent signs of arousal, which typically elaborated as heightened exploratory behavior, more rapid locomotion, grooming, then a coating of the pelt with saliva interspersed with even more rapid locomotion. The rats at 60 mW/g reacted more rapidly after onset of irradiation than did mice at the same $\dot{D}$, 8 to 10 s as opposed to 10 to 12 s, and the mice at 120 mW/g typically reacted after 5 to 7 s. Animals of both species, once there was an unequivocal reaction to irradiation, were decidedly given to running along the floor of the cavity in proximity to its walls. (This marked tendency to run along the periphery of the cavity's false floor also was exhibited initially by faradically shocked animals.) But all animals did enter the safe area from time to time and thus had several opportunities to detect inactivation—to be negatively reinforced by cessation—of the field.

All rats at 60 mW/g and all mice at 120 mW/g convulsed during the first session of microwave irradiation. Two mice in the 60-mW/g condition convulsed, and one did so twice: during the first and second sessions of irradiation. The other mouse convulsed during the fourth session of irradiation. The other eight mice in the 60-mW/g condition exhibited symptoms of thermal stress but did not convulse, although most of them spent nearly all their time in the unsafe area. Each of the 10 mice ventured briefly into the safe area several times during one or more sessions of available irradiation at 60 mW/g, but they quickly returned to the unsafe area, and they appeared to have a different strategy from that of the investigators in coping with the intense field. After an initial bout of intense locomotor activity, they tended to immobilize and to "spread eagle" on the false Plexiglas floor.

Faradically stimulated mice and rats began immediately on receipt of shock to run about the cavity, initially along the periphery of the false floor and then, after the first entry to the circle, there was an ostensible change in behavior. They remained in the safe area for fairly long periods (tens of seconds to minutes), then occasionally would "probe" the unsafe area before returning again to the circle. By the fourth and final session in which faradic stimulation was available, all rats and about half the mice were *avoiding* the stimulus. In contrast, none of the irradiated rats and mice avoided the microwave field. Indeed, with the possible exception of two mice in the 120-mW/g condition, we saw little during the four sessions of available irradiation that even remotely indicated acquisition of a discriminated escape response. These impressions are consistent with the quantitative behavioral data and the lethality data recounted below.

*Quantitative data on behavior.* Figure 5 presents mean numbers of entries by mice and rats of all five groups into the centered circle. Although not a measure of learning, the entry datum is important because it reflects whether an animal had the opportunity to experience escape-response-contingent cessation of irradiation. The baseline means of entry to the circle during the first session are highly variable, ranging from 4.5 to 14.5 among the five groups of animals, but those of the second session, at commencement of which irradiation or faradic shock was introduced, are much less variable, ranging from 4.3 to 4.9 for animals of four groups; faradically shocked rats generated a mean of 8.3 entries during this session.

Figure 6 presents data on the formal measure of acquisition: mean-percent time in the circle. As expected of the two thigmotactic species, the mice and rats of all five groups spent little time in the centered circle during the baseline measure of the first session. During the second session, safe-area times of occupancy by faradically shocked animals rose dramatically: On average, mice spent nearly 50 percent of their time in the safe area; rats, nearly 75 percent. During the third through fifth sessions, the shocked animals spent increasingly more time in the safe area, many animals approaching 100 percent of their time therein. Even during the sixth session, when shock was withheld, the mice on average spent 80 percent of their time in the circle; rats, nearly 100 percent.

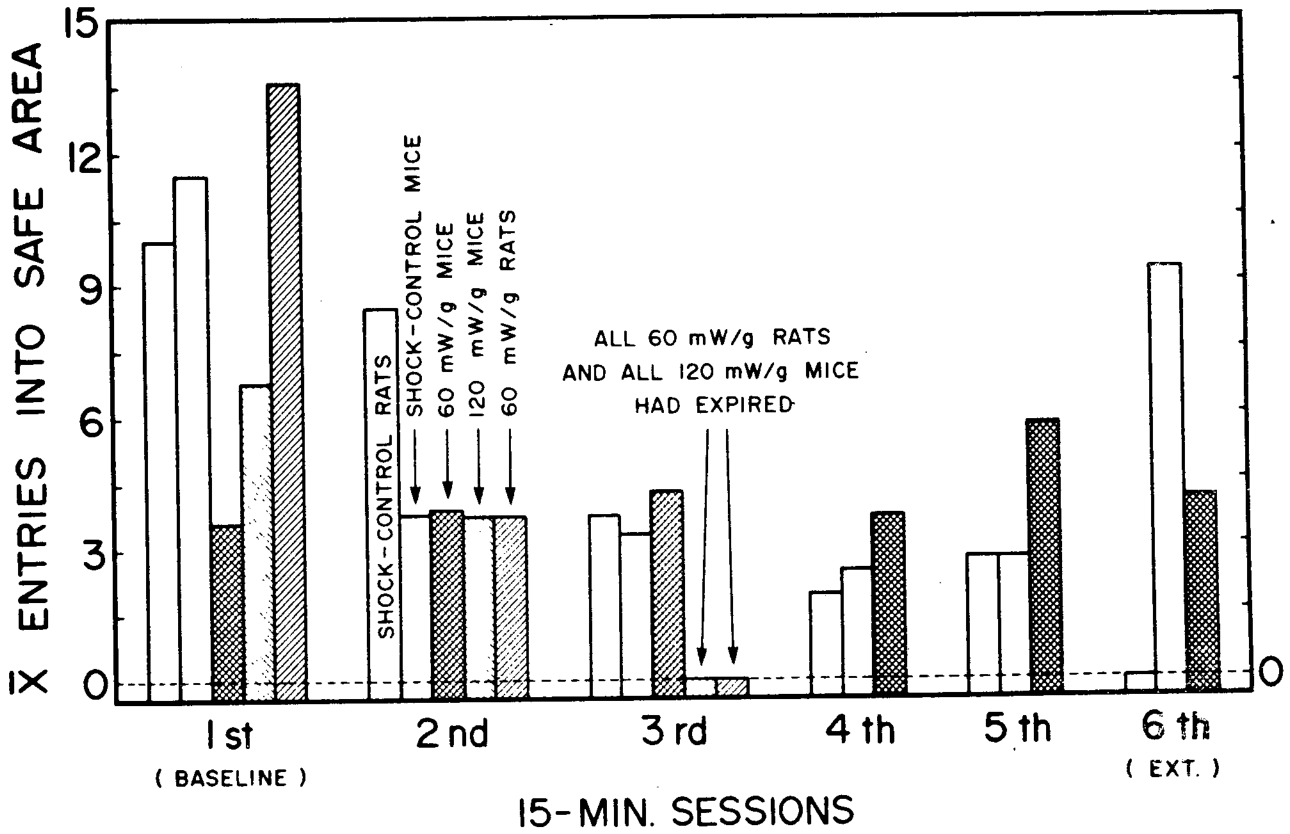


Figure 5. Experiment II: Mean numbers of entries by mice and rats into the safe area of a centered circle are shown for each of six, 15-minute sessions. Each session was separated by ~24 h and, during those of the 2d through the 5th day, faradic shock or 2450-MHz irradiation at 60 or 120 mW/g was applied whenever an animal's head passed from the safe to the unsafe area. Shock and irradiation were not available during the 1st and 6th sessions, to provide baseline data. Four mice and four rats were motivated to escape by faradic shock. Ten each mice and rats were motivated to escape by irradiation at 60 mW/g; and 10 additional mice, by irradiation at 120 mW/g.

Outcomes differed for animals motivated by microwave irradiation. As the data of the 2d session reveal (Fig. 6), means of time spent in the safe area by mice and rats of the 60-mW/g condition differ negligibly from those of baseline measures. On average, mice of the 120-mW/g group during their first exposure to microwaves (2d session), exhibited a relatively large increase in times of safe-area occupancy as compared with their baseline mean, but this increase (from ~3 to ~20 percent) is not indicative of escape behavior, as will be seen in the data on lethality.

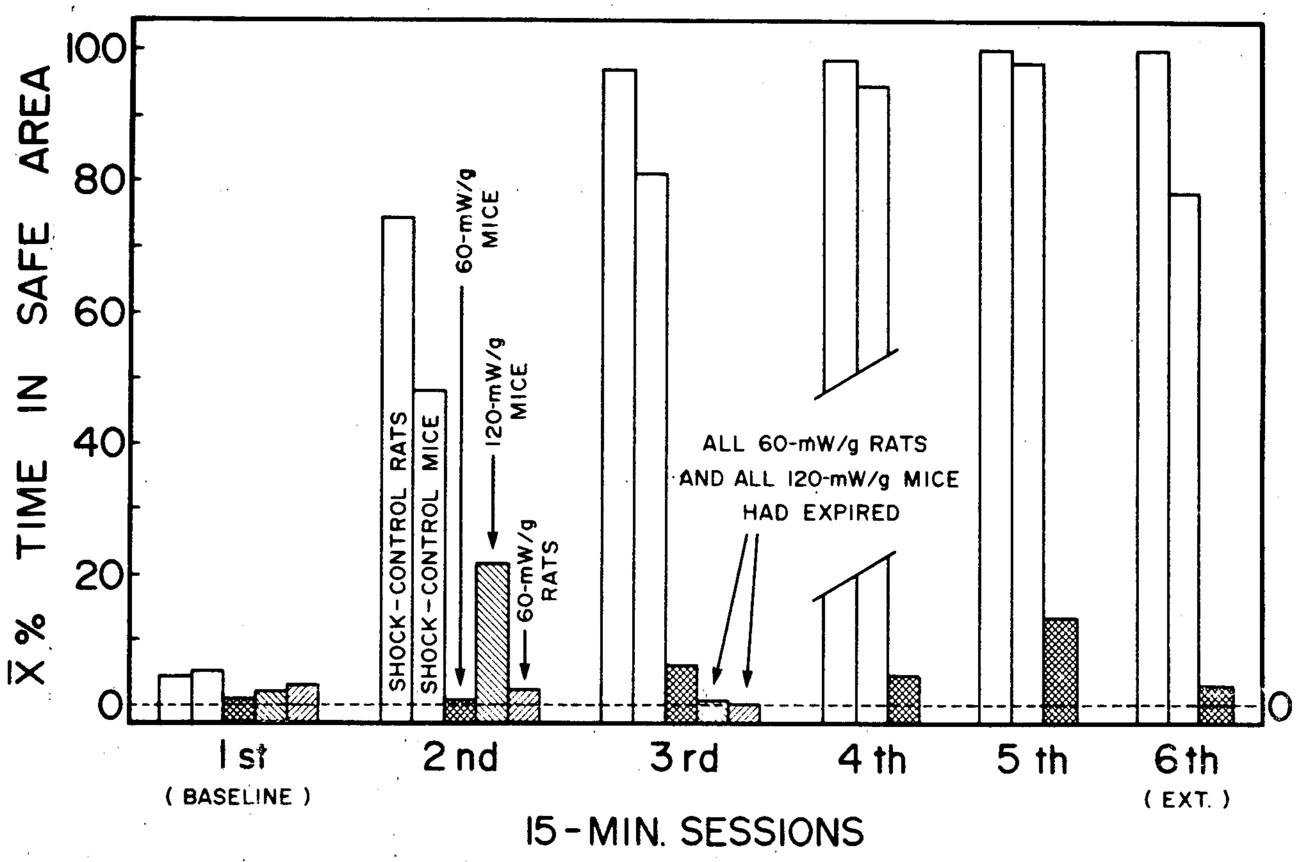


Figure 6. Experiment II: Means of percentage of time spent in the circular safe area by mice and rats. Conditions are described in the caption to Figure 5. Note the failure of all 10 rats to survive escapable irradiation at 60 mW/g and of all 10 mice to survive escapable irradiation at 120 mW/g. In contrast, rats and mice motivated by faradic shock readily acquired the escape response, and the rats eventually avoided shock.

## LETHALITY

All 10 rats of the 60-mW/g condition expired during their first session of irradiation. One of the 10 mice in the 60-mW/g condition expired during the 3d session, and a second mouse expired during the 5th session, but mean times of occupancy of the safe area by the eight surviving animals never exceeded 15 percent. Nine of 10 mice in the 120-mW/g condition failed to survive the first session of irradiation, and the surviving animal expired during the session of the following day. This lone survivor had convulsed midway during its first session of irradiation and, in the throes of its seizure, had moved fortuitously into the safe area where it lay without being irradiated until session's end. Yet another mouse did the same, but it expired during its first encounter with the field. The relatively long times of safe-area occupancy by these two mice inflated the mean value to ~20 percent during the 2d session.

The median time to lethality—as conservatively defined by post-convulsive cessation of all motor (including respiratory) activity—of the rats in the 60-mW/g condition is

598 s; the estimated median lethal dose, 34 J/g. The median time to lethality of the mice in the 120-mW/g condition is 346 s; the estimated median lethal dose, 39 J/g.

INTER-RATER AGREEMENT

Pearson product-moment coefficients were calculated to determine concordance of recording by two investigators of entries and of times spent by animals in the circle during sessions 1 through 6. All **rs** exceed .98, all **Ps** are less than .01.

## DISCUSSION, EXPERIMENT II

The data of Experiment II, like those reported earlier by Carroll et al. (1980) and Levinson et al. (1982), are clearly in support of the proposition that the experimentally naive rodent, in the absence of collateral photic cueing, does not acquire adventitiously an escape or avoidance response under motivation by an intense microwave field. The generality of the earlier findings, which were based on rats subjected to irradiation at 60 mW/g in a 918-MHz field, has been extended to the mouse, to the 2450-MHz field, to a higher $\dot{D}$ in the case of the mouse (120 mW/g), and to a procedure in which the field is continuously available, its inactivation contingent only on the prescribed behavior. The behavior required of the animals, entry to a centered circle, doubtless placed great demand on the thigmotactically disposed animal. However, animals of the same two species under motivation by faradic shock readily mastered the escape response, and many of them eventually demonstrated virtual avoidance. The shock-motivated animals were also singular in exhibiting resistance to extinction.

The data of Experiment II also revealed what we assumed (Carroll et al., 1980) on historical and analytical grounds to be true in our earlier studies: At 60 mW/g, the potentially lethal field is certifiably so for the rat within 10 minutes if intra-session time-outs—periods of automatic inactivation of the field—are not used, i.e., the conservatively estimated, median lethal dose to the rats of Experiment II is 34 J/g, which would result after 9.5 minutes of continuous irradiation at 60 mW/g.

In spite of comparably long times in the unsafe area, 8 of 10 mice in the 60-mW/g condition survived irradiation. The median lethal dose (MLD) to mice at 120 mW/g, 39 J/g, is only 15 percent larger than the rats' MLD at 60 mW/g, an indication that at increasingly higher dose rates there is a significant narrowing of the smaller animal's allometric advantage. The mouse is obviously more refractory to thermal insult than is the rat at 60 mW/g, which reflects, at least in part, its higher surface-area to body-mass ratio, and which enables it to dissipate thermal energy to a moderate (~25 °C) surround more rapidly than can the rat. But we question whether allometry is solely responsible for the mouse's greater robustness. Most of the mice in the 60-mW/g condition survived irradiation by immobilizing and by making close contact with the false floor of the cavity. These behaviors likely would be associated with a reduction in the animal's metabolic rate and with an increase in conductive transfer of thermal energy from the body. Although not the best of adaptive responses, they had ostensible survival value. In addition, two of the mice during the fourth and last session of irradiation began to enter the safe area and to remain within for periods to 30 s.

Perhaps the behavior of these two mice was fortuitous. On the other hand, we might have been observing the formation of a discriminated escape response-or even primitive attempts at behavioral thermoregulation. Whatever, we recognize in the behavior of these two mice the truism of individual differences. One can state with some confidence that, as a rule, the uncued, untrained mouse or rat will not acquire a simple locomotor behavior that averts lethality in an intense microwave field, but one must not discount the possibility of adventitious acquisition by the exceptional animal.

## GENERAL DISCUSSION

Considered in sum, the data of Experiments I and II leave unanswered a question with important ramifications for theoretical biology: Will the sonic stimulus as a discriminative cue facilitate acquisition of escape from or avoidance of an intense microwave field by the naive animal? In Experiment I, times spent in the safe areas by mice and rats invariably increased over pre-exposure baselines, but times of occupancy were not affected by the sonic stimulus. If one interpreted the data as demonstrative of an acquired escape response or as evidence of behavioral thermoregulation, the absence of superior performances by sonically cued animals simply would reflect a ceiling effect. That is, microwave irradiation in isolation might have sufficed optimal performances. But if the data of Experiment I are the result of a thigmotactically inspired, thermokinetic artifact—an artifact that was controlled in Experiment II, which indicated that microwave-lethality, not aversion, is the rule—then it is fair to question whether auditory stimulation will cue escape by the naive animal from a microwave field.

In the light of our earlier finding (Levinson et al., 1982) that photic cueing enabled acquisition of an escape response by microwave-irradiated rats, we find ourselves intrigued by Richard H. Lovely's view that the cutaneous receptors for warmth and the visual receptors for brightness are "genetically wired" in the rodent. Citing unpublished work with Nancy Mizumori and Robert Johnson in the laboratories of Arthur W. Guy at the University of Washington, which was communicated personally to us in May of 1977, Dr. Lovely noted that repeated attempts to train rats to avoid an intense microwave field had failed when sonic stimulation served as an antecedent cue, but had succeeded under identical testing conditions when unpatterned light was the discriminative stimulus. Light was evaluated as both a positive and a negative cue, i.e., for some animals, a small lamp was illuminated at onset of a discrete trial a few seconds before an intense field was activated. For other animals, light from the small lamp was extinguished before activation of the field. Only when light was presented as a positive cue did it function as a discriminative stimulus. The data of Lovely et al., of Levinson et al., and of Experiments I and II are consistent with the thesis that warmth and photic reception are intrinsically organized-and-associated in the nervous system.

That rodents—and perhaps many other terrestrial mammals—may depend on simultaneous activation of cutaneous and visual receptors in the behavioral management of thermalizing stimuli is a reasonable proposition if not pressed to exclusion. Left to cutaneous sensing alone in the absence of light or in the presence of unchanging light, mammals subjected to a spatial gradient of $T_a$s that overlap the thermoneutral zone will, in time, achieve thermoneutrality (see the extensive review by Cabanac, 1983). Or, given two drafts of air, one of which is too warm, the other too cold, the mammal can be trained to control a switch that sequentially activates one draft, then the other, producing thereby stable (and presumably comfortable) body temperatures (see, e.g., Adair & Adams, 1980, 1982). These demonstrations of cutaneously mediated, behavioral thermoregulation exemplify freedom from photic control, but they depended more nearly on time-consuming trial-and-error learning than on the fast reflexive response.

Given the eons of evolution in which both solar (*sunlight* ) and terrestrial sources of thermal energy (*light* of the fire) have been accompanied by visible photons, it should come as no surprise that the temporal conjunction of thermalizing and luminous energies might possess unique stimulus properties. In isolation, cutaneous sensations of warmth as such may be more akin to proprioception (to what is going on inside the body) than to exteroception (to what is going on beyond the body). The exteroceptive character of the luminous stimulus is a given and, when light accompanies a sensibly thermalizing stimulus, the reflexive pathways of the organism may be primed to trigger rapid retreat. Light may thus provide the directive information that signals the where and when of potentially noxious thermal stimulation.

Several lines of evidence comport with the thesis that coincidental light directs the rapid reaction to palpably thermalizing stimuli. One is neuroanatomical: The brightness receptors and the cutaneous thermal receptors have a common embryonic origin in the neural tube (cf. Bannister, 1976; Hartline, 1959; Warwick, 1976). Another is phylogenetic: Many invertebrates exhibit cutaneously mediated photosensitivity; for example, some worms exhibit a marked, thermally independent sensitivity to light that plays on the skin (Milne & Milne, 1959). And finally, there is indirect functional evidence based on nocturnal mammals. Many species (including the rat and the mouse) are negatively phototropic. One could argue that an intrinsic aversion to light reflects selective extinction of forebears that came too close to the fire.

On heuristic grounds, we offer the view that appropriately timed photic stimulation transforms the proprioception of warmth into the exteroception of potential thermal insult. Although current knowledge is consistent with this thesis, it does not confirm its validity. Validation or disconfirmation awaits integral experimentation in which, say, both sonic and photic stimulation as discriminative stimuli are compared for efficacy in cueing aversion of an intense microwave field.

The thesis of photic transformation is not limited to the microwave field and, indeed, implies that far- (nonvisible) infrared irradiation is also a proprioceptive stimulus. Nonlocalized warming of the body by radiant energy of any wavelength may not be referred to an external source unless the visual modality (or, possibly, another cutaneous modality) is simultaneously activated. Piloreception is an exteroceptive modality, and the activation of piloreceptors by a draft of hot air might also serve to refer sensations of warming to an external source.

Many reports of infrared-motivated and -reinforced behavior have appeared in the experimental literature (see the reviews of Satinoff & Henderson, 1977, and Cabanac, 1983). At first blush, the mainifold demonstrations of operant control of infrared irradiation seem to cast doubt on the photic-transformation hypothesis, but Satinoff and Hendersen's caveat (1977) is well taken: Visible light is emitted by conventional laboratory sources of infrared energy and may have been the discriminative stimulus that has controlled the operant response.

We conclude by adding a caveat of our own: The reports in the infrared literature are based almost exclusively on operant behaviors that were well established before control of infrared irradiation was given to and demonstrated by the animal (Satinoff & Hendersen, 1977). Similarly, after extended training, experimentally sophisticated rats (Justesen, 1983a; Justesen et al., this volume) and monkeys (de Lorge, 1984b) can acquire operant control of an intense microwave field. It is noteworthy that acquisition of operant control of the microwave field by the rat and by the rhesus monkey appears to be facilitated, and markedly so, if collateral photic cueing is used during early training.

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# SENSORY, MOTIVATIONAL, and REINFORCING PROPERTIES of MICROWAVES: An ASSAY of BEHAVIORAL THERMOREGULATION by MICE and RATS

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## ABSTRACT

Original data from two experiments are reported in which individual mice and rats were trained to escape from an intense, 2450-MHz field by entering a circular area that was centered on the false floor of a multimode cavity. Then the animals were observed for evidence of behavioral thermoregulation. In Experiment I at an ambient temperature ($T_a$) of 25 °C, the animals were observed for times spent in the circle and in the microwave field under available energy dosing ($\dot{D}$) at 30, 60, 90, and 120 mW/g. In Experiment II, the available $\dot{D}$ was 60 mW/g, and measures of time in circle and field were made at $T_a$s of 20, 25, and 30 °C. The major findings, which are based on 9 weeks of experimentation and on 54 baseline and experimental sessions per animal, are these: (1) After training, all animals demonstrated a stable, periodic sequence of entering and leaving the field; (2) Times spent in the field were inversely related to $T_a$ and to $\dot{D}$; (3) Rats generally spent less time in the field than did mice but times converged at higher $\dot{D}$s and $T_a$s; and (4) Colonic temperatures measured immediately after sessions of irradiation were highly stable, means of the two species not differing and not ranging more than ± 0.25 °C. All criteria of behavioral thermoregulation were met, save one: Post-session temperatures were consistently elevated by 1 to 2 °C. The anomalous hyperthermia also was observed during late baseline measures, which is taken as evidence of anxiety that may be peculiar to warming by microwaves or to an artifact of the behavioral protocol. Experimental approaches to resolution of the anomaly are outlined.

## INTRODUCTION

We have been studying the behavior of mice and rats since the late 1970's in amassing data on motivational and reinforcing properties of intense microwave fields (cf. e.g., Justesen, 1979; Carroll et al., 1980; Levinson et al., 1982; 1985; and Justesen, 1983). The thrust of the data is that the intense, deeply penetrating (918- or 2450-MHz) field is highly motivating but that inactivation of the field by an operant escape response is at best a weak negative reinforcer. Our conclusion that lethality is more probable than is the animal's mastery of an escape or avoidance response is doubly qualified: Pairing a luminous cue with the microwave field does result in the rat's acquisition of an escape response (Levinson et al., 1982); and failure of irradiation as a negative reinforcer has been predicated on adventitious acquisition of escape by the experimentally naive animal (cf., e.g., Carroll et al., 1980; Levinson et al., 1982; 1985).

In this paper, we present original data on experimentally sophisticated mice and rats, i.e., animals that were "shaped" by an investigator to escape from an intense microwave

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field by the method of successive approximations (see, e.g., Ferster & Skinner, 1957), and pertinent chapters in the text by Honig & Staddon (1977). Because previous work by us on microwaves as a motivational stimulus usually has been based on a whole-body-averaged dose rate ($\dot{D}$) of 60 mW/g, we wished to explore the behavioral response to microwave irradiation under a wider range of $\dot{D}$s. Similarly, because previous work has been based on the ambient temperature ($T_a$) in our laboratory (typically, 23 to 25 C°), we wished to explore the behavioral response to microwaves under a wider range of $T_a$s. These aims were joined by two more: to gain comparative data on mice and rats, and to determine the thermal response to irradiation by animals that have acquired operant control of the intense field.

## METHODS AND MATERIALS, EXPERIMENT I

### EXPERIMENTAL SUBJECTS

Six female mice of the B6D21F1 strain and six female rats of the Long-Evans strain were randomly selected from larger lots that were purchased, respectively, from Harlen Co. of Madison, Wisconsin, and from Blue-Spruce Farms of Altamont, New York. Animals of these strains were selected as experimental models because of their neurological integrity and ocular pigmentation, which are prerequisites for tasks, such as that imposed on our animals, requiring rapid pattern recognition and discrimination (cf. Sheridan, 1965; Creel, 1980). The body masses of the mice during a 6-week period of experimentation averaged 18.7 ± 4.5 g; those of the rats, 307 ± 26 g. All animals were individually caged in separate vivaria in which water and Purina Lab Chow were available on an *ad lib.* basis.

### ENVIRONMENT

The $T_a$ in both vivaria was maintained at 25 ± 1 °C; that in the laboratory ranged variably during the period of experimentation between 24.8 and 28.2 °C and averaged 25.3 °C. A 12/12 h light/dark cycle was automatically controlled in both vivaria, lights on at 0600 hours.

### EXPOSURE FACILITY AND PARAMETERS

The Tappan R3L multimode cavity described by Justesen et al. (1971a) was fitted with a false, white Plexiglas floor (Fig. 1). The floor was inscribed on its center with an open circle formed by a 1-cm wide border of black plastic tape. The circular area comprised 25 percent of the floor's surface. Power levels in the cavity were calorimetrically calibrated on mass-equivalent models of water to yield rates of energy dosing (± 10%) at 30, 60, 90, or 120 mW/g, rms. The 2450-MHz field was doubly modulated at 60 Hz (half-wave sinusoid) and, by mode stirring, at 12 Hz. Fan-driven air circulated through the cavity at a spatially averaged velocity of 0.2 m/s, as measured by a Kurz Model-441M air-velocity meter. Two 15-W incandescent lamps (house lights) were mounted above the stainless-steel overhead of the cavity behind grilles of radiopaque holes. On demand, the lamps could be programmed to illuminate in synchrony with periods of activation of the microwave field. A red, 25-W lamp external to the cavity permitted the investigators to observe an animal through a radiopaque grille during periods in which the house lights were not illuminated.

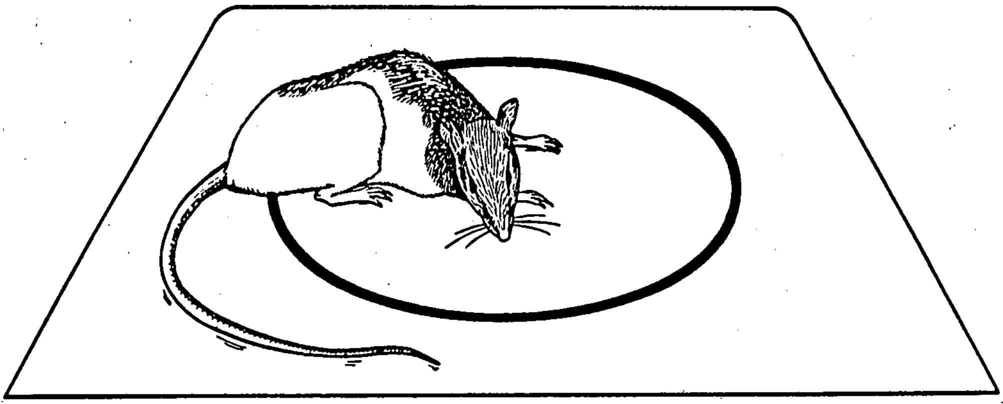

Figure 1. Artist's rendering of a Long-Evans' rat on a false Plexiglas floor that was installed in a 2450-MHz multimode cavity. The circular area described by the black border was centered on the floor and comprised 25 percent of the floor's surface. In the two experiments presented in this paper, entry to the circle by a mouse or rat resulted in cessation of microwave irradiation; exit from the circle, immediate resumption of irradiation.

## PROCEDURE

Each animal performed during a total of 36 once-daily sessions, which were conducted 6 days a week, Monday through Saturday, across 6 contiguous weeks. During once-daily 15-minute sessions of the first week, the 1st and 6th were conducted without irradiation or illumination of house lights to provide baseline data on times of occupancy of the circle. The 2d through 5th daily sessions were devoted to training of individual animals to enter the circle. After activation of the house lights and microwave source, an investigator with a hand-held microswitch inactivated both simultaneously, first for locomotor movement in any direction, then for locomotor movement in the direction of the circle, and finally, only for entries by an animal into the circle. The criterion of entry was passage of an animal's head across the perimeter of the circle. Conversely, the criterion of departure was passage of an animal's head beyond the perimeter of the circle. Each time an animal left the circle, the houselights and field were immediately reactivated.

During the first week, the microwave dose rate ($\dot{D}$) was increased from 30 mW/g (2d session) to 60 mW/g (3d and 4th sessions) and finally to 90 mW/g (5th session). During the 4th and 5th sessions, the house lights were gradually reduced in intensity until only the field was present to motivate entry to the circle. At conclusion of the 5th session, all animals had demonstrated periodic, unassisted entries to the circle under motivation by microwave irradiation.

From the second through the sixth week, all sessions were 10 minutes in duration, photic cueing was not used, and inactivation of the field during the 2d through 5th sessions was solely contingent on an animal's entry to the circle. The field was immediately reactivated upon an animal's departure from the circle. Sessions 1 and 6, as before, were conducted without irradiation to permit measurement of baseline times of occupancy of the circle. The available $\dot{D}$s during the second through sixth consecutive weeks were, respectively, 60, 90, 120, 30, and 60 mW/g. All sessions were conducted between 0800 and 1800 hours, and animals of a given species were observed in sequence before animals of the other species were observed. The daily order of testing species alternated across days. Colonic temperature of each animal was measured at conclusion of each of the 36 sessions by a Bailey Model BAT-8 thermometer with Model-HT1 (mice) and -0T1 (rats) thermocouple sensors.

## APPARATUS SUPPORT, RELIABILITY OF MEASUREMENT

Electromechanical and solid-state modules and timers (Lehigh Valley Electronics) were used to control durations of sessions and to synchronize the luminous stimulus with each period of irradiation. Each of two investigators operated a hand-held microswitch, one of which by alternate depression and release activated and inactivated the microwave field, both of which were tracked by an event recorder (Esterline-Angus Model AW20). From the printed record, cumulative time of occupancy of the circle by each animal was determined for each session. The record also permitted calculation of reliability of measurement (inter-rater accord on durations of time in the circle), which yielded product-moment coefficients approaching unity (rs >.98, Ps <.01).

## RESULTS, EXPERIMENT I

Data on colonic temperatures and on times spent in the circle by six mice and six rats during formal baseline and exposure sessions are presented graphically in Figure 2. Because all animals spent considerable time in the field (outside the circle) during sessions 2 through 5 of each weekly set of sessions, mean-percent times of irradiation at each level of energy dosing are provided in Table 1. As the proportion of time spent in the field during a given 600-s session decreased, an animal's time-averaged dose rate decreased from the limit of the available $\dot{D}$. Means of "received" $\dot{D}$s as well as of the resulting energy doses (Ds in J/g) also are given in Table 1.

Preliminary analyses revealed that the within-week means of times in the circle (sessions 2 through 5) do not differ reliably for either species at any given $\dot{D}$. So, too, for means of the two sets of sessions at 60 mW/g. Accordingly, we pooled the data to permit a 2-by-4, repeated-measures analysis of variance (ANOVA) in assessing species (rats versus mice) and level of energy dosing (30, 60, 90, and 120 mW/g) as sources of variation. In interpreting F ratios, we used conservative degrees of freedom (based on sample ns) and not the larger dfs that are needed to calculate F ratios in repeated-measures ANOVAs.

The means of time spent in the field (second through sixth week) differ greatly as a function of species [F = 70.77 (1/10), $P < 10^{-5}$]; the rats generally spent much less time in the microwave field than did the mice. Level of energy dosing is an even stronger source of variation [F = 222.61 (1/10), $P < 10^{-7}$]; Table 1 clearly reveals that means of time spent in the field are inversely related to $\dot{D}$. The species' difference in time spent in the field narrows reliably as a function of increasing dose rate, as confirmed by the F ratio of the species-by-$\dot{D}$ interaction [F = 17.66 (3/10), $P < 10^{-3}$].

The 2-by-4 ANOVA also was performed on means of colonic temperature. Species is not a reliable source of thermal variation [F <1.0 (1/10), P >.10], but level of energy dosing is [F = 4.32 (3/10), P~.04]. The latter F ratio reflects a weak negative correlation between $\dot{D}$ and means of colonic temperature (the product-moment r is -.48). Because the averaged means of post-irradiation temperatures of the 12 animals per weekly set of sessions range so narrowly (39.5, 39.3, 39.2, 39.3 and 39.3 °C, respectively, for the five sets of sessions from the second through sixth week), and because the highest colonic temperatures coincided with a period in which the $T_a$s in the laboratory reached their highest levels (to 28 °C), the inverse relation between colonic temperature and $\dot{D}$ might be spurious. The interaction of species with $\dot{D}$ is nil as a source of thermal variation [$F = 2.41$ (3/10), $P > .10$], indicating that the elevated temperatures of mice maintained a consistent relation to those of rats across levels of energy dosing.

There were no systematic changes in baseline means (sessions 1 and 6) of time spent in the circle during the second through sixth week. Thus, the frequently repeated exposures of the mice and rats to fields of high to extremely high intensity failed to generate measurable evidence of resistance to extinction, i.e., failed in the absence of irradiation to increase above pre-exposure baselines the amount of time spent in the circle.

The baseline temperatures of mice and rats exhibited small overall increases across the 5 weeks of formal study, but those of mice are the more remarkable for their relatively high mean values, which are well above normal resting levels. Compared with the mean of the rats (38.4 °C), the final baseline mean (the day-6 extinction measure of the sixth week) of the mice's colonic temperature is 39.1 °C. As our thermometers and thermal sensors were calibrated to an accuracy within ± 0.1 °C against an NBS-traceable standard, error of measurement is an improbable explanation.

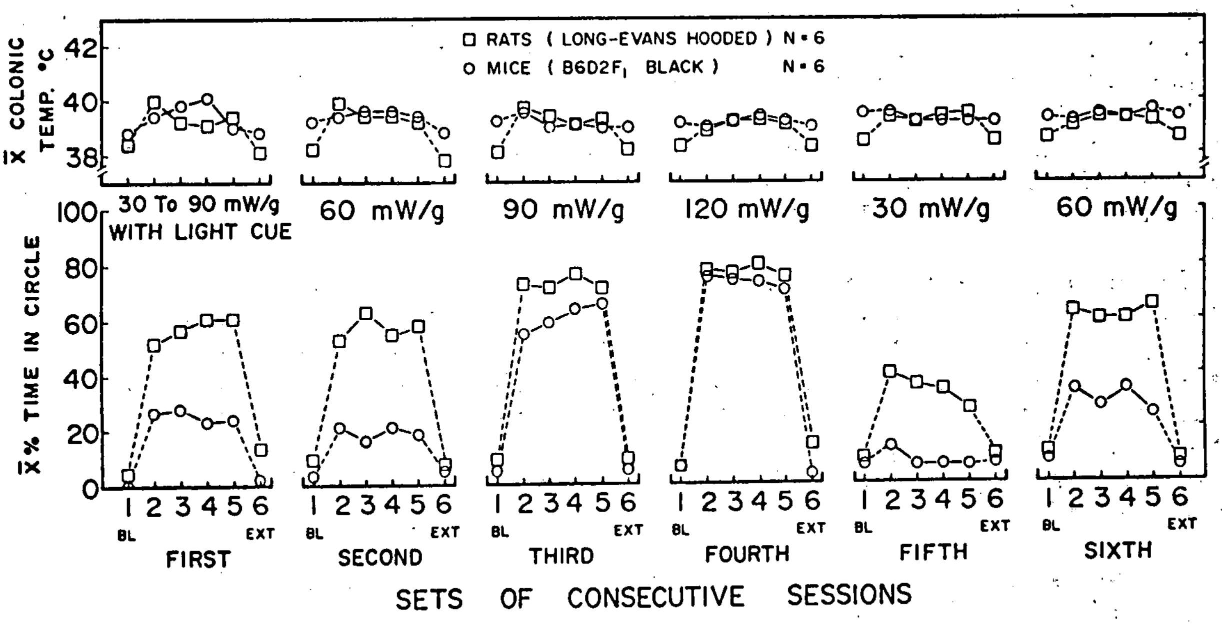


Figure 2. Graphic plots are shown for mean-percent times spent in the circle by mice and rats. Means of the animals' post-session colonic temperatures also are shown. During the 1st (BL) and 6th (EXT) session of each weekly set of six sessions, the animals were not motivated by microwave irradiation, to provide baseline measures. During the 2d through 5th session of each weekly set, microwave irradiation was available at the indicated dose rate. Once-daily sessions of the first set were 15 minutes in duration and were devoted to training of animals; periods of irradiation were accompanied by a luminous cue. During the second through sixth set of sessions, each session was of 10-minute durations and the luminous stimulus was not used. All data are based on an averaged ambient temperature of 25 °C.

Table 1

| | Available Dose Rate | | | |
|---|---|---|---|---|
| | 30 mW/g | 60 mW/g | 90 mW/g | 120 mW/g |
| Mice | | | | |
| $\bar{\%}$ Time in field | 91% | 70% | 39% | 26% |
| Avg. rec'd $\dot{D}$ | 27 mW/g | 42 mW/g | 35 mW/g | 31 mW/g |
| Avg. rec'd D | 16 J/g | 25 J/g | 21 J/g | 19 J/g |
| Rats | | | | |
| $\bar{\%}$ Time in field | 66% | 38% | 26% | 22% |
| Avg. rec'd $\dot{D}$ | 20 mW/g | 23 mW/g | 23 mW/g | 26 mW/g |
| Avg. rec'd D | 12 J/g | 14 J/g | 14 J/g | 16 J/g |

Mean-percent times spent in a 2450-MHz microwave field by six mice and six rats under four levels of available energy dosing. The averaged rate of energy dosing of an animal during a 10-minute session declined from the maximal available $\dot{D}$ in proportion to the time it was not in the microwave field. Accordingly, the time-averaged dose rates ($\dot{D}$ in mW/g) and the corresponding energy doses (D in J/g) *received* by the animals are shown for each level. All entries under a dose-rate column are based on means of four 10-minute sessions. The sessions were conducted during the third through sixth week of Experiment I. All values are rounded to two digits.

## DISCUSSION, EXPERIMENT I

The data of Experiment I indicate that the mice and rats acquired a complex response in which they escaped from but did not avoid the microwave field, even after repeated exposure and $\dot{D}$s as high as 120 mW/g. The gross behavioral picture is consistent with the interpretation that the animals were thermoregulating. During sessions 2 through 5 of the second through sixth week they exhibited an orderly, periodic sequence of entering and departing from the field, spending commensurately more time in the field at lower $\dot{D}$s. The dosimetric data shown in Table 1 provide additional evidence of thermoregulatory activity: Time-intensity reciprocity was strongly evident in mice and was markedly so in rats as indexed by the relatively narrow ranging of energy doses. The mean D of mice, 20 J/g, ranges from 16 to 25 J/g; the mean D of rats, 14 J/g, ranges from 12 to 16 J/g. When compared with the four-fold range of available $\dot{D}$s, 30 to 120 mW/g, it is evident that the animals were selecting discrete quantities of energy by remaining in the field for shorter periods at higher intensities of irradiation.

The temperature data, on the other hand, present a mixed picture with respect to classic criteria of thermoregulation. Means of temperature essentially remained the same irrespective of D, which is a hallmark of adaptive thermoregulation, but this criterion of stability is not matched by the important criterion of amplitude. The grand mean of 24 post-irradiation temperatures of mice is 39.32 °C, that of rats, 39.34 °C, which are considerably above the species' resting diurnal level (~37.50-38.0 °C) in a normal laboratory environment (Durney et al., 1978). A colonic temperature in excess of 39 °C is presumptive of hyperthermia in the murine animal and, although none of the animals presented symptoms of thermal stress during sessions of irradiation, the observed elevations and their persistence are noteworthy.

On first reviewing the data, we believed that repeated scheduling of animals during lengthy sessions would be associated with a gradual decline of post-session temperatures to pre-exposure baselines, but subsequent experimentation in our 2450-MHz cavity has revealed otherwise. Levinson et al. (1984) trained rats to press a small lever to extinguish (escape from) a field that resulted in a $\dot{D}$ of 60 mW/g. After each extinction of the field by the rats, it was automatically reactivated after a 15-s interval. Even after several 1-hour sessions, during which stable, highly periodic lever responses were observed in an environment at 24 ± 2 °C, post-session colonic temperatures of the rats averaged 40.5 °C and exhibited no tendency to decline across sessions.

The persistence of hyperthermia in the highly trained, seemingly autoregulating animal is at odds with the data on rats that thermoregulate in a cold environment by controlling an infrared field (Satinoff & Hendersen, 1977; Cabanac, 1983). Hypothalamic temperatures of infrared-reinforced animals, primates as well as rodents, are within normal levels (<38 °C), which led us to speculate that our post-session handling of animals during the course of measuring colonic temperature might have been producing an artifactual, emotionally inspired elevation (cf. Delini-Stula, 1970; Briese & Quijada, 1970; Justesen et al., 1974; Bermant et al., 1979). Accordingly, in the study of Levinson et al., 1984, we implanted the rats with indwelling cannulae to the preoptic area of the hypothalamus and then observed the non-handled animal via field-non-perturbing sensors for basal temperatures and for temperatures during sessions of irradiation at 60 mW/g.

Highly stable elevations of hypothalamic temperature to 40 ± 0.2 °C (rising from baselines near 38 °C) during the 1-hour sessions were invariably observed. Of interest to us, also, is that house lights were illuminated in synchrony with periods of irradiation—to establish parity with the visible light that accompanies activation of conventional infrared sources—but the presence of the luminous cue had no effect on the colonically indexed hyperthermia. If, as we have reasoned elsewhere (Levinson et al., 1985), a synchronous luminous stimulus can provide the irradiated animal with a precise temporal definition of the field, the animal so cued might avoid thermal overshoot by inactivating the field sooner after onset. But the overshoot—elevation of colonic temperatures to 39-40 °C—was as invariant in the 1984 study by Levinson et al., as it was in the original study reported here, which did not incorporate luminous cueing.

The temptation to conclude that infrared and deeply penetrating microwave fields inherently differ in affecting the thermal response of the thermoregulating animal was tempered by the realization, already alluded to, that the infrared studies have been conducted in cold environments, often with rats that have had their pelts shaved to enhance loss of thermal energy (cf. Murgatroyd & Hardy, 1970; Satinoff & Hendersen, 1977). Conceivably, the cold environment and the loss of insulation might conspire to moderate core temperatures.

Whatever differences may inhere between microwaves and infrared radiation as motivational stimuli, there is another important criterion in evaluating the more deeply penetrating field as a promoter of behavioral thermoregulation: Given options, the organism responds adaptively to changes of environmental temperature. In Experiment II, we observed mice and rats under motivation by an intense microwave field to determine if they will spend commensurately less time in the field as $T_a$s range upward from 20 to 30 °C.

## EXPERIMENT II

Ideally, experimental assessment of motivational and reinforcing properties of an intense microwave field in a cold environment would take place in a refrigerated laboratory of temperatures ranging downward to 0 °C. Lacking such a facility, we explored effects of $T_a$s on microwave-motivated behavior of mice and rats at the limits available to us, 20 and 30 °C. Even achievement of these limits posed problems. The studies comprising Experiment II were performed during the summer months at a time of high outside temperatures and of intermittent operation of the VA Medical Center's central air-conditioning system. A series of baseline and experimental measures at a $T_a$ of 30 °C was performed during a week in which the system was malfunctioning. A window-mount air-conditioning unit was brought into the laboratory and, while the room temperature outside the multimode cavity increased from 27 to 35 °C, the cooled air from the unit was titrated to 30 °C and piped into the cavity through a large flexible conduit. During another period when the central system was operating and the room temperature approximated 25 °C, the window unit was used to lower cavity temperatures to an average of 20 °C. Behavioral measures also were made at 25 °C, to approximate the $T_a$s used in most of our previous work. All three $T_a$s are nominal in being averages, the ranges of which fell within ± 2 °C.

We mention these constraints as an introductory note because they qualify the generality of the findings. Their generality is not diluted, however, by a history of stressful swings of $T_a$ in the mouse and rat vivaria. Fortunately for the animals, the vivaria were environmentally stable because they were serviced by an independent air-conditioning system. The $T_a$s in the vivaria were within ± 1 degree of 25 °C during the collection of data of Experiment II.

## METHODS AND MATERIALS, EXPERIMENT II

The same mice and rats that yielded the data of Experiment I served as the subjects of Experiment II. Also, the same 2450-MHz cavity with the same centered-circle floor was used, and, except for a range of differing $T_a$s (20, 25, and 30 °C) and for the use of one level of energy dosing (60 mW/g), procedures and conditions were identical. A 2-day interval separated completion of Experiment I and inception of Experiment II. Once-daily sessions of 10 minutes each per animal were conducted, six days a week, across 3 weeks. As before, the 1st and 6th sessions of a given week devoted to baseline measures—no irradiation—and colonic temperatures were measured immediately after all sessions. The $T_a$s during the three consecutive weeks of session were, respectively, 20, 30, and 25 °C.

Malfunction of a switch in the circuit that controlled the cavity's magnetron occurred during the first session of irradiation, which resulted in continuous activation of the field and in the death of one rat. The data of Experiment II are based therefore on six mice and five rats. Body masses of the six mice during 3 weeks of experimentation averaged 20.3 ± 1.5 g; Body masses of the five rats averaged 309 ± 28 g. Regimens of caging and feeding of the mice and rats in their respective vivaria were the same as those of Experiment I.

## RESULTS, EXPERIMENT II

Mean-percent times spent in the circle and means of post-session temperature are presented graphically in Figure 3 for all baseline and exposure sessions of Experiment II (2d through 4th set of sessions). The data labeled as the first set of sessions in Figure 3 are from the final week of measures of Experiment I; their inclusion permits a direct graphic comparison with thermal and behavioral findings of Experiment II that were obtained under the same conditions ($T_a$ = 25 °C; $\dot{D}$ = 60 mW/g). Mean-percent times spent in the microwave field during the three sets of sessions of Experiment II are shown in Table 2, which also presents session-averaged $\dot{D}$s and Ds as a function of $T_a$.

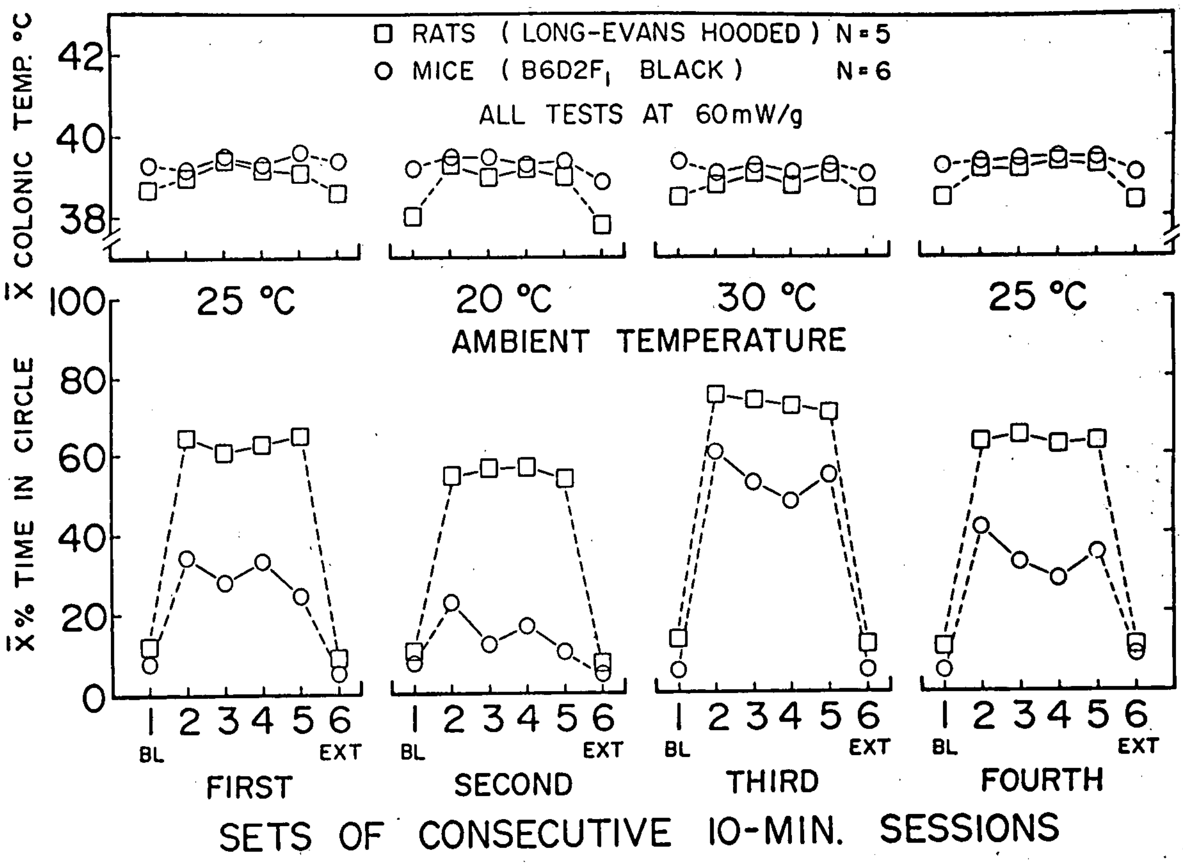


Figure 3. Mean-percent times in the circle by mice and rats and their post-session means of colonic temperature are shown for baseline sessions (BL and EXT) and for sessions (2 through 5) in which energy dosing at 60 mW/g was available. Ambient temperatures ranged from 20 to 30 °C across weekly sets of 10-minute sessions, as shown. The data of the first set of sessions are from the last week of Experiment I; they are incorporated in the figure to permit a direct comparison of the reproducibility of thermal and behavioral data under comparable conditions of ambient temperature and available level of energy dosing (i.e., 25 °C and 60 mW/g).

Preliminary analyses of times spent in the circle and of post-session temperatures revealed that within-week (sessions 2 through 5) differences among means are not reliable, which permitted pooling of data into weekly means, each mean based on four sessions of irradiation. Two-way ANOVAs (2 species versus 3 $T_a$s) were based on the repeated-measures model and were performed on the thermal and behavioral data from the three sets of sessions. The degrees of freedom used to interpret reliability of differences are conservatively based on sample ns, not on the larger dfs needed to calculate F ratios.

Table 2

| | Ambient Temperature ($T_a$) | | |
|---|---|---|---|
| | 20 °C | 25 °C | 30 °C |
| Mice | | | |
| $\bar{\%}$ Time in field | 85% | 66% | 46% |
| Avg. rec'd $\dot{D}$ | 51 mW/g | 40 mW/g | 28 mW/g |
| Avg. rec'd D | 31 J/g | 24 J/g | 17 J/g |
| Rats | | | |
| $\bar{\%}$ Time in field | 44% | 37% | 26% |
| Avg. rec'd $\dot{D}$ | 26 mW/g | 22 mW/g | 16 mW/g |
| Avg. rec'd D | 16 J/g | 13 J/g | 9.6 J/g |

Mean-percent times spent in a 2450-MHz field by five rats and six mice under three levels of ambient temperature. Time-averaged dose rates per 10-minute session ($\dot{D}$ in mW/g) and corresponding energy doses (D in J/g) received by the animals are shown for each $T_a$. All entries under a $T_a$ column are based on means of four 10-minute sessions. The numerical data correspond to graphic data in Figure 3 that are labeled as the second through fourth sets of sessions. During all sessions the available dose rate was 60 mW/g. All values are rounded to two digits.

Species is a highly reliable source of variation in controlling times spent in the field [$F = 135.3$ (1/9), $P < 10^{-7}$], the mice having spent much more time therein than the rats. Ambient temperature is also a highly reliable source [$F = 65.8$ (2/9), $P < 10^{-5}$], animals of both species having spent increasingly less time in the field at higher $T_a$s. Species and $T_a$ interact reliably [$F = 9.71$ (2/9), $P < .01$], the time-in-the-field differences between mice and rats narrowing as a function of increasing $T_a$.

The 2-by-3 ANOVA of the temperature data yielded the following outcomes: Species is a negligible source of thermal variation [$F = 1.74$ (1/9), $P > .10$], but $T_a$ is highly reliable [$F = 22.9$ (2/9), $P < 10^{-4}$] in spite of the narrow ranging of means, i.e., the weekly averaged means of post-irradiation temperatures of the 11 animals are 39.4, 39.1 and 39.3 °C, respectively, in association with $T_a$s of 20, 30, and 25 °C. The lowest post-irradiation temperatures were observed at the highest $T_a$. The interaction of species and $T_a$ is nil [F 1.45 (2/9), $P > .20$], which indicates that temperatures of mice maintained a uniform relation to those of rats under differing $T_a$s.

## DISCUSSION, EXPERIMENT II

By two criteria, the data of Experiment II indicate that the mice and rats were thermoregulating—time spent in the microwave field was inversely related to $T_a$, and post-session colonic temperatures were highly stable across a range of $T_a$s. That the field-behavior relation is robust and general is indicated by the dosimetric data of Experiment I and Experiment II for the case in which conditions overlapped. At a $\dot{D}$ of 60 mW/g and at $T_a$s approximating 25 °C, the energy doses selected on average by the mice were almost the same, 25 versus 24 J/g, as were those selected by the rats: 14 versus 13 J/g (cf. Tables 1 and 2).

Although the Ds selected by mice in Exp. II did not overlap those of the rats, they approached equivalence under a common available $\dot{D}$ of 60 mW/g when the $T_a$ for the mice was 30 °C and that for the rats was 20 °C. This finding confirms anew the allometric advantage of the mouse over the rat in dissipating thermal energy to a cool surround, an advantage that derives from its much larger surface-area to body-mass ratio (cf. Rubner, 1908; Sacher, 1959).

In sum, the evidence revealed by Experiments I and II is overwhelming in support of interpretation of microwave-motivated and -reinforced thermoregulation, but the anomalously high colonic temperatures remain a mystery. The grand mean of the rats' temperatures as measured immediately after each of the 12 sessions of self-selected irradiation in Experiment II is 39.2 °C, that of the mice, 39.4 °C. Supranormal temperatures also were observed during baseline measures, especially in the mice; for example, 24 hours after the 12th and last session of irradiation in Experiment II, the temperatures of the rats averaged 38.4, those of the mice, 39.1 °C. Emotional hyperthermia borne of human handling during acute measurement of colonic temperature is suspect, although after 54 measurements per animal (36 in Experiment I, 18 in Experiment II), the failure of habituation also is suspect.

Pavlovian conditioning of hyperthermia, which has been demonstrated in our laboratories (Bermant et al., 1979), is a distinct possibility. Rats were repeatedly irradiated by 2450-MHz microwaves an an unconditional stimulus (US) that evoked an increase of colonic temperature (~1.5 °C) as the unconditional response (UR). A sonic-conditional stimulus (CS) was presented a few seconds before and during 30- or 10-second periods of intense radiation (220 or 420 mW/g). Even after 200 pairings of CS and US, there was no evidence of a conditional $\Delta T$ to the sonic CS. It was subsequently established, however, that both the environment of the conditioning laboratory and the experimenter that had trained the rats were conditional stimuli (CSs). That is, when brought into the laboratory by anyone, or when lifted from the home cage by the investigator but not by another handler, the rats selectively exhibited elevations of colonic temperature that rose from ~37.5 to as high as 39.5 °C.

Recent pilot work by us on rats with chronically implanted thermal telemeters has revealed that prolonged periods of operant scheduling involving microwaves or faradic shock as a motivating stimulus produces $\Delta T$s of presumptive Pavlovian origin, a datum reported in earlier work by Delini-Stula (1970). She motivated rats to perform an avoidance task with conventional electric shock, then found long after an acquired avoidance response had been extinguished that colonic temperatures were elevated to 39-40 °C whenever the animals were returned to the conditioning apparatus. Unknown but important to delineation of long-term sequelae of microwave irradiation is whether such elevations are indicative of a persisting or recurrent susceptibility to stress with pathophysiological consequences. Aside from acute lethality from overexposure, we have seen no indications of ill after-effects in our intensely irradiated mice and rats during several years of admittedly informal observation. But the possibility of latent insult must be entertained and should be investigated in appropriately designed experiments.

## GENERAL DISCUSSION

Collectively, the data of Experiments I and II are the first to demonstrate that microwave irradiation as such can motivate and reinforce thermoregulatory behavior of a mammal. The demonstration is not unqualified, and we shall address some caveats in later paragraphs. First we note related work that preceded ours.

Exploratory work in our laboratory revealed that time spent by individual mice and rats in a 2450-MHz microwave field (entry to the centered circle inactivated the field) is an inverse function of field intensity (Justesen, 1983), but this work was based on a single $T_a$ ~25 °C. The criterion of differential selection of energy doses under differing environmental temperatures was not demonstrated. Stern et al. (1979) used a 2450-MHz field as a background source of warmth in a cold-air environment in which experimentally sophisticated rats pressed a lever for infrared irradiation. Responding to infrared reinforcement decreased reliably as the intensity of the background-field increased, but control was vested in the infrared, not in the microwave field. Adair and colleagues have published many reports of highly efficient thermoregulatory behaviors of microwave-irradiated squirrel monkeys but, to these animals, akin to the rats of Stern et al., the microwave field was presented as a background source of thermal energy (see, e.g., Adair & Adams, 1980, 1982). Bruce-Wolfe & Adair (1985) found that highly trained squirrel monkeys will thermoregulate by repetitive sequential selection of a draft of thermoneutral air in concert with a 2450-MHz field and of a draft of cold air without the microwaves. Thermal loading by the microwave field doubtless motivated the monkeys to switch to the draft of cold air from time to time, but the rapid upward and downward shifts in the temperature of the air stream probably served as highly salient discriminative stimuli.

In achieving thermoregulation by direct control of the microwave field, our animals were exceptions to the general rule that other mice and rats under motivation by intense irradiation have met with failure. As noted in the introduction to this paper, previous work on these species has revealed that the experimentally naive animal in the absence of discriminative stimulation is unlikely to acquire a relatively simple escape response under irradiation by a potentially lethal (cf. Carroll et al., 1980; Levinson et al., 1982) or a demonstrably lethal microwave field (Levinson et al., 1985). As the same or more difficult escape responses are readily mastered by naive animals under motivation by faradic shock (Justesen et al., 1971b, Carroll et al., 1980; Levinson et al., 1982, 1985), the failure of the highly intense field as a negative reinforcer raises the question of the responsible factor or factors.

We have noted elsewhere (e.g., Carroll et al., 1980) the factor of thermal inertia, i.e., once uncomfortably warmed by a microwave field, an animal may not detect cooling for several seconds after an escape response inactivates the field—and time is of the essence in the animal's ability to associate cessation of annoying stimulation with an adaptive response. Thermal inertia doubtless plays a role, but the findings of Experiments I and II clearly force consideration of a second factor: the affective sign of the intense field during initial periods of application. The animal re-entering the field is met by one of two sensory possibilities: Either the field on application is without sensory consequences for a considerable period or it is initially positively reinforcing. In the first case, the animal that entered the field would have no immediate information about its conduct in relation to the field; in the second case, it would receive information—a "pleasant" sensation of warmth—that would be contradicted by later discomfort. In either case, the animal faces the complex problem of dealing with a stimulus that changes affective sign—neutral to negative, or positive to negative—with the highly probable result that rate of acquisition of a difficult discrimination is retarded.

By carefully "shaping" our animals until they had mastered an operant escape response, and by presenting a luminous cue in synchrony with periods of irradiation during the shaping procedure, we enabled them to acquire the complex discrimination that eventuated in operationally defined behavioral thermoregulation. But unknown to us is what they were discriminating. Was the field acting only as a negative reinforcer? That is, was surcease of thermal discomfort on entry to the circle the only affective property deriving from the field? Or was the animal also positively reinforced, seeking warmth as it were in an environment that ranged variably—but not too far—below the species' preferred $T_a$ between 30 and 32 °C? To gain a purchase on answers to these questions we performed several pilot studies.

Rats were trained to press a lever that inactivated an intense field in the 2450-MHz cavity. Then they were given the opportunity to activate the field for a 12-second period per lever response. The $T_a$ was close to 20 °C, the available $\dot{D}$, 60 mW/g. Only 8 to 10 lever responses were observed during relatively protracted (1-h) periods of scheduling. In similar experiments, when entry to the centered circle was the operant response that activated the field, the results were negative: Our rats, true to the form of a thigmotactic species, seldom ventured from the walls of the cavity, and the small amounts of time they spent in the circle did not increase during extended scheduling. These observations lead us to conjecture that the motive to leave the circle in Experiment I and II was not necessarily to engage warmth but was in part or wholly to return to the wall of the cavity.

If our conjecture is correct, the anomalous post-session elevations of colonic temperature that were observed throughout Experiments I and II have an etiology in anxiety bred by a minus-minus conflict. In pedestrian terms, an animal entered the circle because it got too hot to stay by the wall. And the animal may have left the circle after cooling because of its genetically disposed aversion to open spaces. In technical terms, a sequence of negatively reinforced behaviors may have been responsible for the orderly alternation of movement into and from the centered circle. This sequence contrasts with the traditional thermoregulatory protocol in which the animal in a cool surround seeks warmth and is positively reinforced by a thermalizing stimulus.

The thesis that anxiety may have attended the thermoregulatory activity exhibited by our mice and rats has heuristic value that is the more promising in the stead of findings of yet another pilot study. We placed a Styrofoam partition in our 2450-MHz cavity that divided it into two chambers, each equipped with a lever. After performing dosimetric assays on a model of water in each chamber to ensure near-equivalent energy dosing at 60 mW/g, we placed two rats of equal age and mass in the cavity. One had been trained to press a lever to inactivate the microwave field, the other animal was experimentally naive. The naive animal was placed in a chamber with a disabled lever; the other animal was placed in the second chamber with an operative lever, then the microwave field was activated. We had planned to observe the rats for an hour under a regimen in which each lever response inactivated the field for 12 seconds. Before 30 minutes had elapsed, we aborted the experiment because the rat in the chamber with the inert lever was exhibiting extreme symptoms of thermal stress and was prostrate on the base of the chamber. Immediately after aborting, we measured the colonic temperatures of the animals. The animal that had controlled the field presented no behavioral symptoms of thermal stress but did exhibit a temperature just above 40 °C. The temperature of the non-controlling animal was much higher, near 43 °C.

Concerned that energy dosing had not been equivalent, we performed the experiment again with another pair of matched rats, but reversed the chamber with the controlling lever. The same disparity in symptoms and temperatures was observed. We realized at this juncture that we were observing a marked disparity in the physiological response to ostensibly equivalent physical stimulation, a disparity noted in another context by Weiss. In his classic work on the coping model, Weiss (1971a, 1971b, and 1971c) demonstrated via the yoked-control procedure that equivalent numbers, durations, and intensity of electric shocks yielded highly disparate outcomes in pairs of rats, one of which could cope with each of a series of shocks by turning it off, the other a helpless recipient. The coping animal was essentially normal, the victim subsequently presented marked symptoms of systemic insult. More recently, coping-model experiments on mice and rats (e.g., Sklar & Anisman, 1979; Visintainer et al., 1982; and Laudenlager et al., 1983) have revealed that the victim suffers severe immunological impairment, heightened incidence of malignancies, and shorter life span.

The coping model should lend itself readily to a test of two propositions involving microwave irradiation as motivational stimulus and reinforcer of thermoregulatory behavior. The first is that the noncontrolling victim of intermittent bouts of irradiation after repeated sessions may present marked symptoms of systemic insult. The second is that the animal in control of the microwave field also may present symptoms of insult—if, as we conjectured earlier, its behavior is predicated on a minus—minus conflict that engenders anxiety. Neither proposition, as stated, necessarily implicates the microwave field as such as a source of insult, but this possibility, too, could be evaluated by operant techniques in which the field is unequivocally a positive reinforcer. For example, use of an operant response that permits the mouse or rat to remain in proximity to a wall, use of a very cold environment so that warming by the field is positively reinforcing, and use of a weak luminous cue to define the temporal bounds of the field—all in combination should yield an unconfounded assay of microwaves as an intrinsic source of stress.

The question may arise in connection with the coping model whether the time-averaged $\dot{D}$ and resulting $\dot{D}$ per session would be sufficient to induce insult. Taking note of the data in Tables 1 and 2, one can see that the rats under energy dosing at 60 mW/g and under a $T_a$ of 25 °C spent about 75 percent of their time in the circle, the remainder in the field. The resulting averaged rate of energy dosing, ~15 mW/g, is many times larger than the level used by Szmigielski et al., (1982) to induce spontaneous malignancies in the mouse, which, as our data showed, is generally much more tolerant of the microwave field than is the rat.

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# MICROWAVE RADIATION EFFECTS on LOCOMOTOR BEHAVIOR in the RAT

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## INTRODUCTION

In recent years a variety of alterations in animal behavior has been reported following exposure to microwave radiation. Alterations have been reported on two general classes of behavior: acquired and innate. Many of the effects on acquired behavior are reviewed elsewhere in this volume. This chapter will review the effects of microwave radiation only on locomotor behavior in the rat—a spontaneous innate behavior. The following paragraphs define locomotor activity and briefly review the methods used in measuring this behavior. Subsequent paragraphs will compare several recent studies on microwave exposure and locomotor activity in the rat.

## DEFINITION AND MEASUREMENT OF LOCOMOTOR BEHAVIOR

There are many forms of innate behavior. All types of motor activity such as locomotor activity, sniffing, grooming, eating, drinking, mating, and nest building are innate behaviors. Many such motor acts occurring individually or in combination comprise an animal's behavioral repertoires. However, developing methods for the precise measurement of motor sequences that characterize specific innate behaviors is a difficult task. A simple example will make this point clear. In the broadest sense motor activity refers to the whole repertoire of unconditioned innate behavior, while locomotor behavior refers only to the motor acts necessary for movement from one place to another. Locomotor activity itself, however, is not a unitary class of behavior. Locomotor activity in the rat can refer to a variety of motor acts such as walking, running, rearing, jumping and turning. Often, in past studies, locomotor behavior and other innate behaviors have been simply described as general motor activity. A complete assessment of general motor activity would then require a composite measure of all of the components of an animal's innate behavioral repertoire. Reiter & Macphail (1979), in a recent review on motor activity, discuss the problems inherent in defining and quantifying general motor activity. They point out "because of the heterogeneous nature of general activity it is doubtful that a single measure could ever be developed". Consequently, particular components of general motor behavior must be selected for measurement. While it is important to determine which components of motor activity will be measured, finding techniques and instruments that are selective and sensitive to individual motor components can be a difficult task. It is essential then to first define discrete components of innate behavior and second determine how they are to be measured before an understanding of how microwave radiation or other external agents can influence this form of behavior.

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Two approaches have been followed in recent years to measure spontaneous innate behaviors. The classical approach has been *direct observation* to quantify individual and well defined components of general activity. The most extensively used observational technique has been the open field test. This procedure simply uses a large arena in which the rat is placed and a variety of motor components are recorded by one or more observers. The most frequently observed behaviors are ambulation over grid squares painted on the floor of the arena and the number of times the rat rears upward on its hindlimbs. Other observational techniques are more refined and measure different positions of both the rat's body and limbs while it is confined in a small Plexiglas box. The behaviors are scored in short epochs of time (1 sec.) during a fixed total time interval. This method has recently been used by Norton (1973) employing time-lapse photography to study the effects of amphetamine on 15 components of motor activity in rats. Her results demonstrated that amphetamine produced differential effects on various components of innate activity. For example, the frequency of occurence of behaviors such as walking, turning and rearing increased following amphetamine injections while other behaviors such as grooming, eating, scratching and sitting decreased. Some behaviors, such as looking, pawing and head turning did not show alteration after amphetamine. A simple composite measure of the total behavior emitted, if such were possible, would miss the differential effects of a drug on individual motor acts. The observational approach to measuring innate behaviors, however, has a major drawback. A tremendous amount of time is required to score the behavior of moving animals. The use of video tape and time-lapse photography has improved the objectivity of scoring but not the amount of time necessary to quantify the behavior. This approach is very labor intensive and can only be used with a few animals and a limited number of experimental treatments.

The second approach to quantify spontaneous innate behaviors has utilized a variety of *automated techniques* to measure and record components of motor activity. These include devices which either (1) directly measure animal activity: photocell cages, ultrasonic detectors, capacitance circuits, and touch detectors or (2) indirectly measure animal activity by measuring movement of the animal's cage: stabilimeter cages, tilt cages and exercise wheels. Generally, movement of the cage is detected by using mechanical transducers attached to the cage. The automation of locomotor activity measurement does provide a reliable and objective approach in quantifying behavior. However, each automated method is unique in the different components of behavior that are detected and measured. This outcome has led to the significant problem of poor correlation between the various devices used to measure locomotor activity. An increase in locomotor activity may be seen in one measurement device while a decrease may be observed in another automated device for the same experimental treatment (Tapp, 1968). Therefore, it is important to know which components of behavior any particular automated device is sensitive to in order to better understand the effects of experimental treatments. It has been strongly recommended that a protocol using direct observation followed by testing in several automated devices be employed to understand the effects of treatments (Reiter & Macphail, 1979). In the following paragraphs it will be apparent that this protocol has not been followed in studies of the effects of microwave radiation. Consequently, it is very difficult to directly compare the effects or lack of effects reported by different laboratories following microwave exposures.

## MICROWAVE RADIATION EFFECTS ON LOCOMOTOR ACTIVITY

A limited number of studies have been performed using some of the locomotor activity measurement techniques listed above. Several studies have examined the response of rats to chronic microwave exposure, while only one study has dealt with the effects of short term microwave exposure in the rat. The following paragraphs and Table 1 briefly summarize exposure parameters and any alteration of locomotor behavior consequent to microwave radiation exposure. This review is not comprehensive and additional studies from the Soviet Union measuring locomotor activity during or after exposure to microwave radiation exposure are summarized in the article by C.L. Mitchell (page 1).

Table 1

| | | | Exposure conditions | | | |
|---|---|---|---|---|---|---|
| Behavioral measurement method | Effects | Frequency | Intensity | Duration | SAR | Reference |
| 1. Lafayette Activity Platform | Activity decrease | 2450 CW | — | 550 | 2.3 | Mitchell et al. (1977) |
| 2. Stabilimeter<br>Exercise Wheel | Activity decrease<br>No effect | 2450 CW | 5.0 | 640 | 1.2 | D'Andrea et al. (1979) |
| 3. Open field | Activity decrease | 2450 CW | 2.5 | 686 | 0.7 | D'Andrea et al. (1984a) |
| 4. Open field | No effect | 2450 CW | 0.5 | 630 | 0.14 | D'Andrea et al. (1984b) |
| 5. Capacitor Plate - Activity Meter | No effect<br>No effect<br>No effect<br>No effect | 10,700 CW<br>3000 CW<br>3000 PW#<br>3000 PW# | 0.6-0.9<br>0.5-1.0<br>1.5-2.0<br>24-25 | 185<br>185<br>185<br>408 | 0.10*<br>0.25*<br>0.53*<br>7.50* | Roberti et al. (1975) |
| 6. Observation | Activity decrease | 918 CW | 10.0 | 210 | 3.6 | Moe et al. (1975) |
| 7. Stabilimeter<br>Exercise Wheel | No effect<br>No effect | 915 CW | 5.0 | 640 | 2.5 | D'Andrea et al. (1980) |
| 8. Observation | No effect | 918 CW | 2.5 | 210 | 1.0 | Lovely et al. (1977) |
| 9. Columbus Activity Platform | Activity decrease | 2450 PW% | 0.5 | — | 6.0 | Hunt et al. (1975) |

*Author's estimate
%Pulse duration 2.5 msec 120 pps
#Pulse duration 1.3 microsec 769 pps

## CHRONIC MICROWAVE EXPOSURE EFFECTS

Mitchell et al. (1977) exposed rats to 2450 MHz CW microwaves (SAR = 2.3 W/kg) in a multimode cavity for 5 hours each of a 22 week period. Rats were tested once each week (60 min. sessions) after the microwave exposure on a Lafayette Activity Platform which was adjusted to sample only gross body movements. Microwave exposed rats showed an increased locomotor activity beginning with the second week of irradiation and lasting throughout the remaining exposure period.

In a study reported by D'Andrea et al. (1979) 15 rats were exposed to microwave radiation at 2450 MHz in a CW field power density of 5 mW/cm$^2$ (SAR = 1.2 W/kg; total exposure 640 h). The exposures were given 5 days per week in an exposure chamber equipped with a monopole antenna mounted on a ground plane. The rats were tested at 2 week intervals (60 min. sessions) immediately after microwave or sham exposure on stabilimeter platforms and were then housed in exercise wheels until return to the microwave or sham exposure chambers the following day. The stabilimeter device used in this study was sensitive only to lateral movements of a rat and its restraint cage. A decrease in stabilimeter activity for the exposed group was found for each test during the initial 8 weeks of microwave exposure as compared to values for the sham exposed group. Significant differences in exercise wheel performance were not observed.

D'Andrea et al. (1984a) exposed 14 rats to CW 2450 MHz microwave radiation for a 98 day period. The rats were exposed 7 h a day, 7 days per week to a field power density of 2.5 mW/cm$^2$ (SAR = 0.70 W/kg; total exposure 686 h) in the monopole above ground chamber. Upon completion of the 98 day exposure period the rats were tested under several behavioral paradigms including an open field test. The rats were tested daily in the open field on three consecutive days (60 s test each day). The evaluation was based on the number of times the rat reared up on its hind legs and the number of grid markings over which the rat passed both forelegs. This test was given twice; once at the end of the microwave exposure period and again 30 days later. The number of rearings and number of grid squares crossed were scored by direct observation. A significant increase in the frequency of grid crossings was observed for the 14 microwave exposed rats as compared to the 14 sham exposed rats on the second open field test.

In the recent experiment by D'Andrea et al. (1984b) 10 rats were exposed to CW 2450 MHz microwave radiation for a 90 day period and compared to 10 sham exposed rats. The exposures were given 7 h each day 7 days per week in the monopole above ground exposure chamber at a field power density of 0.5 mW/cm$^2$ (SAR = 0.14 W/kg; total exposure 630 h). The open field test was given after the 90 day exposure period and again following a 30 day delay. No differences between microwave and sham exposed rats were observed with the open field test in this study.

Roberti et al. (1975) did not see alterations in spontaneous locomotor behavior consequent to 185 hours of 0.6-0.9 mW/cm$^2$ CW microwave exposure for several exposure parameters; 10.7 GHz (estimated SAR = 0.10 W/kg), 3 GHz 1.5-2.0 mW/cm$^2$ estimated SAR = 0.53 W/kg). An additional experiment was conducted with an exposure time of 408 h using PW microwaves, 3 GHz, at 24-25 mW/cm$^2$ (estimated SAR = 7.5 W/kg). A capacitance plate device was used to measure motor behavior. This automated device produces a uniform electric field between two parallel metal plates. Movement of the rat placed between the plates causes a disturbance of the field which is proportional to its movement. These authors reported that the device was simultaneously sensitive to several individual components of the rats behavior: respiration, sniffing, walking, and rearing. Behavior of the microwave exposed rats did not differ from sham exposed rats.

In experiments performed by Moe et al. (1975) rats were exposed for 15 h daily to CW 918 MHz radiation at 10 mW/cm$^2$ (SAR = 3.61 to 4.16 W/kg; total exposure 210 h) in cylindrical waveguides. Direct observation was used to evaluate alterations in behaviors such as eating, drinking, grooming, activity and rest. The observations were made at three times (10:30 pm, 3:00 am, 7:30 am) with five 1 sec. samples taken at each observation period. This study revealed significant differences between eight microwave exposed and eight sham exposed rats for food intake, and level of activity. The exposed rats were less active than the control rats and spent more time in a stretched out prone position whereas controls spent more time in a curled body posture.

D'Andrea et al. (1980) exposed rats for 8 h daily to 915 MHz CW microwaves at a field power density of 5 mW/cm$^2$ (SAR = 2.5 W/kg; total exposure 640 h). The exposures were given 5 days per week in the monopole above ground plane chamber. Rats were tested at 4 week intervals (60 min. sessions) on a stabilimeter platform. This automated device measures locomotor activity by detecting lateral movements of the rat within its cage. During the period between microwave exposures the rats were housed in exercise wheels. Statistically reliable alterations of stabilimeter activity and average wheel revolutions were not observed. No differences were observed in food intake between microwave and sham exposed rats.

Lovely et al. (1977) exposed rats to microwaves and measured behavior using the same procedure reported by Moe et al. (1975). In this study eight rats were exposed to 918 MHz microwaves in cylindrical waveguides for 13 weeks at 2.5 mW/cm$^2$ (SAR = 1 W/kg). The differences in motor activity and food consumption reported earlier by Moe et al. (1975) were not observed in this study at a lower SAR.

## ACUTE MICROWAVE EXPOSURE EFFECTS

Hunt et al. (1975) found a decrease in exploratory behavior on a Columbus Activity Platform. This measurement device has a surface which is sensitive to rat movements while it is confined within a plastic cage. Microwave exposures took place in a multimode cavity at 2450 MHz PW with a pulse duration of 2.5 microseconds at 120 pps. The resulting SAR was 6.3 W/kg with core body temperature of the rats increasing to an average of 40.3 °C at termination of the exposure. Decreases in locomotor activity were evident both during the hyperthermia and also 1 h after the exposure.

## CONCLUSIONS

This chapter has briefly reviewed several studies that have investigated the effects of microwave radiation exposure on locomotor behavior in the rat. Eight experiments conducted chronic exposures of the rat to microwaves. Four of the chronic exposure experiments were conducted at 2450 MHz with alterations of behavior observed in three (see Table 1). The study by Mitchell et al. (1977) observed an increase in rat locomotor activity following microwave exposure at an SAR of 2.3 W/kg. However, the study by

D'Andrea et al. (1979) observed a decrease in locomotor activity following microwave exposure at an SAR of 1.2 W/kg. In contrast, the study at an SAR of 0.7 W/kg found an activity increase 30 days following microwave exposure (D'Andrea et al. 1984a), while the study at an SAR of 0.14 W/kg found no effect of microwave exposures (D'Andrea, et al. 1984b). Based on such results, a tentative conclusion that the threshold for chronic microwave radiation induced alteration of locomotor behavior for 2450 MHz can be found between SAR's of 0.7 and 0.14 W/kg. Specific conclusions as to the effect of microwave exposure on rat behavior, however, cannot be drawn at this time. There are several reasons for this. For the 2450 MHz chronic exposure studies locomotor activity increases were found in two studies while a decrease was found in the third study. An observational technique and two different automated techniques of measuring locomotor behavior were used. Since the correlation between the various methods of measuring locomotor activity has historically been very low (Reiter & Macphail, 1979) cause and effect statements regarding radiation exposure conditions (frequency, SAR, exposure system) and the directionality of the behavioral effect increase - decrease cannot be made. At the present time only simple statements, that an alteration of behavior occurred, for each exposure parameter can be made. Studies using a standardized protocol of both observational and several automated techniques are needed before a full understanding of how microwave radiation interacts with rat locomotor behavior.

For the microwave radiation exposures of 915-918 MHz no conclusions can be drawn with regard to threshold of effect. Only the study by Moe et al. (1975) observed a change in rat behavior during chronic microwave exposure while the other studies utilizing different behavioral measurement methods did not observe an effect (D'Andrea, et al. 1980; Lovely et al. 1977).

Finally, the single acute exposure study by Hunt et al. (1975) observed an activity decrease under exposure conditions producing a moderate hyperthermia for the rat (approximate temperature increase of 2.5 °C). Further research is needed using different levels of SAR and several locomotor measurement methods to determine thresholds of effect and to support specific statements on the effects of acute microwave exposure on rat locomotor activity.

In conclusion, several statements regarding further research of microwave radiation effects on rat locomotor activity can be made. First, the use of a testing protocol employing several behavioral measurement methods, both observational and automated, would increase our understanding of how microwaves alter behavior. Second, a standardization of both the testing protocol and other important parameters is needed. For example, a variety of internal and external factors are known to influence the measurement of locomotor activity. Extensive reviews have dealt with this subject and have shown that both (1) internal factors such as: species and strain of subject, age, sex, hormonal states, endogenous rhythms, nutritional state, and (2) external factors such as illumination, noise, temperature, humidity, measurement device and previous experience with the measurement device can influence locomotor activity measurement (Reiter & Macphail, 1979; Tapp, 1969; Strong, 1957). Any effort made to standardize testing protocols and control these influences would improve further experiments.

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# MICROWAVE IRRADIATION and THERMOREGULATORY BEHAVIOR

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## INTRODUCTION

Most species, from single-celled organisms to man, adjust their behavioral strategies to provide a hospitable thermal microclimate for themselves. The function of thermoregulatory behavior is to optimize the transfer of heat between the body and the environment so that there will be a minimal involvement of innate mechanisms of heat production and heat loss. While economizing on body energy stores and body water, the major objective of thermoregulatory behavior is thereby achieved, that of maintaining the deep body temperature at a characteristic optimal level.

Behavior is one of two general classes of effector response that is available to endothermic (warm-blooded) species for the regulation of the body temperature. This paper will deal only with thermoregulatory behavior and not with the innate (reflexive) mechanisms of heat production and heat loss. The stimulus to a behavioral response is normally a temperature change that occurs at the surface of the organism. The thermoreceptors are located within the first millimeter of the skin surface and in order for a thermal stimulus to trigger these receptors effectively, the energy must be deposited in their vicinity. Therein lies a real problem for animals exposed to microwave fields, particularly to near-resonant frequencies, since the thermalizing energy may be selectively deposited in deep tissues, effectively bypassing the thermoreceptors. The resulting temperature profile may well be a kind of reversed thermal gradient in which the deep tissues can be warmed more than the surface. The problem then involves the conduction of the heat outward to the surface to stimulate the appropriate receptors.

One of the major functions of thermoregulatory behavior is the *anticipation* of hyperthermia; i.e., the organism adjusts its behavior to avoid becoming hyperthermic. It moves to a cooler environment, it removes layers of clothing, it goes for a cool swim, etc., when confronted with heat stimuli even though the internal temperature has not changed. The organism also can respond to changes in the temperature of the body core, as is the case during exercise. Such responses result from the direct stimulation of thermoreceptors distributed widely within the CNS (e.g., hypothalamus, medulla, spinal cord, etc.) or in the internal organs such as the gut. Thus when an animal is exposed to a deeply-penetrating microwave field, deep body thermoreceptors may be stimulated to mobilize effector responses. The animal may not "appreciate" this stimulation in the same way that he "appreciates" heating and cooling of the skin. Although exploring this question in depth is beyond the scope of the present paper, it is sufficient to note in the present context that such phenomena as altered thermal gradients in the tissues surrounding cutaneous thermoreceptors, and lack of "appreciation" of temperature changes deep in the body, may have great import for effective thermoregulatory behavior in the presence of microwave fields.

## IMPORTANCE OF STUDYING THERMOREGULATORY ENDPOINTS

Recently, comments have been made implying that research into the thermoregulatory consequences of microwave exposure may be fruitless, leading into a cul de sac (Medici, 1982). After all, the argument runs, microwaves heat body tissues, and animals will respond in predictable ways to body heating; so what more can be learned by assessing thermoregulatory responses in the presence of microwave fields? My response to such comments is manifold. In the first place, the response of an animal to a microwave field is not at all obvious for the very reason (noted above) that some of the primary sensory receptors may be inadequately stimulated or virtually bypassed. Second, it was only 2 or 3 years ago that the very great sensitivity of the thermoregulatory system was demonstrated in experimental animals exposed to microwave fields. Before that time, irradiation at equivalent plane-wave power densities above 100 mW/cm$^2$ were considered unequivocally to produce "thermal" effects; irradiation within the range from 10 to 100 mW/cm$^2$ might or might not produce "thermal" effects; while effects observed at power densities below 10 mW/cm$^2$ were assumed to be "nonthermal" in nature. Recent experiments have shown this scheme to be an incorrect oversimplification. A case in point is a recent report by Smialowicz et al. (1980) who demonstrated that fields as weak as 1 mW/cm$^2$ can be thermogenic. Current research in thermoregulation is beginning to allow us to quantify the effects of microwave exposure in terms of the individual responses of the experimental animal. These include not only thermoregulatory behaviors, but metabolic responses, sudomotor and vasomotor responses, respiratory evaporative heat loss, etc. It is now abundantly clear that when the internal body temperature of an experimental animal rises, this indicates that the thermoregulatory system has been compromised and that the heat generated in the tissues by the imposed radiofrequency field (plus the heat generated by metabolism) exceeds the heat-loss capabilities of the animal. Not long ago, such a temperature rise was regarded simply as evidence for a "thermal" effect.

## BEHAVIORAL PATTERNS AND THERMAL VARIABLES THAT AFFECT THEM

In the last few years, we have learned a great deal about behavioral thermoregulation in the presence of radiofrequency fields. Several variables that influence such behavior and that are commonly manipulated in thermoregulation research, have already been investigated, others have not. *Intensity* of the microwave stimulus has been studied most extensively, primarily to permit the determination of thresholds for a change in thermoregulatory behavior. The upper limit of tolerable intensity, often designated the ceiling intensity, has not yet been determined, at least in terms of thermoregulatory responses. *Duration* of the microwave stimulus has been studied extensively in my laboratory, and some pertinent results are outlined below. *Frequency* of the radiation is a variable that has been neglected in studies of behavioral thermoregulation--almost every study reported to date has been conducted at 2450 MHz. There is a clear need for studies of thermoregulation at other frequencies, particularly those close to resonance for the animal under study. To date, no systematic research has involved exposure of animals in the near field or to pulsed or sinusiodally modulated fields. Finally, until recently, only unrestricted exposures of experimental animals have been conducted. Some pilot studies from my laboratory that were designed to probe the effects of partial-body exposure on theremoregulatory behavior are summarized in a later section.

What do we know about changes in thermoregulatory behavior when an animal is exposed to a microwave field? Our knowledge depends upon the particular questions we ask or, more explicitly, upon the specific stimulus contingency under consideration. In my view, there are two fundamental contingencies of exposure to microwaves, designated as 1 and 2 in Table 1. In Case 1, the organism is engaged in some behavior, either an instinctive behavior (A) such as movement along a thermal gradient, or a learned operant response (B) by which it controls conventional radiant or convective climate-conditioning sources. Into the midst of this ongoing behavior, microwave irradiation intrudes. Assuming that the microwave field is of sufficient intensity and duration to disturb the thermal balance of the organism, what does the organism do? What we seek are the rules that govern observed changes in the organism's behavior.

Table 1. Contingencies of exposure to microwave irradiation and fundamental behavior patterns

1. Microwave field intrudes upon ongoing behavior, disturbing thermal balance:
   - A. Instinctive escape and avoidance behaviors. (Thermoregulatory?)
   - B. Learned operant control of environmental temperature.
2. Microwave field utilized directly as heat source to achieve thermal balance:
   - A. Instinctive approach behavior in thermal gradient incorporating microwave source.
   - B. Learned operant control of microwave source.

In Case 2, the microwave source is made available to the organism for its direct manipulation. In other words, the source of heating may be utilized by the organism to achieve thermal balance. Either the source is part of the complex thermal environment so that the organism orients about it (A), or the organism learns to control the source directly (B), i.e., to turn it on and off. What are the rules governing the organism's behavior in this case? It is important to remember that in both cases the animal is used as a null instrument; that is, an absence of a change in internal body temperature when the microwave field is present means that adjustments in the organism's behavior (or other responses) have maintained thermal balance.

As illustrated in Table 1, there can be both instinctive and learned behaviors. Indeed, the instinctive behaviors may be considered to be extremes on an approach-avoidance continuum. For example, if the environment is cold and the microwave source strategically located, the organism may bask in the radiation. This case is similar to that proposed by Pound (1980). Alternatively, escape from or avoidance of an intense microwave field, especially when the environment is thermally neutral or warm, are also instinctive behaviors. It is difficult to classify the latter as thermoregulatory behavior in the traditional sense because thermoregulatory parameters (e.g., panting, sweating, body temperatures) have not as a rule been measured during such experiments until very recently (see below). However, it seems safe to assume that the basis of such escape behavior is a desire to maintain thermal homeostasis.

# THERMOREGULATORY BEHAVIOR WHEN MICROWAVES DISTURB THERMAL BALANCE

## EFFECTS OF FIELD INTENSITY

A series of experiments from Justesen's laboratory (Carroll et al., 1980; Levinson et al., 1982) have investigated many of the variables controlling the escape behavior of murine species exposed to high intensity microwave fields in a cavity. Experimentally naive mice and rats have great difficulty learning to escape such fields by moving to a circumscribed region of the cavity. Even when cued by tones and lights, escape behavior is markedly inferior to that provoked by electric shock to the feet. Presumably, termination of the field itself does not provide an abrupt enough reduction in the activity of thermodetectors in the body to serve as a sensory reinforcement to support learning of the escape response. It is reasonable to assume that the animals would be motivated to respond by an increase in body temperature or even in anticipation of such an increase were the imposed microwave field properly discriminated. An experiment by Monahan & Henton (1977) was somewhat more successful, demonstating that mice in a waveguide can learn to escape from an intense field (46 mW/g) when guided by the presence or absence of an intense 2900 Hz tone. Still, the import of this behavior for thermoregulation was not demonstrated in this study.

Recently Justesen reported that when the escape response has been properly learned, an animal's rate of responding is governed by field intensity and some regulation of the body temperature is achieved thereby (Justesen, 1983). Data of Riffle (cited by Justesen, 1983) show that four rats with a history of cavity exposure to an intense 2450 MHz field learned to escape the radiation by moving to a "safe" region marked on the cavity floor. Extinction of the microwaves (the reinforcement) was cued by a 2900 Hz tone for two of the animals, uncued for the other two. Dose rates of 30, 60, and 120 mW/g were studied. Each experimental set comprised four daily 10-minute sessions at a given dose rate, preceded by one baseline session and followed by one extinction session in which no radiation was present. Four such experimental sets were conducted in the following order: 60, 30, 120, and 60 mW/g. The first set of data was regarded by the experimenters as a "tutorial" for the ensuing sets, and these data are not further discussed below.

The results from the final three experimental sets demonstrated, both in terms of the percentage of time the animal spent in the safe (non-irradiated) area and the post-session rectal temperature, that the rats behaved in a purposeful manner relative to the thermalization produced by the field. As the dose rate increased, so did the time the rats spent in the safe area. Post-session means of colonic temperature were found to be remarkably stable at ~2 °C above the normal level but not significantly different from the baseline level (measured on days when microwaves were absent), even at a dose rate of 120 mW/g. These results indicate (1) that instinctive escape behaviors can be thermoregulatory and (2) that experience and/or training facilitates escaping or avoiding such high intensity fields.

Case 1B in Table 1 is the one about which we know the most; i.e., when animal controls conventional sources of thermal energy so as to provide an acceptable microclimate for itself, a microwave source intrudes. The animal's thermoregulatory behavior will change in predictable ways that are directly related to the intensity and duration of the microwave exposure.

Stern et al. (1979) were among the first to investigate these fundamental problems. They trained shaved rats in a 5 °C environment to press a lever for 2-second bursts of heat from an infrared lamp. Individual rats worked inside a Styrofoam chamber that was located under a horn antenna inside an anechoic chamber. After behavioral training, each animal was exposed for 15-minute periods to 2450 MHz CW microwaves at power densities of 5, 10, and 20 mW/cm². Individual microwave exposures were separated by 15-minute control periods in which no microwaves were present. Both ascending and descending power density series were explored.

Stern et al. found that when the microwave field was present, even at the lowest power density, the rats worked for less infrared heat than in control periods. Whenever the microwaves were turned on, a reliable reduction in bar pressing rate appeared quickly, reversed when the field was extinguished. Of more importance, the higher the power density, the less infrared heat was demanded by the rats—the suppression of bar pressing was a linear function of power density. In other words, as more thermalizing energy was supplied by microwaves, less infrared heat was required to produce a state of "thermal comfort" in a cold environment. Although Stern et al. did not routinely monitor the body temperatures of the rats during their experiments, a few spot checks of rectal temperature indicated that the animals were achieving thermal balance by appropriate adjustments in thermoregulatory behavior. Since Stern et al. explored irradiation at only three power densities, they could not determine a precise threshold for alteration of thermoregulatory behavior. However, irradiation at 5 mW/cm² interrupted ongoing lever-pressing behavior reliably; this intensity represents a mass-normalized rate of energy deposition (SAR) equivalent to 15 to 20 percent of the resting heat production of the adult rat.

In my laboratory, we have taken a somewhat different approach to the study of similar problems. We believe that the environmental temperature (microclimate) selected by the animal and the body temperatures achieved thereby are of vital importance to the understanding of thermoregulatory behavior, and have designed experiments to measure these variables. Our subjects are adult male squirrel monkeys, each highly trained to regulate the temperature of the environment behaviorally. Animals are chair-restrained in the far field of a horn antenna inside an anechoic chamber. The space occupied by the monkey is heated and cooled by forced convection; the animal controls the temperature of the circulating air by pulling a response cord to select between two preset air temperatures, one hot (50 to 55 °C) and the other cold (10 to 15 °C). Usually the animal is exposed to one of these air temperatures and works to obtain 15-s reinforcement of the other. Most animals respond at a rate that yields a time-averaged air temperature of 35 to 36 °C. During all experiments, rectal temperature and four representative skin temperatures (abdomen, tail, leg, and foot) are measured continuously. (Technical details of the exposure arrangement, dosimetry, and response measures are given in Adair & Adams, 1980.)

We first determined the power density of 2450 MHz CW microwaves that would reliably alter this thermoregulatory behavior. Monkeys were exposed to microwaves for 10-minute periods at discrete power densities that ranged from 1 to 10 mW/cm². Individual exposures were separated by 10-minute periods with microwaves absent. In other experiments, the same monkeys were exposed for 10-min. periods to infrared radiation at comparable power densities, or to no radiation (control).

The results of five microwave experiments on each of three monkeys showed that irradiation at power densities above 6 to 8 mW/cm² reliably stimulated the animals to select a cooler environment (Adair & Adams, 1980). Comparable intensities of infrared radiation were found to have no such effect, presumably because the intact pelage insulated the skin from significant amounts of radiation. These results indicate that the behavioral change in the presence of microwaves may have resulted primarily from activation of thermodetectors located deep in the body rather than in the skin. Thus, under these conditions, microwave irradiation at a power density of 6 to 8 $mW/cm^2$ may be considered a threshold intensity for the alteration of normal thermoregulatory behavior. The mass-normalized SAR at this intensity is ~1.1 W/kg, representing about 20 percent of the resting heat production of the squirrel monkey, and is similar to the ~1.0 W/kg found by Stern et al. (1979) to alter thermoregulatory behavior in the rat.

In our experiments, we have consistently found that when squirrel monkeys select cooler environments in the presence of a microwave field, this behavior allows them to regulate their body temperatures at the normal (thermoneutral level). During brief (10 minute) exposures at power densities up to 22 $mW/cm^2$, the reduction in air temperature selected is a linear function of power density above the threshold level. It seems reasonable to assume that these animals could deal with irradiation at power densities substantially in excess of those we have imposed so far, without significant increase in body temperature, provided sufficient environmental cooling was available to them. We predicted on the basis of our behavioral data and our dosimetry that irradiation at a power density of 37 $mW/cm^2$, which would result in SAR equivalent to the resting metabolic heat production of the squirrel monkey (~5 W/kg), would provoke a reduction in the selected environmental temperature of 5 °C. In a pilot experiment, one monkey behaved exactly as predicted and exhibited no increase in deep body temperature. To date, the upper limit, or ceiling, of behavioral thermoregulatory capability has not been determined experimentally for any species. Clearly, this ceiling will depend upon many variables, the most important of which will be the duration of the exposure to microwaves.

## EFFECTS OF EXPOSURE DURATION

All the findings described above pertain to 10- or 15-minute microwave exposures, but shed no light on behavioral adjustments during longer exposure durations. Will a behaviorally-selected cooler environment persist unchanged while a microwave field is present, or is the behavioral adjustment only transitory, exhibiting modification over time? Investigation of this question has enabled us to discover a new phenomenon, at least one that has not been reported in the literature, which may have great import for behavior.

Initially, we conducted experiments in which monkeys were exposed to microwaves at a suprathreshold power density (10 $mW/cm^2$) for varying durations, 5, 10, 15, 20, and 25 minute (Adair & Adams, 1983). These exposures were separated by periods of like duration in which no microwaves were present; i.e., 5 minutes on, 5 minutes off, 10 minutes on, 10 minutes off, etc. Results from two monkeys showed that during each microwave exposure, the air temperature was lowered by a characteristic amount and held there for the duration of the exposure. However, we did find a difference in thermoregulatory behavior exhibited during the initial microwave presentation (always 5 minutes in duration) and subsequent exposures (of longer duration) during the same test session. The results of these experiments are summarized for two animals in Figure 1. The figure shows the mean air temperature selected during the consecutive 10 $mW/cm^2$ microwave exposures (and resulting skin and rectal temperatures) as a function of exposure duration. The ambient temperature selected when the exposure duration was 10 to 25 minutes was in all cases significantly lower than that selected when no microwaves were present (control). The two upper functions in the figure demonstrate that the skin and deep body temperatures remain stable at the normal level as a result of efficient behavioral responding.

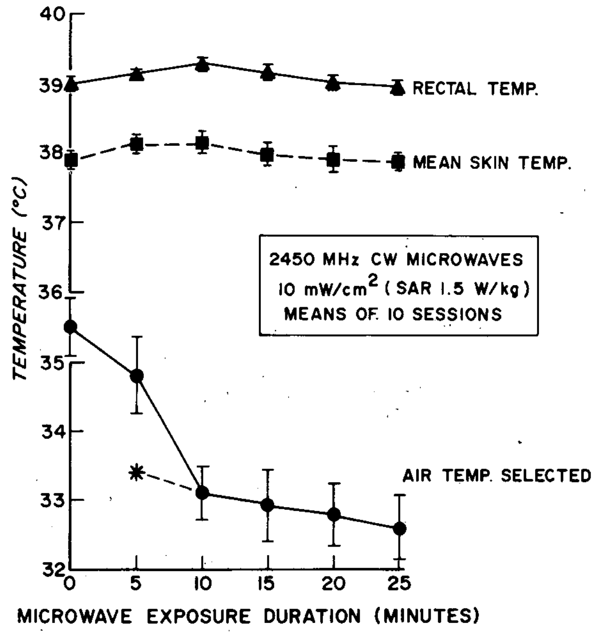


Figure 1. Mean air temperature (± 1SEM) selected by two monkeys exposed to 2450 MHz CW microwaves at 10 mW/cm² (SAR=1.5 W/kg) as a function of exposure duration. Weighted mean skin and rectal temperatures achieved (± 1SEM) are also shown. For meaning of *, see text.

The most striking aspect of Figure 1 is the minimal behavioral effect during the initial 5-minute exposure period; the mean air temperature selected does not differ significantly from the control condition. For purposes of comparison, the mean air temperature selected in the initial 5 minutes of the four subsequent (longer) microwave exposures was calculated across sessions and this value is indicated in the figure by an asterisk. This point (*) falls on the extrapolated linear function determined by the points for the 10 to 25 minute durations, implying that a 5-minute exposure to a 10 mW/cm² microwave field should stimulate a vigorous and appropriate change in thermoregulatory behavior.

To pursue this matter a bit further, we exposed the same two animals repeatedly to the same microwave stimulus, 10 mW/cm² for 10 minutes, consecutive exposures being separated by 10-minute periods of no microwaves. We were intrigued to see, as illustrated in Figure 2, that the first presentation of the series provoked no significant behavioral alteration of the ambient temperature whereas all subsequent presentations did. This minimal behavior change when the microwave field was first presented resulted in an elevated rectal temperature, elevated skin temperatures, and especially an elevated brainstem temperature, which we assessed in these experiments with a

Vitek probe (Bowman, 1976) inserted in a Teflon re-entrant tube permanently implanted in the preoptic area of the hypothalamus. This is a curious phenomenon; it has been dubbed by various researchers a "priming effect," an "overnight performance decrement," a "warm-up" effect, "arming" of the system, etc. In general, it appears that there must be some thermalization of the body tissues before the behavioral response can be effectively mobilized.

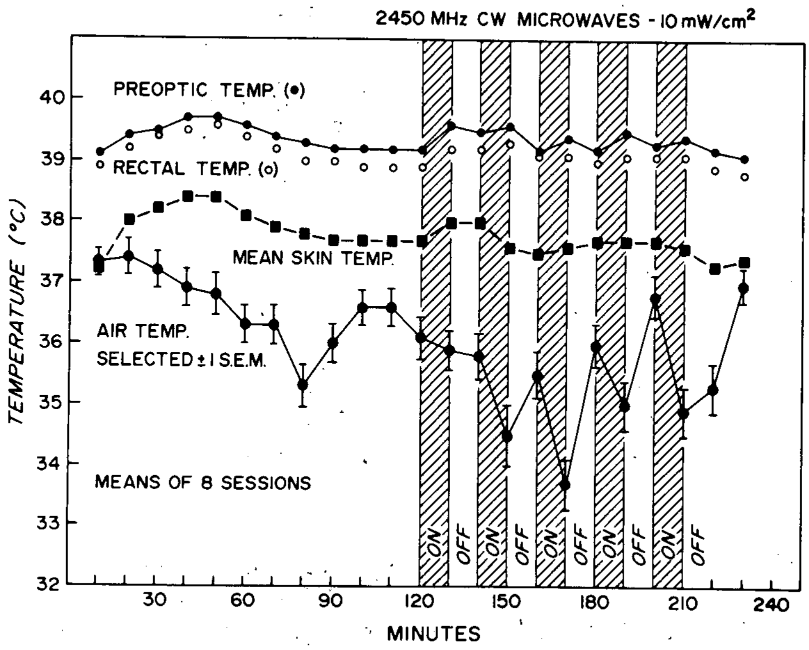


Figure 2. Mean air temperature (± 1SEM) selected by two monkeys, four sessions each, exposed repetitively at 10 mW/cm² for 10 minutes. Weighted mean skin temperature, rectal temperature, and preoptic/anterior hypothalamic temperature changes resulting from the behavior are also shown.

Another example of this phenomenon appears in data of Levinson et al. (1982). In an attempt to train rats to escape from near-lethal microwave fields inside a multimodal cavity, these investigators offered various concomitant sensory stimuli as cues to the presence or absence of the microwave field. Whereas animals learned after many days of training to escape from microwaves that were paired with a visual cue (cf. Fig. 3), there was a recurring deficit in the learned response at the beginning of every daily session, as though the animals had to be primed by a spell of irradiation before exhibiting the appropriate learned response. A clue to the underlying cause may reside in the elevated body temperatures we observed in the monkeys; widespread thermalization may be necessary to trigger thermosensitive cells in the thermoregulatory neural network that are normally stimulated quickly by peripherally-absorbed thermal stimuli such as infrared radiation.

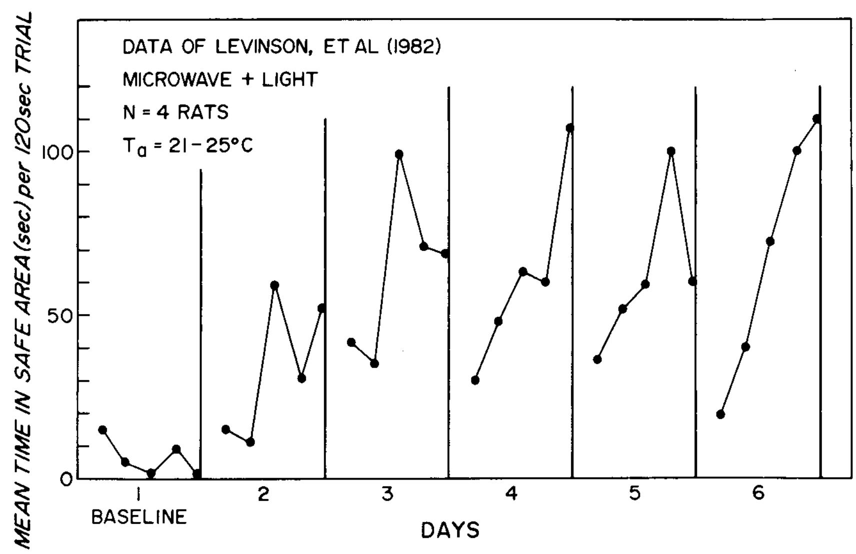


Figure 3. Mean time spent by four rats in the "safe" area of a cavity during five 2-minute periods within 22-minute sessions when microwaves (60 mW/g) + photic illuminance of 350 lx were present. (Data adapted from Levinson et al., 1982).

Durations of exposure to microwaves longer than 25 minutes produced little adaptation in the animal's thermoregulatory behavior. Adair & Adams (1983) exposed monkeys for 2-1/2 hours to 2450 MHz CW microwaves at power densities of 10 and 20 mW/cm$^2$. They found that within 10 to 20 minutes of microwave onset, the animals lowered the air temperature by an amount appropriate to the power density and that this level was maintained with only minor fluctuations until the microwaves were turned off. A replication of these results appears in Figure 4 which shows the air temperature selected by one monkey during experiments when no microwave field was present (large open circles) and when 2450 MHz CW microwaves were presented at a power density of 20 mW/cm$^2$ for 2-1/2 hours (large solid circles). During the period of microwave exposure, the animal selected an air temperature 2.5 to 3.0 °C lower than that normally preferred in the absence of microwaves, thereby regulating its skin and deep body (rectal) temperature efficiently at the normal level. An elevation in the preoptic/anterior hypothalamic temperature during the first 20 minutes after microwave onset is a provocative new finding, echoing that described above. A rapid rise in the temperature of this highly thermosensitive area may help to mobilize effective thermoregulatory behavior so that other body temperatures sustain only minor perturbation.

To summarize, we know a great deal about what an animal may do when a low intensity microwave field intrudes on ongoing thermoregulatory behavior. If the field strength equals or surpasses a threhold level, the animal will select an environmental temperature that is lower than that normally preferred. The reduction in preferred environmental temperature will be a linear function of the intensity of the microwave field above the threshold, at least for moderate levels. The ceiling for this relationship has not been determined for any species but it will clearly depend on the characteristics of the climate-conditioning available to the animal. Altered thermoregulatory behavior appears to persist relatively unchanged as long as a microwave field is present, although the first brief presentation of the day may not stimulate the dramatic behavioral alteration that is seen during subsequent presentations.

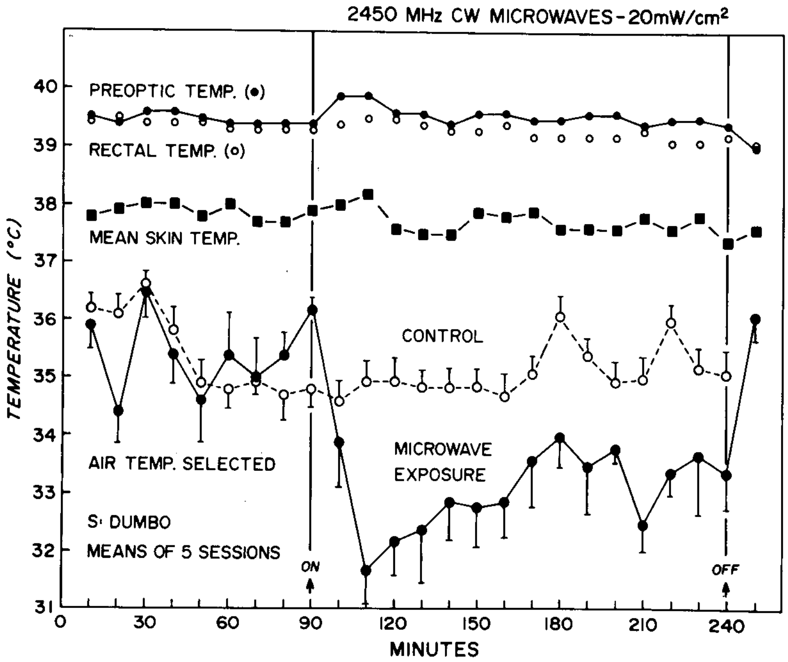


Figure 4. Mean air temperature (± 1SEM) selected by one monkey exposed to 2450 MHz CW microwaves for 2½ hours at a power density of 20 mW/cm². Weighted mean skin temperature, rectal temperature, and preoptic/anterior hypothalamic temperature changes resulting from this behavior are also shown.

## RESTRICTED EXPOSURE OF THE BODY

We have conducted some pilot experiments to explore the thermoregulatory consequences of exposing only a limited part of the body to a microwave field. Although we have made extensive measurements of the fields to which the monkeys were exposed and have performed a few dosimetric evaluations, the partial-body-exposure data reported below must be regarded as preliminary in nature.

During the experiments, the monkey was restrained inside a ventilated Styrofoam box and exerted behavioral control over the temperature of the circulating air in the usual manner. A three-panel plywood screen covered with 20-cm pyramidal microwave absorber was interposed between the horn antenna and the animal's box inside the anechoic chamber. A 30 x 30 cm aperture was cut in the center panel of the screen so that during the first series of experiments, only the monkey's head received substantial radiation, the rest of the body being screened fairly effectively, given the limits imposed by diffraction.

Extensive field measurements across a plane passing through the center of the monkey's location orthogonal to the direction of propagation of the incident microwaves showed steep power-density gradients in the vicinity of the monkey's head but fair uniformity over the rest of the body. In general, the power density measured at the location of the head was ~10 dB greater than that of the whole-body average.

The experimental protocol, identical to that reported by Adair & Adams (1980), featured a 2-hour baseline period of behavioral thermoregulation followed by six 10-minute microwave exposures of increasing power density. The power densities explored ranged from 15 to 60 mW/cm$^2$ (measured at the location of the head), which represented a whole-body-averaged range of power density of 1.5 to 6 mW/cm$^2$, as estimated from the field measurements.

The results of one experimental series appear in Figure 5, which shows the skin and rectal temperatures of one monkey and the air temperature selected during the baseline period and subsequent microwave exposures of the head. Power density in this series ranged from 15 to 40 mW/cm$^2$ (measured at the head). Although the animal often selected a slightly cooler environment ($T_a$) during the 10-minute periods when the microwaves were on (compared with the immediately-preceding period when the microwaves were off) at no power density was this $T_a$ reduction statistically significant. Other power density series, ranging to 60 mW/cm$^2$, on this and one other animal yielded the same inconclusive results. Furthermore, no reduction in rectal temperature, such as might be expected if hypothalamic temperature sensors were being heated, was ever recorded during microwave exposure of the head. Our single positive, but unquantified, finding was an observation of increased behavioral agitation which accompanied power densities of 45 mW/cm$^2$ and above. Clearly the monkeys did not like this stimulus configuration.

The three-panel screen used in the experiments described above was modified: this 30 x 30 cm aperture was closed with a plywood insert covered with 20-cm pyramidal microwave absorber; a new aperture, 30 cm wide and 45 cm high, was cut just below the location of the original one in the center panel of the screen. Now when the screen was interposed between the horn antenna and the monkey, the body from the neck down received substantial radiation, the head being screened fairly successfully. Once again, extensive field measurements at the animal's location revealed steep power-density gradients in the center of the aperture, and the field strength in the vicinity of the head was nominally 10 dB lower than that over the remainder of the body. Thus, a power density of 5 mW/cm$^2$ measured at the chest produced ~1.4 mW/cm$^2$ at the head and ~12 mW/cm$^2$ at the lower trunk. As a general rule, the power density averaged across the silhouette the whole animal presented to the radiation was 23 percent lower than that measured at the location of the chest.

Experiments were conducted to determine the effects on thermoregulatory behavior of screening the animal's head while exposing the rest of the body to the microwave field. The experimental protocol involved a 2-hour baseline period of behavioral thermoregulation followed by six 10-minute microwave exposures of increasing power density (2, 4, 6, 8, 10, and 12 mW/cm$^2$). Five such experimental sessions were conducted on each of three animals.

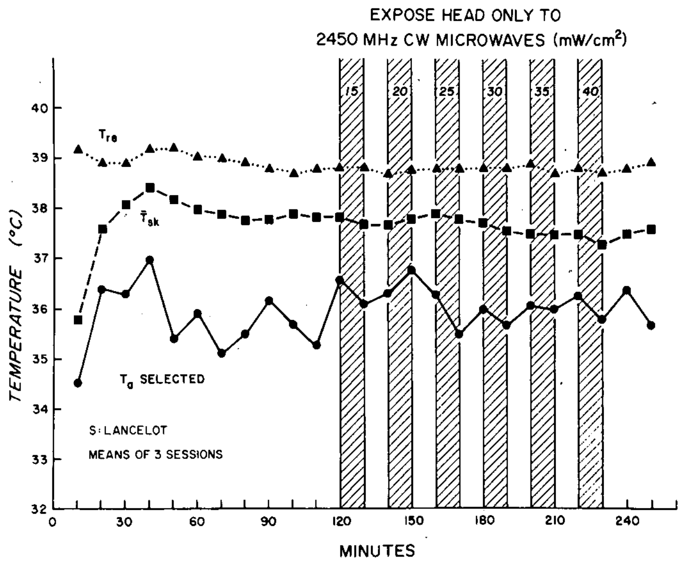


Figure 5. Mean air temperature ($T_a$) selected in three experiments by one monkey whose head was exposed for 10-minute periods to 2450 MHz CW microwaves at power densities ranging from 15 to 40 mW/cm² (measured at the head). Weighted mean skin ($T_{sk}$) and rectal ($T_{re}$) temperatures resulting from this behavior are also shown.

Mean results for one monkey appear in Figure 6, which shows the air temperature selected during the baseline period and subsequent exposures of the trunk and extremities to 2450 MHz CW microwaves, together with the skin and rectal temperatures achieved. In general, this animal prefers a somewhat cooler environment (~32 °C) than most of the monkeys in our colony, but is nevertheless adept at regulating body temperature behaviorally. A reliable reduction in preferred ambient temperature (threshold) occurred when the power density (measured at the chest) was 12 mW/cm², and a strong tendency toward such a reduction occurred at 8 and 10 mW/cm² as well. The threshold is 2 mW/cm² higher than that determined for this animal when the whole body was exposed to the microwave field, but when the power density is averaged over the total cross sectional area of the body in both cases, the experimentally-determined thresholds are the same. This result was generally true for all three test animals and indicates that during partial-body exposure the behavioral response will depend upon the integral of energy absorption by the whole body, not upon energy deposited in some particular body locus. A similar finding was reported by Adair & Adams (1982) for changes in the metabolic heat production of monkeys undergoing partial-body microwave exposure in cool environments.

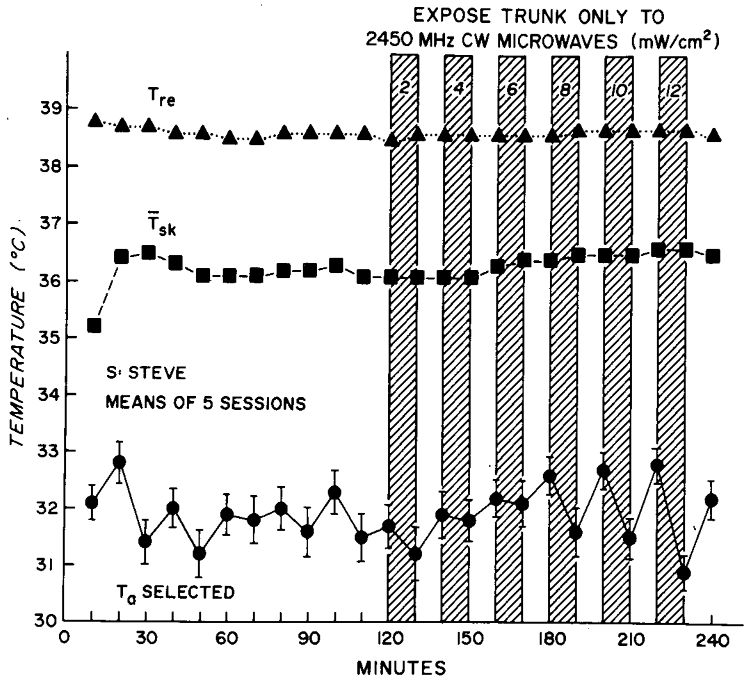


Figure 6. Mean air temperature ($T_a$) selected in five experiments by one monkey whose trunk and extremities were exposed for 10-minute periods to 2450 MHz CW microwaves at power densities ranging from 2 to 12 mW/cm² (measured at the chest). Weighted mean skin ($T_{sk}$) and rectal ($T_{re}$) temperatures resulting from this behavior are also shown.

## DIRECT UTILIZATION OF MICROWAVE FIELD TO ACHIEVE THERMAL BALANCE

Let us now turn to the second contingency of exposure outlined in Table 1, the direct utilization or manipulation of a source of microwaves in order to achieve thermal balance. During World War II, when radar systems were first in use, every Navy corpsman knew that standing in front of a radar antenna would keep him warm on a cold day (Susskind, 1979). So, too, the "insouciant sparrows of Constantinov" (Bem & Trzaska, 1976) which were observed to nest and raise their young at the feedpoint of a 2-megawatt transmitting antenna built by the Polish Broadcasting Company, must have discerned the warming effects of the field in which they prospered. Utilization of a microwave source to heat the human occupants of an enclosed space (rather than the walls and the air) has been proposed formally by R.V. Pound (1980) as an economical and efficient alternative to conventional methods of heating the home. Two formal experiments have probed thermoregulatory behavior under this general contingency of exposure and these have both involved animal subjects.

## THERMOREGLATION IN A MICROWAVE GRADIENT

The first study designed to quantify instinctive thermoregulatory behavior in proximity to a microwave source was conducted by John D'Andrea and his colleagues at the University of Utah (D'Andrea et al., 1978). They introduced six whiptail lizards (Cnemidophorus tigris) from the Lake Powell desert to the Department of Engineering.

The lizards took up residence in a glass terrarium where they were observed carefully for 1 week. Every day, from 7 a.m. to 9 p.m., an infrared heat lamp irradiated one corner of the terrarium. Five times a day, for 1/2-hour periods, the lizards' activity was monitored and the cloacal temperature of each animal was recorded. The following week, the lizards obtained new quarters in a Styrofoam and Plexiglas terrarium located inside an anechoic chamber in full view of an antenna radiating 2450 MHz CW microwaves. The terrarium was oriented in such a way that an effective "microwave gradient" was created within, i.e., the field strength in the corner nearest the antenna was ~90 mW/cm$^2$ and this decreased to ~2 mW/cm$^2$ in the opposite corner. Thus the lizards could regulate their capture of microwave energy by varying their position within the microwave gradient. Again the lizards' activity was monitored 5 times a day, in this case over closed-circuit TV system, and the cloacal temperature was measured at the end of each observation period as before.

The first (baseline) body temperature of these ectotherms recorded each day was close to that of the environment, i.e., 23 °C. After the source of radiation (either infrared or microwaves) was turned on, D'Andrea et al. found that the lizards quickly raised their internal temperatures to a level close to that measured in the natural habitat by appropriate orientation and movement vis-a-vis the radiation source. By remaining inactive (i.e., basking) in proximity to the maximum radiation, the lizards maintained a near-normal cloacal temperature throughout the day. D'Andrea et al. reported that in the microwave gradient, the lizards moved gradually toward the microwave source so that by late afternoon they were all piled up in the 90 mW/cm$^2$ corner of the terrarium. While this behavior provided rather complex dosimetric problems, it pointed out clearly that these animals were able to sense and utilize a microwave field nearly as efficiently as a source of infrared radiation to regulate their body temperatures behaviorally.

## DIRECT OPERANT CONTROL OF A MICROWAVE SOURCE

Bruce-Wolfe recently conducted an experiment that demonstrated that squirrel monkeys could be trained to exert direct control over a source of 2450 MHz CW microwaves (Bruce-Wolfe & Adair, 1981). Individual animals were chair-restrained inside a climate-conditioned Styrofoam box that was located in the far field of a horn antenna inside an anechoic chamber (for details of this exposure arrangement, see Adair & Adams, 1983). First, each monkey learned to select appropriate amounts of circulating hot (50 °C) and cold (10 °C) air to provide a comfortable thermal environment inside the box. Each time the animals responded, the incoming air temperature changed: if it had been cold, it became hot, or vice versa. The animal's rectal temperature and four representative skin temperatures, as well as the behaviorally-produced air temperatures changes, were monitored continuously during the 2-hour experimental sessions.

Following this behavioral training, the stimulus conditions were changed: 2450 MHz CW microwaves accompanied by thermoneutral (30 °C) air replaced the 50 °C air, but all other experimental conditions remained the same. In other words, the monkeys now chose between cold air and microwaves instead of between cold air and hot air. Three 2-hour experimental sessions were conducted with each animal at each of three microwave power densities, 20, 25, and 30 mW/cm$^2$ (SAR = 0.15 [W/kg]/[mW/cm$^2$]).

A summary of the major results of this study appears in Table 2. For the three microwave power densities, together with the 50 °C air available during training sessions, the table shows (for the final 30 minutes of all experimental sessions) the mean percentage of time the animals selected the cold air which was always available as the alternative to the source of thermalizing energy. The mean ambient temperature produced by this behavior and relevant measurements of the body temperature are also shown. The most striking finding is that the animals somehow discerned the endogenous consequences of the available sources of thermalizing energy and altered their thermoregulatory behavior appropriately. Normal thermoregulatory behavior in this apparatus results in a 30 percent selection of 10 °C air over 50 °C air, which yields an average ambient temperature of 36 to 37 °C. When microwaves at a power density of 20 mW/cm$^2$ replaced the hot air, this percentage was lowered to less than 10 percent. As a consequence of this behavioral change, mean ambient temperature fell to the level (30 °C) of the circulating air that accompanied the microwave field (a necessary control for air movement), but relatively minor reductions occurred in the temperature of the skin. Despite the fact that the microwave field was on more than 90 percent of the time at the two lower power densities (20 and 25 mW/cm$^2$) and nearly 80 percent of the time when the power density was 30 mW/cm$^2$, no significant alteration occurred in any measured body temperature. Indeed, these behavioral changes demonstrated a remarkable sensitivity to the strength of the incident field on the part of the animal. On the basis of the data in Table 1, one may conclude that behavioral manipulation of a source of microwave radiation will not only be purposive and appropriate, but also efficient, since this behavior always produced precise regulation of the internal body temperature at the physiologically neutral level. Whether such precise thermoregulatory behavior would be exhibited by a naive (untrained) animal, or whether it would be exhibited in a cold surround of invariant temperature, are questions that are not addressed by this study. These are only two among many questions yet to be answered with regard to changes in thermoregulatory behavior when a source of microwaves is available for manipulation.

Table 2. Behavioral thermoregulation by direct control of microwave source

The percentage of time cold (10 °C) air was selected over a heat source and the resulting ambient and body temperatures achieved when the source of thermalizing energy was either 50 °C air or microwaves (at 20, 25 or 30 mW/cm$^2$) paired with thermoneutral (30 °C) air. All values are means (± 1SEM) for the final 30 minutes of three experimental sessions conducted on each of three squirrel monkeys (unpublished data of Bruce-Wolfe and Adair).

| | Available source of thermalizing energy | | | |
|---|---|---|---|---|
| Response Measure | 50 °C Air | 20 mW/cm$^2$ + 30 °C Air | 25 mW/cm$^2$ + 30 °C Air | 30 mW/cm$^2$ + 30°C Air |
| % Time in 10 °C air | 27.0 ± 1.5 | 8.5 ± 2.0 | 9.5 ± 2.0 | 18.5 ± 1.5 |
| Ambient temp. (°C) | 36.55 ± 0.25 | 30.25 ± 0.25 | 30.25 ± 0.2 | 29.1 ± 0.35 |
| Foot skin temp. (°C) | 37.8 ± 0.2 | 36.2 ± 0.2 | 36.3 ± 0.25 | 36.1 ± 0.25 |
| Tail skin temp. (°C) | 38.0 ± 0.2 | 37.0 ± 0.2 | 36.8 ± 0.25 | 35.25 ± 0.25 |
| Mean skin temp. (°C) | 38.5 ± 0.15 | 37.5 ± 0.1 | 37.3 ± 0.15 | 37.1 ± 0.1 |
| Rectal temp. (°C) | 39.4 ± 0.1 | 39.3 ± 0.08 | 39.4 ± 0.12 | 39.2 ± 0.1 |

## CONCLUSIONS

Only a few studies have examined changes in thermoregulatory behavior in the presence of microwave fields and most of these are preliminary in nature. So far, we have learned that in most situations, especially when the experimental animal is trained to manipulate environmental thermal stimuli, microwave exposure at moderate intensities will be countered by appropriate adjustments in thermoregulatory behavior. Thus no significant change occurs in the regulated internal body temperature. Generally speaking, the animal will select a cooler environment or less infrared or convective heating in direct proportion to the imposed strength of the microwave field. In addition, while we know that irradiation at a minimal power density (threshold) must be exceeded before overt changes in thermoregulatory behavior can be measured, we as yet have no measure of the maximal power density that can be dealt with efficiently. It seems clear that the occurrence and effectiveness of behavioral responding in the presence of intense microwave fields will be governed in large measure by the prevailing ambient temperature; however, many parameters of the microwave stimulus itself as well as the experience of the subject will be important.

Many variables have so far been ignored in studies of thermoregulatory behavior. All such studies reported to date have utilized 2450 MHz microwaves in far-field, waveguide, and cavity exposure. We need data based on many other frequencies. As a case in point, recent evidence (Lotz, 1982; Krupp, 1983) indicates that exposure to frequencies near whole-body resonance might pose special problems for a behaving animal because of greatly enhanced rates of energy absorption at low power densities that may overwhelm the thermoregulatory system. In addition, we need data on the impact of pulsed fields and of modulated fields. While a few pilot experiments have explored the impact of exposing only part of the body to a microwave field, these experiments are crude and require refinement and appropriate dosimetry.

So far, all of the data in hand have been derived from rats, mice, lizards, and squirrel monkeys. We need data collected from a much wider representation of species, including man. We cannot forever hope to extrapolate from Rattus norvegicus to Homo sapiens with benefit of the "Radiofrequency Radiation Dosimetry Handbook" (Durney et al., 1978) and a few computer models such as those of Stolwijk & Hardy (1977) and Gandhi (1982). We must devise ways to expose human subjects to controlled microwave fields that are carefully held within the current exposure guidelines. We need to assess thermal sensations and derive judgments of thermal comfort using standard psychophysical techniques and an assortment of thermoregulatory parameters, both physiological and behavioral.

Finally, there are many critical questions involving a compromised thermoregulatory system that have yet to be examined. For example, how will thermoregulatory behavior in the presence of a microwave field be changed during alteration of the thermoregulatory set point such as may occur during febrile states, under the action of certain drugs, or even during normal circadian variation? What might be the impact of defective neurophysiological control of the thermoregulatory effector system such as would be produced by lesions in certain CNS sites that are thermosensitive (e.g. anterior hypothalamic/preoptic area, medulla) or others that are involved with motivation (e.g. lateral hypothalamus). Such sites are surely warmed to some extent during microwave exposure (Kritikos & Schwan, 1979; Burr & Krupp, 1980) and must be involved in the mobilization of efficient thermoregulatory behavior. Definitive answers to these questions will begin to provide some insight into the mechanisms that underlie detection of microwave radiation and transform that detection into effective behavioral action, whether the microwave field upsets an animal's thermal balance or is used directly by the animal to achieve thermal balance.

## ACKNOWLEDGMENTS

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# EFFECTS of RADIOFREQUENCY RADIATION DURING DEVELOPMENT: The PRENATAL PERIOD as a MODEL SYSTEM

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## INTRODUCTION

Environmental conditions or agents capable of producing biological alterations that may damage future generations pose a serious threat to the human population. Such alterations that result from interference with embryonic or fetal development constitute the subject matter of the field of teratology. The prime question for teratology is whether an agent, at any dose, can produce birth defects. Thus, teratology is concerned with the establishment of dose-response relations. If and when a teratogenic dose is determined, the next step is to attempt to ensure that developing organisms are prevented from encountering such levels of that agent. The actual preventive planning involves the medical and scientific community as well as industry and various agencies of local and federal government. However the determination of these dose-response relations is time-consuming and sometimes is based on questionable assumptions about the nature of the interaction between environmental conditions and the developing organism.

Traditionally, the type of effect considered to be teratogenic consisted of anatomical or structural alterations such as deformed or missing appendages. Only recently has the field of teratology expanded to include the question of whether there are agents that produce functional (i.e., behavioral) alterations. The investigation of functional deficits produced prenatally and manifested postnatally now constitutes a large segment of the subject matter of the relatively new area of behavioral teratology. This paper will present a brief overview of the data regarding teratogenic effects of radiofrequency (RF) fields including the limited number of studies reported with respect to behavioral teratology and RF exposure. The fact that the developing organism can be used as a model system for study of biological and behavioral effects and mechanisms in general, will also be discussed.

## TERATOLOGY: A BRIEF INTRODUCTION

A typical teratogen is an environmental agent that produces specific malformations at specific stages of development. The developing organism can come into contact with such agents directly, via the maternal organism, or both. The stage of development during which this contact occurs is predictive of both the nature and the extent of the malformation. The teratogenic literature contains numerous examples of agents that produce effects only at a given stage of development.

The prenatal development of an organism can be divided into three successive stages which are, of course, not absolutely demarcated. The time between fertilization of the ovum and its attachment to the uterine wall is described as the preimplantation period. The stage following preimplantation during which the major organs are formed is termed organogenesis. The third phase is the fetal period and represents the final stage of prenatal growth. The day of gestation serves as a marker of the stage of develoment.

Any environmental agent encountered during pregnancy that interferes with development during any of the stages is a teratogen. The extent as well as the type of effect that is produced is dependent upon the gestational stage during which the agent is encountered, the type of agent, the duration of the interaction, the intensity of the dose, and the species used in the study. Since all agents do not produce malformations during a single or particular stage of develoment, no single stage can be labeled as the most susceptible period. Susceptibility will vary across agents both with respect to what type of effect might be produced and the stage of development during which it can be produced.

Most teratogens operate within critical periods that vary depending upon the agent and the species. Although peak sensitivity differs, the period of early development corresponding to implantation and early organogenesis is usually a highly sensitive time. During the later stages of development, that are largely occupied with growth, the organism is usually immune to all but the most severe insults. However, the central nervous system (CNS) matures relatively late in development and thus this immunity may not refer to damage to the CNS. Since behavior is an overall indicator of the functioning of the CNS, functional alterations could be expected from exposure during these later stages of development. In general, an insult introduced during the preimplantation phase results in high proportions of prenatal death and resorption. The occurence of defects in specific organs is most likely if the insult is encountered during organogenesis. Later stages have been considered resistant if not immune to damage but this may not be true with respect to the CNS and behavior.

## RADIOFREQUENCY RADIATION AS A TERATOGEN

There is no question regarding the fact that RF radiation is capable of heating tissues. And so, it is of considerable import that heat stress has been shown to be teratogenic in several species. Edwards & Wanner (1977) have compared several small mammals with regard to their teratogenic susceptibility to heat stress. They noted both the level at which effects started to appear and the type of effect. Of these small mammals, the rat is the least likely to develop specific, anatomical defects following prenatal heat stress. The response of the rat is likely to be in the form of resorptions. The heat stressed mouse exhibits decreased birthweight and also a rather high incidence of exencephaly. Of the small animals they compared, the guinea pig was considered to be the most susceptible and the most likely to exhibit structural and functional defects following prenatal heat stress. These differences are important since most of the studies investigating the teratogenic potential of RF radiation have used the rat or the mouse as the experimental subject.

The teratogenic effects reportedly induced by RF radiaton are markedly similar to those reportedly induced by other forms of heating. At high levels that clearly induce an increase in the core temperature of the maternal subject, RF can induce teratogenesis (O'Connor, 1980). Whether the teratogenesis is strictly due to the thermal nature of the stimulus or to some other aspect of the radiation is a question that cannot be answered at the present time. However, the evidence that is accumulating favors the idea that the dose required to produce teratogenesis approaches hyperthermic lethality for the maternal subject. To date no specific teratogenic effect has been reported in cases where exposure conditions did not involve relatively high levels of irradiation. The conclusions with regard to data for observation of more general effects such as reducted body mass or retarded growth is not as clear. The teratogenic level is apparently that which raises the core temperature of the maternal subject to 40 °C to

42 °C. This appears to be true for several species but has only been empirically delineated for the rat (Lary et al., 1982). A core temperature at and above 42 °C is frequently lethal for the maternal organism (O'Connor, 1980). This termal threshold is nearly identical to the teratogenic threshold reported for exposure to other forms of heat stress (Edwards & Wanner, 1977).

In some of the earliest teratogenic studies, Rugh used high power levels (over 100 $mW/cm^2$) at 2450 MHz for a maximum of 5 minutes. Mice of the CF-1 strain were exposed for 5 minutes or until a convulsion occurred. In several studies (Rugh et al., 1974, 1975) they reported increased incidence of exencephaly but did not establish a threshold level for the effect. The percentages of exencephalic fetuses in a litter were reported to increase as microwave dose increased.

Chernovetz[1], Justesen, King & Wagner (1975) were the first to propose that teratogenic effects hinged on a thermal threshold that was nearly lethal to the dam. In this study the C3H/HeJ mouse was exposed to 2450 MHz microwave exposure singly and in combination with a known teratogen (i.e., cortisone). The results of this 38 mW/g, 10 minute exposure prompted the authors to hypothesize that effects did not begin to appear in the developing organism until the maternal subject was heated to a point of near lethality (i.e., the maternal lethality hypothesis). Subsequent studies using the Holtzman rat (Chernovetz et al., 1977, 1979) supported this hypothesis and indicated higher core temperatures (approaching 43 °C) that produced maternal lethality were required before even general effects such as smaller mass were observed. In these studies the rats were exposed for 20 minutes and the pre- and post-exposure core temperatures were taken. In each study at least two levels of radiation, intermediate (13-17 mW/g) or high (28-31 mW/g), were compared. In the first of the two studies none of the maternal subjects died and no abnormalities were observed. In the second study the dose rates were only slightly higher (17 or 31 mW/g) and yet 21 percent of the dams in the 31 mW/g condition died during or immediately following the exposure. In the surviving litters both resorptions and abnormalities increased in the subjects treated in the higher exposure condition. In a followup study, pregnant rats were again exposed to either 17 or 31 mW/g for 20 minutes on the 8th, 10th, 12th, or 14th day of gestation. The percent lethality in the 31 mW/g condition was 19 percent, the incidence of resorption and abnormality was significantly increased, and fetal body mass was decreased. These data provided further evidence that microwave radiation can be teratogenic, but that levels must be so intense as to result in lethality in a given group of dams (O'Connor, Justesen & Reeves, 1979). Berman, Carter, & House (1979) exposed female Sprague-Dawley rats to 2.45 GHz at a power density of 0 or 28 $mW/cm^3$ for 100 minutes daily from days 6 to 15 after breeding. They reported no significant differences between irradiated and nonirradiated groups in pregnancy rates, number of live, resorbed, or total fetuses, nor in the incidences of external, visceral, or skeletal anomalies. They concluded that a teratogenic effect in the rat at this frequency will only be observed if the exposure is at a level high enough to produce a significant maternal thermal hazard.

Lary, Conover, Foley, & Hanser (1982) investigated the effects of 27.12 MHz RF radiation at intensities high enough to raise maternal temperatures to 43.0 °C over a 20 to 40 minute duration. Their rats were irradiated to a constant temperature (43 °C) rather than for a constant time period on either day 1, 3, 5, 7,9, 11, 13, or 15 of gestation. They reported increased fetal malformation and decreased fetal body mass in the post-implantation groups (day 7-15). They did not report differences between RF irradiated

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[1]References to M.E. Chernovetz and M.E. O'Connor refer to the same investigator.

fetuses and those from a control group of pregnant rats heated to the same core temperature in a water bath. The results of this study coupled with previous pilot work led these authors to observe that most malformations occur in maternal subjects whose pose-exposure temperature reached 43.0 °C and no malformations were observed if core temperatures remained below 41.9 °C. As is true of most areas of investigation involving RF fields, only a few studies have attempted to extend findings beyond those based on a single exposure to an intense field. Berman, Carter, & Kinn (1978) reported on exposure of mice throughout the gestation period. Also, Berman, Carter, & House (1982) have investigated the teratogenic effects of RF energy in another mammalian species, the Syrian hamster. They concluded that SARs of 16 mW/g and above were required to produce reduced fetal body mass in mice while 9 mW/g produced similar changes in the hamster. The Syrian hamster thus appeared to be more susceptible to microwave radiation as a teratogen than are rats or mice.

Several investigators have worked with the pupae of darkling beetle *Tenebrio molitar* (Carpenter & Livstone, 1971; Olsen, 1977; and Picard & Olsen, 1979). The summary statement for this work indicates that the teratogenic effects observed were due to thermalization. Some work on avian species has provided data on reproduction, teratogenesis, and developmental effects (Galvin et al., 1981). With respect to teratogenic effects, the avian data indicate that the radiation is not harmful until levels are reached that definitely place a thermal burden on the developing organism.

There are several main points that we may draw from the RF teratogenic studies, all of which are of import to the behaviorist. The first is that the response of an organism to RF irradiation appears to be highly similar to the response to other forms of heat stress. In the area of teratogenesis this response is considered to be of a more general variety. Highly specific anatomical and structural abnormalities are rarely observed. Resorption of the fetal material and decreases in fetal body mass are more commonly observed than something highly specific such as cleft palate or deformed appendages.

Of the more specific effects that have been observed, the two most common are exencephaly and tail abnormalities. Exencephaly is considered to result from a failure of the skull to close, and the brain thus protrudes on top of the head. It is not the result of abnormal growth within the brain. This effect has been reported by Rugh et al. (1974), Lary et al. (1979), and O'Connor et al. (1979), all at high levels of RF irradiation. Berman et al. (1978) reported data from three levels of microwave radiation, the highest of which was 28 $mW/cm^2$ for 100 minutes at 2450 MHz. The rectal temperature of the CF-1 maternal mice did not show a statistically significant rise over the 100 minute exposure for any of the groups. When the data was pooled across all three exposure levels there was a statistically significant higher incidence of exencephaly in the exposed versus the nonexposed groups. The abnormal data were clumped within the 28 $mW/cm^2$ group. However, the high group did not differ significantly from either the control or the other groups receiving lower levels of irradiation. Tail abnormalities have been reported by both Chernovetz et al. (1975) and Dietzel (1975). The tail alterations suggest some deviation in the proper formation of cartilage or bone. As mentioned previously, this is also the cause for the abnormality referred to as exencephaly.

The most common general observation is reduced fetal body mass. This reduction has been reported to persist for at least 7 days postnatal (Berman et al. 1982). Lower birth weight was one of the common observations in the early Eastern European reports of birth defects. They repeatedly mentioned that the animals in their studies weighed less at birth (McRee, 1980). Body mass is used by the teratologist-toxicologist as an indicator of general health of the newborn. There is some indication that there is also a fetal brain mass reduction following exposure to RF fields (Chernovetz et al., 1979).

The brain mass, body mass ratio is considered by a number of investigators to be a specific indicator of the general health and survival index for the newborn. It was the premise of the late George Sacher that the brain to body mass ratio for a given species is the best metabolic predictor of the longevity of a given species (Sacher, 1976; 1978). Decreased mass of the brian is a symptom in at least three human clinical conditions: vitamin deficiencies, Altzheimers's disease, and hyperkinesis in children. These diseases have a very marked behavioral component that could be placed in the category of an attentional deficit. There are no laboratory studies on functional deficits associated with reduced brain mass at birth. This lack of data is characteristic of the behavioral teratology literature with respect to RF radiation. Only a few studies have been undertaken and the results are inconclusive a this time.

## BEHAVIORAL STUDIES FOLLOWING PRENATAL EXPOSURE TO RADIOFREQUENCY FIELDS

A group of investigators at Thomas Jefferson University have assayed various behavioral parameters (Jensh et al., 1978a, 1978b, 1979). They exposed pregnant rats to 2450-, 915-, and 6000-MHz microwave radiation daily from day 1 to 6 or from day 6 to 15 of gestation. They observed a significant decrease in pregnancy rate and a decrease in maternal body mass gain due merely to handling. The combination of handling and heating was associated with reduced fetal body mass but the effect was similar in animals that received microwave heating or infrared heating. Most, if not all of their work has resulted in negative results with regard to the observation of behavioral differences.

McRee & Nawrot (1979) reported on the effects of handling on certain teratogenic endpoints in mice exposed to 2450 MHz radiation. A combination of both prenatal and postnatal irradiation with subsequent study of the effects on development, specifically behavioral development, has also been explored (Johnson et al., 1977; Lovely et al., 1983). In these studies the exposures were typically for 8 hours daily throughout gestation. The maternal subjects were allowed to give birth and the offspring were observed for development of reflexes. They also used post weaning measures of performance such as activity level, open field behavior and performance in avoidance tasks. Some differences were reported in individual cells of the experimental subgroupings but no main effect due to microwave exposure was statistically evident. As a result the studies are inconclusive.

The question of whether an organism can be sensitized during fetal development to specific kinds of environmental stressors has not been widely investigated with regard to any environmental agent for which there is a known or suspected biological effect. Whether the stressor the animal responds to postnatally is related to the type of stress to which it may have been sensitized prenatally remains an unanswered question.

## THE USE OF THE FETAL PERPARATION AS A MODEL SYSTEM

The main reason for investigating the effects of prenatal exposure to potentially harmful environmental conditions such as RF is obvious: It represents the only way to determine if birth defects can be caused by exposure to RF. This question has been of considerable concern with regard to RF because most RF sealer operators are women, almost all are of child-bearing age, and the levels of radiation to which they may be exposed are in ranges that are still considered questionable with regard to safety. If an increase in birth defects is determined to result from occupational exposure to RF, then the question of whether it results from the thermal nature of the radiation is academic. If this is the case, the population, particularly women of child-bearing age and capability, must not be exposed at these levels.

However, there is at least one other important reason to employ studies in which the exposure is given prenatally. There are several characteristics of prenatal development that recommend it as a model system for biological and behavioral studies. In some ways the developing organism is a most sensitive biological preparation. Not only is this preparation sensitive to direct insult, but functional systems can be separated according to major developmental stage as well as by rate of development. It is possible to pinpoint the particular structure or system of interest by conducting the investigation at the time during which that structure is developing, or is undergoing its fastest rate of development. It is true that much of evolutionary progress has apparently proceeded to protect the developing organism. However, these mechanisms are easily bypassed experimentally. Consider as one example the ease with which almost all psychopharmacological agents cross the placental barrier.

This developing system could also be used to address the question of whether animals can be sensitized to a certain type or category of stimulus during the developmental period. If the organism was stressed via heat as an embryo, will it be more or possibly less sensitive to those stimuli in the environment that produce heat? If the organism is exposed prenatally to certain drugs, that organism may tend to be more susceptible as an adult to the effects of the same category of drug. The prenatal model is a remarkable biological preparation that could be used to better advantage in general. However the conclusion of this author is that it has been underutilized with respect to investigations on potential effects of RF exposure and the physiological mechanisms underlying those effects.

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## ALBINISM as a FACTOR in THE the SELECTION of INFRAHUMAN MODELS in PREDICTING the HUMAN RESPONSE to MICROWAVE IRRADIATION

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### ABSTRACT

Melanin and the metabolic roles of its chemical precursors affect a number of biochemical, developmental, physiological and sensory-neural systems. Albino animals are metabolically and neurologically abnormal. Particular caution should be exercised in using albino animals as models in research on microwave radiation.

### INTRODUCTION

In all areas of biological research there is concern that appropriate infrahuman models be used in experimentation. Some methodological errors inherent in experiments are due to adherence to historical precedence in the design of experiments. One highly recurrent error is the use of albino animals as models in most biological studies. Albinos are acceptable models for some types of experiments, but one should be aware of the limitations of the model, particularly if the results of an experiment are to be generalized to a pigmented organism such as normal human beings.

The use of albinos in research is an historical accident, the exemplar being the rat. The laboratory albino rat is a domesticated variation of the Norway rat, *Rattus norvegicus* (Robinson, 1965). During the 19th century albino forms of *Rattus norvegicus* were perpetuated by animal fanciers in Europe for show purposes. They were used in research studies during the second half of the 19th century and Donaldson was using them at the University of Chicago by 1893. Donaldson's colony of albino rats was the origin of the strain at the Wistar Institute, which also produced the founding stock of the Sprague-Dawley strain. In 1924, Donaldson published "The Rat," in which he emphasized physiological similarities between rats and humans. This publication provided justification for the use of the albino rat as a model in biological research.

What are other justifications for using albinos? A prevalent argument is that albinos are nonaggressive. The paradox is that albinism *per se* is not a genetic determinate of docility. The apparent docility of albinos is associated with a nonagouti gene and independent polygenes for docility. Most strains of albino rats and mice are carriers of a recessive, pigment modifying nonagouti (a) allele that is not expressed. The normal wild type agouti (A) produces a pigment pattern characterized by a band of yellow near the tip of each hair. Nonagouti (aa) hairs lack the band. When hairs lack the band they become uniformly black. The modifying allele nonagouti (a) is not expressed because the albino mutation prevents the expression of coat color. It is *nonagouti* that is associated with docility (Keeler et al., 1941, 1942, 1970; Robinson, 1965). Albino rats are docile because they carry the double recessive genotype nonagouti (aa). Solid black rats, which also carry aa, are just as docile as their albino counterparts.

## DOMESTICATION

Many gene pools and organ systems are affected by domestication. The effects of domestication on behavior is an issue defensible from several points of view. If social behavior is an important consideration in an experiment, the arguments of Lockard (1968) and Boice (1973) should be considered. Lockard argued that the domesticated laboratory animal, particularly the albino, was an unnatural animal model. He considered domesticated albino strains a fabrication of the highly unusual environment of the laboratory that should not be used as research models. Boice argued that domestication provides separation from instinctive and biological roots, suggesting the domestic rat may be a good model for domestic man.

What happens to organ systems when a feral (normal) animal is introduced to a laboratory environment and bred for a number of generations? In the case of the laboratory rat the adrenal glands were reduced in mass to one-tenth of that of their feral counterpart, and the liver, spleen, heart, brain and some sensory projections were reduced in mass or quantity. With the reduction in mass of the adrenals, there was compensatory enlargement of the pituitary, thymus, thyroid and parathyroids. Researchers should be aware of these differences between domesticated and feral models when designing their experiments.

## SUBMASS EFFECTS

When any infrahuman model is used there are thermal and microthermal dose effects that should be considered. Although overall mass differences between infrahuman models are being carefully considered in microwave irradiation experiments, there are differential effects of radiation on these models because of both relative mass of organ systems and differences in physiological response. Submass effects because of relative sizes of organs such as the heart, brain, liver and spleen may produce thermal effects at variance with those of the feral organism.

## PHYSIOLOGICAL DIFFERENCES

The combination of microwave irradiation and drug treatment offers further possibilities to confound experiments, depending upon the model being used. The binding of various chemicals and the detoxification of drugs varies extensively among species and between albino and pigmented strains of the same species. In general, most drugs are metabolized more rapidly by laboratory rodents and more slowly by human beings as compared with other domesticated mammals (Davis, 1979). For example, in human albumin the half-life of phenylbutazone, an analgesic used to treat rheumatoid arthritis, is 72 hours versus 6 hours for dogs. The plasma half-life of salicylate is 5 hours for human beings, 6 hours for dogs, but 38 hours for cats. There are significant differences among laboratory rodents; e.g., the anesthetic hexobarbital has a duration of effect in mice 8 times that of rats. Strain and species differences in the effects of barbiturate anesthesia are particularly important to microwave irradiation experiments because of their disruption of thermoregulation (Justesen, 1980; Putthoff et al., 1977). Most of the species and strain differences are due to the considerable differences between rates of metabolism (Gardner and Reiser, 1979; Nakanishi et al., 1978; Batipps et al., 1981). Among the more commonly used infrahuman models there are differences among organ systems and the metabolic biotransformations that occur when these systems are challenged by drugs or microwave irradiation. These inherent metabolic differences should be considered in the design of experiments.

The presence or absence of melanin pigment in an infrahuman model used in microwave irradiation experiments contributes several sources of variation that may confound experiments. Melanin pigment is widely dispersed in nature and has survived millions of years of selective evolution, indicating that it has very basic functions. Melanin pigmentation is present not only in the skin -- where its role is principally to act as a shield to solar radiation -- but is also present where it cannot interact with solar radiation such as deep in the brain in the substantia nigra (Barden, 1969). Melanin pigment is metabolically very active, playing a key role in sensory physiological processes. Wald (1961) postulated analogous functions of the sheath of Schwann cells, which surround myelinated neurons, and melanin pigment in the epithelium of the retina. Melanin is also found in the inner ear except in the semicircular canals (LaFerriere et al., 1974). Although the amount of melanin in the inner ear is less than that in the eye, there is a high and positive correlation between relative amount of pigment in the eye and the amount of pigment in the inner ear (Bonaccorsi, 1965). The complete roles of melanin in the eye and ear are not yet known.

Functions of the pigmented retinal epithelium include the uptake of retinol from the extravascular space and its transfer to and from photoreceptor cells (Ishikawa & Yamata, 1970; Maraini et al., 1977). Melanin attracts and binds intermediaries during the chemical visual cycle. Evidence also indicates that melanin acts as an amorphous semiconductor-threshold switch (McGuinness et al., 1974). The presence of melanin where charge transfer occurs suggests its ability to function as an electrophysiological substrate. Melanin pigment is also capable of absorbing free electrons (Longuet-Higgens, 1960; Mason et al., 1960), which could be produced both by thermal and by microthermal effects of microwave irradiation.

## METABOLISM OF MELANIN

What is the chemical composition of melanin pigment and what is its relation to other pertinent metabolic pathways? Melanin pigment is produced by one of several metabolic pathways that begin with the basic amino-acid sequence of the hydroxylation of phenylalanine to form tyrosine. The initial step in the composition of the various melanin pigments is the oxidation of tyrosine to dopa, and dopa to dopaquinone, in the presence of the copper-containing enzyme tyrosinase (Fig. 1). Most forms of albinism are the result of the absence or insufficient activity of tyrosinase. The brown/black pigments (eumelanins) are then formed by a series of reactions involving cyclization and oxidative polymerization of a half-dozen intermediaries resulting in the formation of a brown/black melanin. To produce the red/yellow melanins (pheomelanins), dopaquinone interacts with cysteine residues that contain a reactive sulfhydryl group initiating several intermediate steps resulting in red/yellow melanin. The trichromes, low-molecular-weight red/yellow pigments, are also formed as a divergent branch to this pathway (Prota, 1980; Prota & Thomson, 1976; Weston, 1970;Witkop et al., 1978).

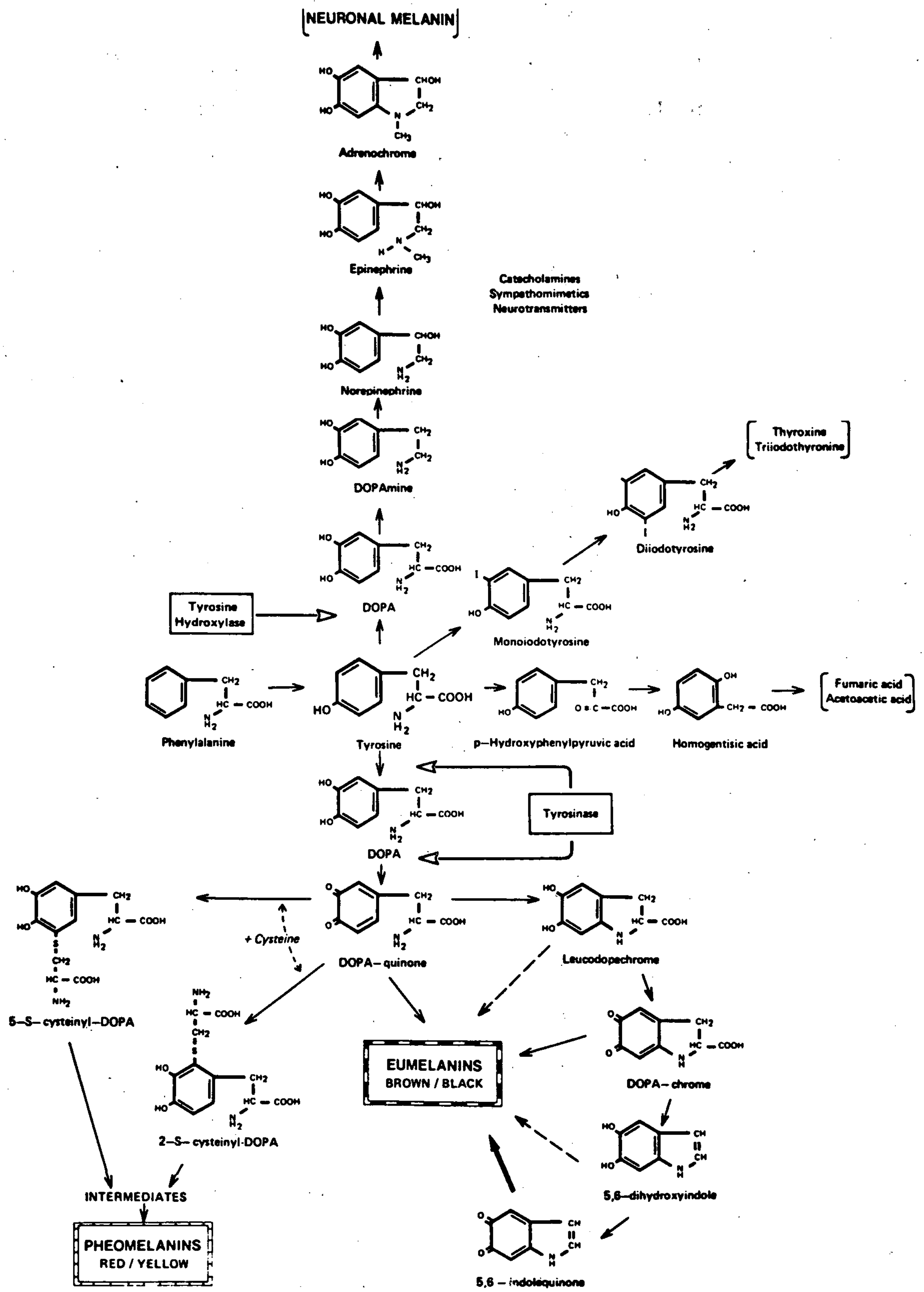


Figure 1. Metabolic pathways of melanin and related pathways of tyrosine in the liver, brain, adrenal medulla and thyroid. From Creel (1980).

Other metabolic pathways that begin with the formation of tyrosine include the catecholamines, thyroid metabolism, and oxidative liver metabolism. The oxidation of tyrosine in the presence of tyrosine hydroxylase produces dopa and initiates the catecholamine sequence of dopa, dopamine, norepinephrine, epinephrine. The chemical products following epinephrine in this series are adrenochrome and then neuronal melanin. Forms of melanin pigment can be produced both by the pathway initiated by tyrosinase that takes place in the pigment cell, or as a product following the catecholamine sequence in the nervous system. The basic chemistry of the thyroid involves the addition of iodine to tyrosine resulting in triiodothyronine and thyroxine. The majority of patients with thyroid disease have concomitant changes in skin pigmentation (Nerup, 1974). The basic metabolism of the liver involves the chemical sequence tyrosine, p-hydroxyphenylpyruvic acid, homogentisic acid, fumaric acid, acetoacetic acid. Each of these metabolic routes is dependent on the availability of tyrosine. It is my contention that the disturbance of the chemical pathways producing melanin pigments alters the balance of availability of tyrosine and dopa thereby disturbing the normal metabolic pathways of several systems (Creel, 1980; Gibson et al., 1982; Gibson & Wurtman, 1978).

Dopa and 5-S-cysteinyldopa levels were found to be lower in the serum of albino guinea pigs as compared with black and red guinea pigs (Hansson et al., 1980). Albino mice have a greater turnover of tyrosine in the liver than do normally pigmented animals (Mojamdar et al., 1976). Deletion studies by Gluecksohn-Waelsch and colleagues (1975, 1979) have shown that genes at or near the albino locus in mice regulate several perinatally-developing enzymes and plasma proteins of liver and kidney cells (Garland et al., 1976). Differences in liver cytochrome P-450 levels were found among several strains of albino rats when compared with pigmented strains of rats (Creel et al., 1976). The cytochrome P-450 system involved in oxidative detoxification was reported not to be detectable in newborn albino mice (Thaler et al., 1976).

Genes causing hypopigmentation without complete albinism are also associated with biochemical anomalies. For example, the buff gene (bf) produces a dilution of pigment in the mouse that affects kidney lysomal glycosidases (Hakansson & Lundin, 1977). Genetic loci around c locus, including shaker to ruby, are the same loci that control liver and kidney enzymes (Gluecksohn-Waelsch, 1979).

There is increasing evidence that significant differences exist between albino and pigmented strains of rats in the sensitivity to and metabolism of drugs. For example, the response of the liver to barbiturates has been associated with degree of pigmentation (Belknap et al., 1973; Collins & Lott, 1968; Furner et al., 1969; Jori et al., 1972). Albino mice have longer sleep times than do pigmented mice treated with either alcohol or pentobarbital (King & Rush, 1976; Randall & Lester, 1974; Westenberg & Pakalnis, 1979). Albino rats show a linear attenuation of components of the visually evoked potential following progressively increasing doses of pentobarbital, as compared with pigmented rats, which show a "rebounding" of the visually evoked potential (Creel et al., 1974). A comparison of the effects of pentobarbital on the visually evoked potential in congenic albino and pigmented mice demonstrated a linear effect in the albino and a curvilinear effect in pigmented mice (Henry & Rhoades, 1978). When choosing an infrahuman model the pigmentation of the animal should be considered because its pigmentation may be a symptom of possible abnormalities that could affect the outcome of microwave irradiation experiments.

In addition to possible metabolic abnormalities in albino models there is another factor that must be considered when choosing a model for drug studies. A number of drugs and chemical substances, mainly those that are polycyclic, bind to melanin pigment and are retained for long periods with adverse effects (Dencker & Lindquist, 1975; Dencker et al., 1975; Lindquist, 1973; Lindquist & Ullberg, 1974). Albino animals were studied in early autoradiographic investigations using drugs labeled with radioactive isotopes. Research on albino animals indicated that most organs were usually clear of a drug within a few days after a single dose. When Lindquist and colleagues tested pigmented animals, melanin was found to accumulate some drugs and keep them bound for months.

The dangers of not recognizing drug interactions with melanin are not just hypothetical. In the latter 1950's and 1960's the use of phenothiazine tranquilizers, especially chlorpromazine, was found to be associated with pigment disturbances in the eye. Deposits of pigment on the iris and cornea were observed in a high percentage of patients receiving high-dose long-term chlorpromazine therapy. Chloroquine is a more potent chorioretinotoxic drug than are the phenothiazines. Higher dose levels used over long periods in the treatment of collagen diseases can cause retinal and auditory damage because of chloroquine's affinity for melanin-containing tissues (Baweja et al., 1977; Hart & Naunton, 1964). Other drugs that have known affinity for melanin include clindamycin, gentamicin, streptomycin, dopamine, epinephrine, norepinephrine, serotonin, and nicotine. Melanin affinity for substances is known to contribute to lesions in the brain, inner ear, eye, reticuloendothelial system and skin (Barza et al., 1979; Betten et al., 1973; Lindquist, 1973; Sheffield & Turner, 1971). Caution should be used when generalizing the results of drug studies using albino models to pigmented organisms, especially in attempts to generalize directly to human beings.

Some differences among models used in research concerning the effects of microwave radiation have been reported. A study of albino rats indicated that sodium salicylate, an analogue of aspirin, is a true hypothermal agent, not merely an antipyretic compound (Satinoff, 1972). Several species were subsequently tested after microwave hyperthermia. The hypothermic effects were found to be peculiar to rats, especially albinos, and did not generalize to the guinea pig or rabbit (Putthoff et al., 1977). In another experiment, behavior of albino mice differed from that of pigmented mice when they were exposed to low-frequency (60 Hz) magnetic fields (Smith & Justesen, 1977). Caution should be exercised in using albino models in microwave research, including studies of induced febrility, unless differences between albino and pigmented animals are resolved.

There are several other organ systems in which albino mammals are susceptible to abnormalities including sensory misrouting of neurons and neural-crest anomalies (Creel, 1980; Creel et al., 1981, 1983). These anomalies include misrouting of visual projections and cellular development of the brainstem auditory pathways (Conlee et al., 1983).

## CONCLUSIONS

The experimenter in designing microwave irradiation experiments should first pose the question: Is the treatment being tested in this model susceptible to confounding by the presence or absence of melanin, by an interaction with the chemical melanin pigment pathway, by the pigment's ability to act as an ion sink or reservoir for a drug being tested, or by an interaction with the chemical pathways related to that of melanin such as the catecholamines? The experimenter should also be cautious of interspecies differences in anatomy and physiology, and interspecies strain differences, particularly those related to pigmentation, which may restrict one's ability to predict the human response to microwave irradiation based on data from an infrahuman model.

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# CAN MICROWAVE RADIATION PRODUCE STATE-DEPENDENT BEHAVIOR?

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One of the questions that greatly concerned psychologists during the 1930's was whether a motor response was necessary for learning to occur. Harlow & Stagner (1933) failed to condition curarized cats and dogs and therefore concluded that conditioning is possible only if a response occurs. On the other hand, Light & Gantt (1936) were able to condition dogs that had responding blocked by crushing the spinal motor nerves. The learning became apparent when the crushed motor neuron regenerated. Girden & Culler (1937) attempted to resolve the question by determining whether the muscle semitendinosus could be conditioned in dogs given a dose of di-hydro-beta erythriodine, a crude form of curare that has a slight depressant effect on the central nervous system. In the course of their experiment, they presented the first laboratory description of state-dependent behavior. They found that dogs could be conditioned under the influence of the drug, but when the drug effect wore off the conditioned response was lost. Similarly, dogs conditioned in the nondrugged state lost their response when drugged but the conditioned response returned when the animal returned to the nondrugged state. State-dependent behavior, then, was first described as a phenomenon in which responses acquired in a paricular drugged state are not performed or have a reduced probability of occurrence when the animal is no longer in that drugged state. The learned response can be reinstated with the reintroduction of the drugged state that existed at the time of response acquisition. Thus recall or performance of a response is associated with the particular state in which learning occurred.

Despite Girden and Culler's description of state-dependent behavior, the phenomenon was largely ignored and research on the topic was sparse during the 1940's and the 1950's. The impetus for further research on state-dependent behavior stemmed from the theoretical position of Hebb (1949). Hebb postulated that there are synaptic changes in a large number of cells that fire in a particular pattern, called a phase sequence, when learning has occurred. Overton (1964) was the next to describe state-dependent behavior when he tested Hebb's theory. He argued that drugged states influence the pattern of neural activity as measured by such changes as alterations in EEG activity. Learning in a drugged state should produce a different phase sequence because there are different patterns of brain activity than that produced in the nondrugged state, and the result should be state-dependent behavior. Hebb's theory and Overton's experimental support for the predictions made from it stimulated a great deal of research into state-dependent behavior during the 1960's. Overton (1971) has summarized the literature to 1971 to show that state-dependent behavior is produced by many kinds of drugs, in a wide range of tasks using a variety of animal species.

Research into state-dependent behavior in the late 1960's and throughout the 1970's was characterized by investigations of agents other than drugs that could produce the phenomenon. Nielson (1968) whose work was confirmed by Devietti & Larson (1971), reported that electroconvulsive shock (ECS) did not prevent the memory from being established as previously thought, but rather produced state-dependent behavior. Holloway & Wansley (1973a, b) showed that retention was not uniform throughout the day, and that the variations in retention were state-dependent based upon changes in the time of day. Holloway's (1978) recent description of time-of-day-dependent recall in the rat for a passive-avoidance task shows that when the rats learned this task they tended to "forget" it 6 hours later, remember it 12 hours later, "forget it" again 18 hours later, but again show recall of the task every 12 hours thereafter. State-dependent behavior has since been produced by REM sleep deprivation (Joy & Prinz, 1969), the induction of hypnotic states (Evans, 1972), affective changes associated with manic-depressive psychosis (Weingartner, 1973), hypnotically-induced mood states (Bower, 1981), steroid hormones (Stewart, Krebs, & Krczender, 1967), adrenocotrophic hormone (ACTH) (Gray, 1975), low-level stimulation of the caudate nucleus or nuclei of the amygdala (McIntyre & Gunter, 1979), hypothermia (Boyd & Caul, 1979), and hyperthermia (Misanin, Vonheyn, Bartelt, Boulden & Hinderliter, 1979). It is clear that state-dependent behavior is produced by a wide variety of agents, in a wide variety of species and with a wide variety of tasks. It seems likely agents can produce changes in moods, can change an organism's biological rhythms or release a variety of hormones which have the potential to produce state-dependent behaviors.

What is the likelihood that low-level microwave radiation can produce state-dependent behavior? The answer to that question is difficult because no experimental attempt has been made to address the question. It is possible that chronic exposure to microwave radiation could produce no decrement in behavior yet the behavior could become state-dependent based upon some physiological consequences of the microwave radiation. The decrement in behavior from the microwave radiation would be detected when the behavior was tested in the absence of microwave radiation. A candidate for possible microwave-induced physiological change that could serve as the basis for inducing state-dependent behaviors is a change in body temperature. The body temperature change could be either a change in core body temperature or perhaps a change in the temperature of a region of the brain.

Researchers have long known that hypothermia can impair memory (Beitel & Porter, 1968; Misanin & Hoover, 1971; Riccio & Stikes, 1969) but recently Boyd & Caul (1979) have described a hypothermia-produced state-dependent failure of recall of a brightness discrimination. With body temperatures reduced by 7 °C to 13 °C, there was no impairment in learning, but learning was not evident when the body temperature was changed from the body temperature that existed during learning. ECS, which produces state-dependent learning also produces cortical hypothermia (Oke, Mendelson, & Justesen, 1974; Wetsel, Riccio, & Hinderliter, 1976) and alters the rat's core body circadian temperature rhythm (Hoyt & Rosvold, 1951). Hyperthermia, induced by immersion in a 45 °C water bath, has also reported to produce memory deficits similar to those produced by ECS for a passive-avoidance task (Misanin, Vonheyn, Bartelt, Boulden, & Hinderliter, 1979). Furthermore, these investigators (Misanin et al., 1979) report an amnesic gradient for the memory of the passive-avoidance task can be produced by varying the time between the training trial and the immersion in 45 °C water that was similar to the amnesia gradients produced by ECS (McGaugh, 1966).

An additional correlation between body temperature shifts and state-dependent behavior is that many, if not all, of the drugs that produce strong state-dependent behavior effects also produce effects upon core temperature. For example, pentobarbital, when given at doses that produce state-dependent behavior (25 mg/kg i.p.), produce a drop in brain temperature of 2 °C to 3 °C 30 minutes after the injection with ambient temperatures between 20 °C and 25 °C (Baker, Frye, & Millet, 1973). This resultant change in core temperature apparently induces changes in evoked responses recorded from the brain in response to either auditory or visual stimulation. Alcohol, a drug that readily produces state-dependent behavior, also produces changes in the brainstem auditory evoked potential of cats (Squires, Chu, & Starr, 1978). Squires et al. attributed the changes in the evoked potential to the direct pharmacological action of the drug on the neuron. This may not be the case however. Jones and his colleagues (Jones, Schorn, Siu, Stockard, Rossiter, Bickford, & Sharbrough, 1977) have shown that a reduction in core temperature will produce a similar change in the auditory evoked potential of cats. The specific effects in cats were changes in the interwave intervals of the various components of the evoked response that appeared with temperature changes of less than 1 °C either above or below the normothermic level (Jones, Stockard, & Weidner, 1980). Jones et al. (1980) not only showed that changes in the auditory evoked potential are correlated with drops in body core temperature but that restoring the core temperature of the drugged cat to normal also restored the evoked potential to normal. They concluded that the changes in the auditory evoked potential of cats, that follow a dose of ethanol, is strictly a consequence of changes in body temperature and is not due to any pharmacological action other than that influencing body temperature.

Virginia Bruce-Wolfe and D.R. Justesen (unpublished, personal communication) have conducted similar experiments on the effects of pentobarbital upon visually evoked responses (VERs) in the rat. They found that pentobarbital induced changes in both core body temperature and the VERs. They, like Jones et al. (1980), concluded that the changes in the evoked response are due primarily to changes in core temperature although other physiological changes may be induced by the drug. Bruce-Wolfe and Justesen have recorded VERs from a variety of control groups to arrive at their conclusion that certain changes in the VERs following injections of pentobarbital are due to its effect upon body temperature. The controls include recording VERs from rats with elevated core temperatures induced by microwave radiation alone, as well as recording from rats whose body temperature was lowered by housing them in cold chambers.

It is clear that changes in core temperature can have profound effects upon brain potentials evoked by auditory or visual stimulation. The usual inferences that are made from changes in evoked potentials is that there has been some change in the transmission of information to, or the processing of, sensory information to the brain. We believe that there is a similar change in the processing of sensory information associated with the drugged state in experiments of state-dependent behavior. In our experiments we have identified what we believe is a restriction in the animals' use of sensory information in the drugged state. Our belief is that this restriction in the ability of the drugged animals to use peripheral sensory information stems from the faulty processing of that sensory information.

Robert Pusakulich and I (Pusakulich & Nielson, 1976) investigated the kinds of stimuli that rats used in the drugged and the nondrugged state to learn to escape from a water maze. The apparatus we used in these experiments was a Dashiell maze modified to hold water. The floor plan of the maze is shown in Figure 1. The walls were 24 inches high, each alley was 12 inches long and 4 inches wide. Movable inserts were used so that various patterns could be arranged and any area of the maze could serve as either a starting or goal area. Water temperature was maintained at 13 °C throughout the experiment. The dashed lines represent two particular maze arrangements. In the $S_1$ arrangement, some animals were trained to swim to goal escape area, $G_2$; others were trained to escape to $G_3$. The rats could learn the place of the particular goal area or learn a series of responses (R-R-R) to get to $G_2$ or L-L-L for rats trained to $G_3$. They were then tested to discover which learning strategy they actually used by starting them at $S_2$. If the rats that went to $G_2$ during training swam to $G_7$ during testing they had learned to escape from the maze using the strategy of learning a response sequence of R-R-R turns. If they swam from $S_2$ to $G_2$ they had learned to escape from the maze by using a place-learning strategy.

One of the findings was that the nondrugged and drugged animals used different cues to solve the maze. Nondrugged rats could escape from the water maze either by learning the place of the escape ladder, or by learning a sequence of responses to reach the ladder. The drugged-trained rats could learn only response sequences; they could not learn the place of escape. This indicated to us that different stimuli (cues) are associated with different states. A related finding was that learning was impaired if the rats were required to learn to escape from the maze using the same cue in the different states. We now feel that this impairment in learning, when the same cue is used in both states, represents a form of inhibition of one state by another. We interpreted the restriction of learning in the drugged rats as resulting from a restriction in the processing of environmental stimiuli as cues for escape learning. The drugged rats were not blind, deaf, or anosmic, yet, they did not appear to be able to use environmental stimulation as the basis for learning.

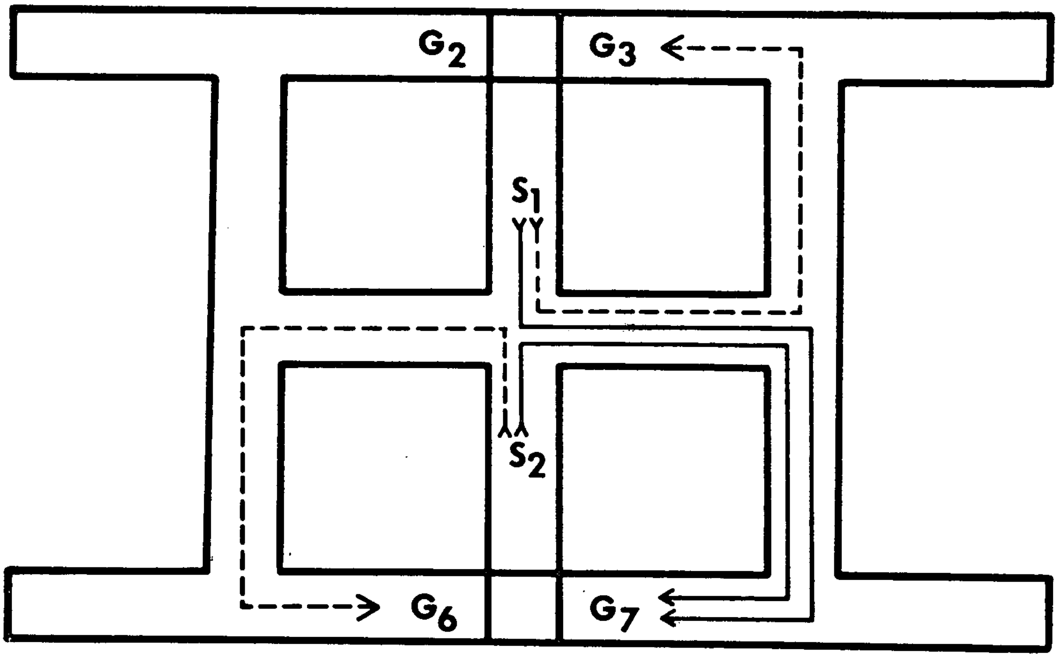


Figure 1. The water maze used by Pusakulich & Nielson (1976).

That there is a restriction in the processing of environmental stimuli in the drugged state was subsequently verified (DeWitt & Nielson, 1980). They used the conditioning procedure of Doty et al. (1956) and Pusakulich & Nielson (1972) to establish CRs in cats to direct electrical stimulation of the brain. In this procedure, cats are habituated to a hammock which allows the cat free movement of his head and limbs but his gross locomotion is restricted. When the cats are tolerant of this restriction and remain quiet, they are anesthesized and surgically fitted with pairs of bipolar stimulating electrodes that are connected to a Winchester female socket which is chronically attached to the skull. When the animal had recovered from surgery, they begin avoidance training. A conditioned stimulus (CS), a train of electrical impulses is delivered directly to the brain and bypass without a sensory system. The CS train of electrical impulses lasts for 2 seconds. The unconditioned stimulus (US) is another train of electrical impulses, that last .2 sec and overlapped the CS by .05 second, that is applied by a cuff on the animal's right foreleg and a grid upon which the foreleg rests. The cat learns to avoid the footshock by making a right foreleg flexion to break the US circuit between the cuff and the grid. Then conditioning thresholds, the intensity of the brain stimulation necessary to maintain CRs, is determined by gradually lowering the intensity of the brain stimulation until no CRs are obtained. A CR threshold is defined as the intensity of the CS that maintains 50 percent CRs. Once the cats are trained to the brain stimulation CS, they are then to make the foreleg flexion CRs to tone or light CSs. Thus CRs are established to conditioned stimuli from the normal sensory systems, or the normal sensory systems are bypassed. Then the cats are given drugs that produce state-dependent behavior. There were doses of these drugs that abolish the cats' CRs to the tone CS, but left the same response established to direct electrical stimulation of the brain intact. Thus the drug's first effect was not on the motor system because the cats could respond to the brain stimulation CS. It was the peripheral sensory stimulation that was no longer being processed and being attended to. The drug dose data for three drugs that are known to produce state-dependent behavior (chlordiazepoxide, meprobamate, and chloral hydrate) and which we believe restrict the processing of peripheral stimulation are shown in Table 1.

**Table 1. Brain stimulation thresholds and percent CRs given to tone and brain stimulation by cats as a function of drug dose**

| | | Dose (in milligrams per kilogram) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Chlordiazepoxide (ip) | | | | | Meprobamate (Oral) | | | | | Chloral Hydrate (Oral) | | | | |
| Cat | CS | 0 | 7.5 | 12.5 | 17.5 | 22.5 | 0 | 50 | 75 | 100 | 125 | 0 | 50 | 75 | 100 | 125 |
| ND-4 (SC) | CR Threshold | .09 | .09 | .13 | .16 | .18 | .09 | .13 | .180 | .24 | | .09 | .20 | .25 | | |
| | Percent CRs | 80 | 80 | 80 | 60 | 60 | 80 | 100 | 60 | 70 | | 80 | 100 | 60 | | |
| | Tone-Percent CRs | 75 | 14 | 29 | 3 | 3 | 75 | 20 | 11 | 3 | | 75 | 14 | 0 | | |
| ND-5 (SC) | CR Threshold | .05 | .06 | .07 | .09 | | .05 | .07 | .075 | .07 | | .05 | .05 | .05 | .05 | * |
| | Percent CRs | 88 | 70 | 80 | 80 | | 88 | 70 | 80 | 100 | | 88 | 80 | 100 | 90 | 0 |
| | Tone-Percent CRs | 80 | 77 | 0 | 0 | | 80 | 77 | 6 | 0 | | 80 | 34 | 5 | 0 | 0 |
| ND-6 (SC) | CR Threshold | .15 | .15 | ** | | | .15 | .15 | .180 | .45 | * | .15 | .16 | .19 | .40 | .42 |
| | Percent CRs | 85 | 60 | | | | 85 | 80 | 100 | 70 | | 85 | 90 | 60 | 60 | 60 |
| | Tone-Percent CRs | 85 | 71 | ** | | | 85 | 71 | 25 | 49 | | 85 | 28 | 20 | 5 | 0 |
| ND-7 (SC) | CR Threshold | .22 | .28 | .34 | .38 | .47 | | | | | | | | | | |
| | Percent CRs | 68 | 80 | 60 | 70 | 80 | | | | | | | | | | |
| | Tone-Percent CRs | 83 | 80 | 31 | 11 | 0 | | | | | | | | | | |
| ND-8 (SC) | CR Threshold | .08 | .11 | ** | | | .08 | .14 | .180 | .17 | | .08 | .15 | .23 | .15 | 0 |
| | Percent CRs | 88 | 70 | | | | 88 | 60 | 80 | 100 | | 88 | 80 | 60 | 60 | |
| | Tone-Percent CRs | 80 | 11 | ** | | | 80 | 57 | 43 | 6 | | 80 | 42 | 26 | 0 | |
| ND-9 (SH) | CR Threshold | .04 | 07 | .11 | .28 | .28 | .04 | .06 | .080 | .09 | .16 | .04 | .07 | .10 | .23 | .26 |
| | Percent CRs | 82 | 60 | 60 | 90 | 60 | 82 | 60 | 60 | 60 | 70 | 82 | 60 | 90 | 100 | 60 |
| | Tone-Percent CRs | 94 | 86 | 60 | 46 | 54 | 94 | 89 | 68 | 3 | 0 | 94 | 94 | 69 | 34 | 3 |
| ND-10 (SH) | CR Threshold | .06 | .13 | .16 | * | | .06 | .12 | .110 | .13 | | .06 | .10 | .28 | * | |
| | Percent CRs | 82 | 70 | 60 | 10 | | 82 | 60 | 70 | 60 | | 82 | 80 | 60 | 10 | |
| | Tone-Percent CRs | 73 | 0 | 14 | 0 | | 73 | 6 | 0 | 0 | | 73 | 63 | 3 | 0 | |

Note–CS thresholds are given in milliamperes. SH = stimulation of hippocampus. SC = stimulation of caudate.
*Cat did not give enough responses to determine a threshold.
**Cat showed extreme distress when dosed with chlordiazepoxide and could not be tested in hammock.

From DeWitt and Nielson, 1980.

That this restriction in the processing of sensory stimulation does not leave the animal blind or deaf had been pointed out earlier. To show this, DeWitt & Nielson tested the drugged cats, that did not repond to a peripheral CS with the avoidance response, to determine whether they could respond to peripheral stimulation to catch mice, detect and evade dogs, or locate food. Despite their drug-induced ataxia from the injection of pentobarbital and their failure to respond to the peripheral CS, they would nevertheless attempt to catch mice, evade the dog, and locate food. DeWitt & Nielson resolved the apparently discrepant findings, the drugged cats would attend to some stimuli such as mice, dogs or food, but not other stimuli such as tone or light CS by making a distinction between "hard-wired" and "soft-wired" behaviors. "Hard-wired" behaviors were those whose sensory components had central representations which may be genetically based.

"Soft-wired" behaviors were viewed as those whose central representations are established by learning. The peripheral stimuli used by DeWitt & Nielson have been tones and light flashes as have the stimuli used to evoke brain potentials. These stimuli are those whose central representations must be established by learning. It seems reasonable to us to infer that the state-dependent failure to attend to a tone or light CS may be due to the interference with a drug-induced, temperature dependent central processing of stimuli whose central representations must be established by learning. The meaning of tones and lights used as either conditioned stimuli or stimuli to evoke potentials in the brain fall into this "soft-wired" category. Stimuli from food, prey, or enemies do not.

That there may be a temperature dependent of central processing of stimuli whose meaning must be learned is not farfetched in light of the experiment by Bermant et al. (1979). They monitored reliable rises in the core temperature of rats as they were transported from the home cage to an experimental laboratory in which the animals had a history of restraint. When core temperature fell with transport back to the home cage, it became clear that changes in body temperature could be associated with learning situations.

Changes in mood produce state-dependent recall (Bower, 1981; Weingartner, 1973; Weingartner, Murphy, & Stillman, 1978) and in some of these cases, there may be changes in body temperature associated with mood changes, but whether it is the change in mood or the change in body temperature that is responsible for the state-dependent behavior is not known. We noted earlier that state-dependent behavior was associated with the mood fluctuations of manic-depressive psychosis. That these fluctuations in mood may be accompanied by fluctuations in body temperature has been described by Ziegler and cited by Richter (1967). While mood and core body temperature changes both produce state-dependent behavior, we know of no study that has measured both mood and body temperature in a single investigation of state-dependent behavior. That changes in the core temperatures of normal humans can induce changes in mood has been reported by Justesen (1982, personal communication). He and some of his coinvestigators pre-tested the utility of vapor-barrier suits as a means of elevating core temperatures. An elevation of 1 °C of core temperature was associated with dramatic changes in mood and difficulty in sleeping the following night. Additionally, they found changes in the latencies of components of a visually evoked response induced by a 1 °C temperature change, a finding similar to that reported for a 1 °C elevation in the core temperature of cats reported by Jones et al. (1980).

One further observation needs to be made before we again ask the question "Can microwave radiation produce state-dependent behavior?" This observation is that if body temperature changes are a sufficient condition to produce state-dependent behavior, it seems likely that the changes in body temperature need be of such a magnitude that the whole body is involved. Rather, it seems likely that small regional temperature changes in the brain could produce state-dependent behavior. The reason for this assertion is that electrical stimulation of small discrete brain areas (from the stimulus intensities we estimate the size of the stimulated area to be no larger than 1 cubic millimeter) has been reported to produce state-dependent behavior (McIntyre & Gunter, 1979). These workers produced state-dependent behavior with low level electrical stimulation of the caudate nucleus and the amygdaloid nuclei. That thermal stimulation of small nuclei of the brain can produce behavioral effects has been shown by Adair (1970). She reports that small temperature changes of the medial preoptic nuclei will activate thermoregularity behavior, and the magnitude or the behavioral activation is a linear function of the hypothalamic temperature.

What then do we know and what can we reasonably infer about temperature changes and state-dependent behavior. (1) Changes in core body temperature are a sufficient condition to produce state-dependent learning. (2) Drug induced reductions in core temperature change sensory evoked potentials in the brain and these evoked potentials are thought to reflect the transmission and processing of sensory information. (3) The same drugs that produce temperature dependent alterations in evoked potentials, by inference produce a restriction in the ability of animals to use sensory information in drugged states and force the animals to learn different things in the drugged and non-drugged states. (4) Mood changes associated with manic-depressive psychosis can produce state-dependent behavior and body temperature shifts have also been associated with these mood shifts. (5) Elevations of body temperature, like reductions in body temperature, also produce state-dependent behavior changes in sensory evoked potentials, and changes in mood. (6) Body temperature rhythms are disrupted by electroconvulsive shock, and the memory system of rats is based upon time of day and could therefore be based upon body temperature shifts. (7) Additionally, we know that there are core body temperature changes associated with learning situations. (8) We believe that we can infer that temperature changes in small discrete areas of the brain are also likely to produce state-dependent behavior. This inference is based upon the report that low-level electrical stimulation of small discrete brain areas does produce state-dependent behavior and the report that temperature changes of a discrete brain area activated thermoregulatory responses with the strength of the responses directly proportional to the brain temperature changes.

Can microwave radiation produce state-dependent behavior? I think it likely that the use of microwave radiation in experimental designs that would disclose state-dependent behaviors would reveal state-dependent effects. To my knowledge, which is certainly limited concerning the behavioral effects of microwave radiation, no investigation of the behavioral effects of microwave radiation has used a paradigm which would identify possible state-dependent effects. Yet the findings of D'Andrea (1982), that low-level radiation in rats produces "hot spots" at the base of the skull, and possibly in the brain, suggest a real possibility for the production of state-dependent behaviors. Similarly, stimuli that have the capability of producing emotional arousal have the capability of producing state-dependent effects and small changes in temperature have been shown to do this. Justesen (1982) suggested that microwave radiation might produce state-dependent behavior and his suggestion deserves to be taken seriously.

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## DOSE-RESPONSE CONCEPTS IN RADIATION—ONE MAN'S VIEW

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There are many approaches that could be taken in comparing or contrasting the dose-response relationships for nonionizing and ionizing radiation. I have chosen to eliminate from consideration the visible, near UV, and near IR. First, the history could be recounted of the two areas indicating where the effects were discovered to be hazardous and the resulting standards imposed (Fig. 1). A second consideration could be the history and development of the understanding of the mechanisms of interaction, e.g., genetic, somatic, and life shortening for ionizing radiation and thermal insult for nonionizing radiation.

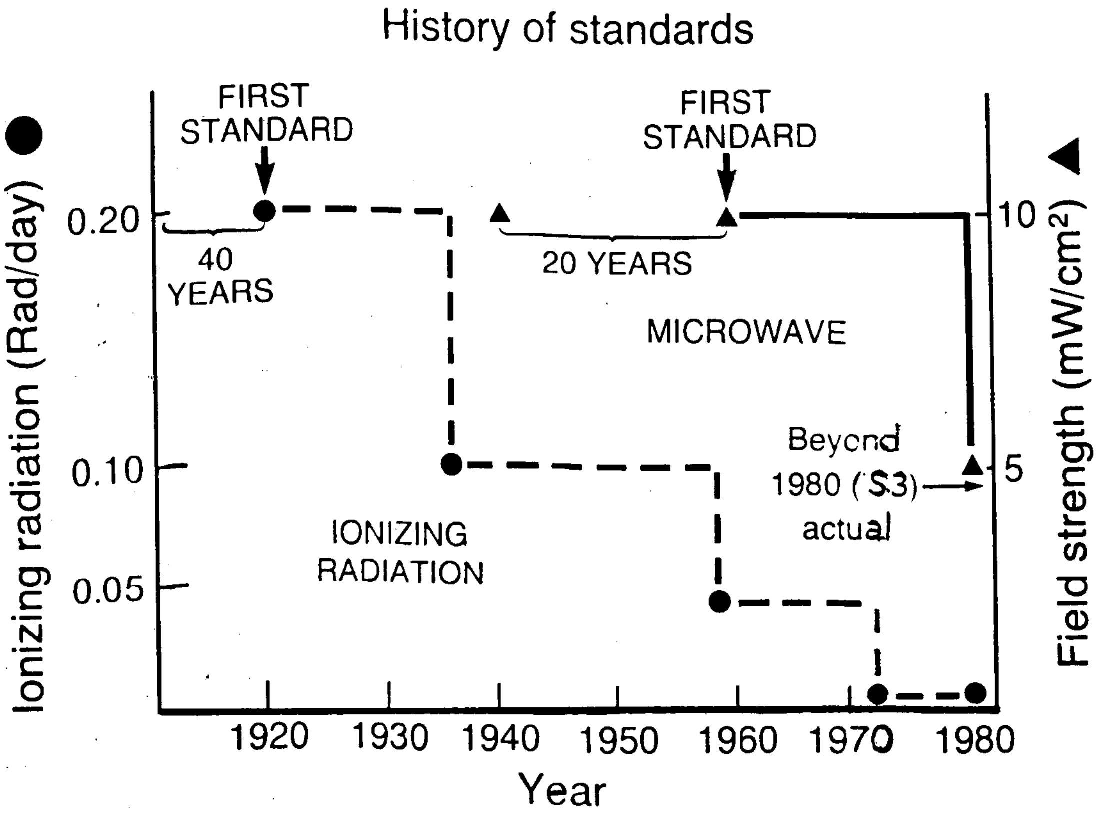


Figure 1. History of Standards. Combined graph designed to compare ionizing and nonionizing (microwave) standards. The years indicated, 40 and 20, are the approximate time from general use until an exposure standard was proposed. The actual ANSI standard beyond 1983 is more complete than shown here, 5 mw/cm² was used for comparative purposes only.

First I would like to briefly mention the histories. The rather complicated graph, Figure 1, is an attempt to indicate the changes, in very broad strokes, for whole-body ionizing radiation and microwave standards. In the 1920's, the ionizing exposure was limited by a fraction of the dose that would cause erythema. In today's terms, this is equivalent to approximately 0.2 RAD/day. This level was also supported for a few years as the "tolerance dose," a dose where no acute changes were observed in blood. In 1936 the numbers were revised to 0.1 RAD/day, probably as a result of the appearance of "genetic effects." As more and more information became available, this was reduced further in 1959 to 0.042 Rem/day. By 1972 the present limits for occupational workers and the general population had been reduced to 5 Rem in any year, or 0.001 Rem/day. Since 1972 only changes in specific body organs (e.g., gonads) have been made. Dose limitations to specific organs, however, represented a new direction in the thinking regarding standards. Today there are recommendations that the amount of radiation should be as low as reasonably achievable (ALARA).

By comparison the nonionizing standards in the microwave region are very familiar to this audience. The 10 mW/cm$^2$ exposure standard, established in the early 1960's by ANSI has stood until a proposed revision was made in 1980. Maybe we should take heart in the fact that we did learn from our ionizing radiation colleagues. It took only 20 years to recognize the need for an exposure standard for microwaves in contrast to nearly 30 years for ionizing radiation.

The mechanisms of interaction of ionizing radiation with biological material are fairly well understood. Energy is imparted to the system in discrete, high energy packets which cause specific changes in important molecules within the cell (e.g., changes in DNA resulting in both somatic and inherited changes). I grant you this is an oversimplification but for the purposes of comparison, it is adequate.

Researchers in nonionizing radiation have assumed that the energy of microwaves is more likely to change the energy state of the system rather than to cause specific molecular changes. In general, the concept of thermal insult by microwave radiation has been the primary concern of workers in this field.

Researchers in ionizing radiation have a better understanding of specific interaction mechanisms than do researchers in nonionizing radiation. However, progress is being made in the nonionizing research area. However, we are still in our infancy.

Finally, I should like to address the problem of dose-response curves. Those involved in ionizing radiation have little question of the shape of the curve above about 100 R; it is basically linear. This is true for both acute lethality or long-term mortality. Below 100 RAD the shape of the dose-response curve is uncertain. Recent evidence from Hanford and elsewhere, e.g., Hiroshima and Nagasaki, has suggested the linearity can be extended to 0.25 R (Curve D, Fig. 2). Below this level there are many possibilities. Some believe that there is a threshold and above this linearity is observed (Curve A, Fig. 2), while below threshold there are no hazards and some will suggest hormesis will occur. Others suggest that at these low levels the response is proportional to the square of the dose (Curve B, Fig. 2). Another group suggests supra-linearity in this region (Curve C, Fig. 2). The evidence for these proposals is generally based on the results from specific populations under study, e.g., the incidence of leukemia in Japan. It is difficult to resolve this issue because low level effects may not be detectable within background noise of the biological endpoint.

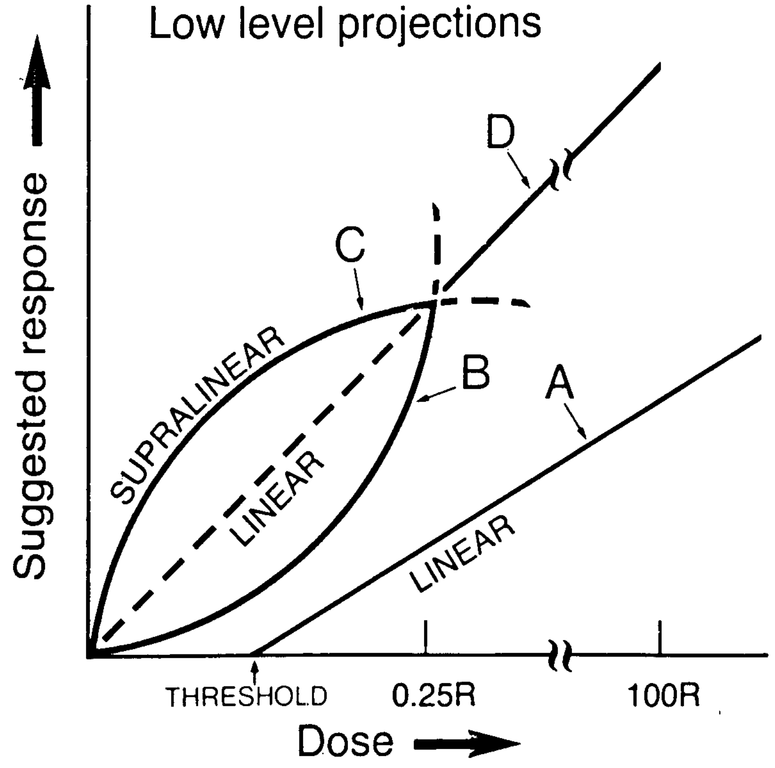


Figure 2. Dose-Response Projections at Low Dose Levels. Curve A represents a threshold and linear dose-response relationship above threshold. Curve B represents a no threshold but a reponse compared to the square of the dose. Curve C represents a greater than linear response at low dose levels. Curve D represents a linear response with no threshold.

What about the microwave area - what are "our" beliefs? In Figure 3 I have attempted to relate the body temperature ($T_B$) to ambient temperature ($T_A$), with and without the addition of microwave energy. One can see that $T_B$ does not change over a rather broad range of $T_A$, but under specific environmental conditions, such as $T_A$ > 30 °C at high humidity 80 + % SAT, $T_B$ will increase. The imposition of microwave energy produces a curve of the same shape as the environmental heating curve but at a higher level. As an example, assume $T_B$ of 50 °C for 1 hour to be lethal, 39.2 °C for 1 hour to be stressful, then one can calculate the SAR at resonance (70 MHz). In this calculation the humidity and other physical parameters, e.g., air velocity, clothing, and surface temperatures must be included. The SAR values calculated under these conditions are shown on the right side of the graph.

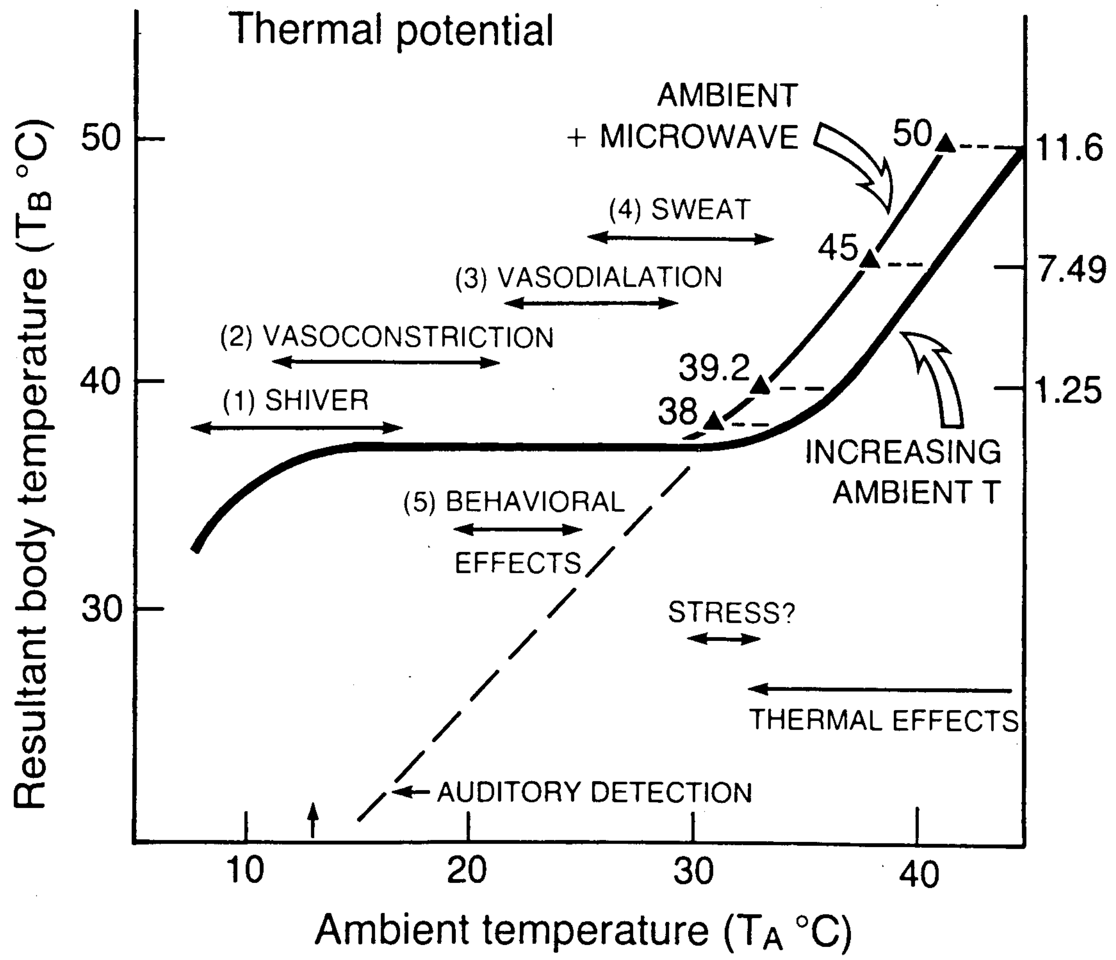


Figure 3. Thermal Potential. This figure compares the Body temperature ($T_B$) to the ambient temperature $T_A$. Included as #1, 2, 3, & 4 are the normal response of the individual to $T_A$. In addition the possible responses to microwave energy absorption including behavior effects, stress, auditory detection and thermal effects are represented These should be related to the right side scale, the calculated SAR values.

Consider the curve from $T_B$ = 39.2 °C to below the level of effective thermoregulation say $T_A$ = 13 °C, I have attempted to indicate a few of the reported changes that occur from microwave absorption. These include stress, behavioral effects, and auditory detection (Fig. 3). Under the conditions suggested for increasing $T_B$ stated above, the absorbed energy responsible for these effects, at least for a 1 hour exposure, would have little thermogenic potential. The question remains, are we at hazard below the level of thermal insult?

Another consideration is the range of response of the individuals in a population to any insult. As an example, what fraction of a human population is at risk from thermal insult? Assume the response to a particular insult follows a normal distribution (Fig. 4), some individuals may be at risk at a temperature $T_x$ (shaded area in Fig. 4). If environmental conditions are in the proper range this fraction may be rather large. Conversely in more normal environmental situations, this fraction may be very small. I believe this fraction is real and should be considered in any future analysis of hazards.

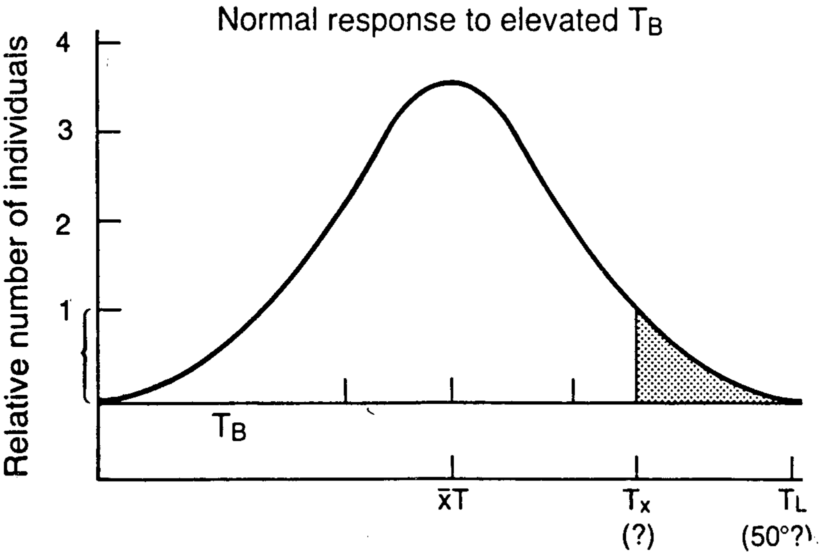


Figure 4. Normal response to elevated $T_B$. Stippled area represents the fraction of a population at risk if $T_B$ exceeds $T_X$, $T_X$ is an arbitrary $T_B$. See text for details

Finally, what are the hazards, if any, below an SAR of 1.25 W/kg? Many workers in the microwave field favor a view that suggests a threshold and a linear response above that level. As a beginning point, I should like to suggest that "effects" of many kinds have been reported below the level of thermal insult and that some of these may increase "stress" in an individual. If "stress" is capable of causing acute or long-term effects, then there are potential hazards below the level of thermal insult.

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# RESEARCH ON NONIONIZING RADIATION: PHYSICAL ASPECTS in EXTRAPOLATING INFRAHUMAN DATA TO MAN

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## ABSTRACT

Extrapolation of research results from infrahuman animals to man presents many difficulties. In addition to species differences in biological parameters, there are formidable dosimetric problems in research involving nonionizing radiation. Many factors that influence coupling of energy are discussed. Specific absorption rate (SAR) is widely accepted as a unit for quantification. The SAR can be easily measured from the temperature rise in tissues exposed briefly to high power electromagnetic fields. The electric field or induced current density in the tissue can be calculated from the SAR data. Measurement of temperature rise is merely a simple method of determining SAR and has no implication as to the mechanism of any biological effects. Several examples of comparative dosimetry are given to illustrate the complexity of energy coupling and to emphasize the importance of quantification in the interspecies extrapolation of data.

## INTRODUCTION

Many experiments that ethically cannot be performed on human beings can be performed on lesser mammals, but the results obtained are not always directly applicable to man; extrapolation of data is fraught with complications. Various biological differences, such as species, age, sex, mass—and even more subtle factors such as pigmentation (Creel, 1980)—must be considered. In research involving nonionizing radiation, not only must one consider differences in biological endpoints, one must also deal with the difficult problem of physical extrapolation. For example, if a behavioral effect in a rat under exposure to a 2450-MHz field at 0.5 mW/cm$^2$ is observed, one cannot conclude that microwave irradiation at the same power density will elicit that behavior in human beings. Unlike the case in ionizing radiation, the same intensity of nonionizing radiation can result in markedly different biological effects in animals of differing species because of variation in the quantities of energy absorbed from electromagnetic (EM) fields.

Some physical aspects of energy coupling in mammalian tissues will be reviewed and a few examples of exposure conditions and dosimetric measurements to illustrate the variability and complexity of energy coupling across the species will be presented. These examples will serve to emphasize the importance of quantification of energy absorption in the extrapolation of laboratory data.

## FACTORS THAT DETERMINE ENERGY COUPLING IN TISSUES

### DIELECTRIC PROPERTIES

EM waves propagate differently in tissue than in air because of the dielectric properties of the tissue, which vary with the water content. In general, tissues can be divided into those with high water content, such as muscle, skin, liver, and kidney, and those with low water content, such as fat and bone. Other tissues that contain intermediate quantities of water, such as brain, lung, and bone marrow, have dielectric properties that lie between those tissues with high and low water content. The dielectric constants and conductivities of tissues vary over a wide range as a function of frequency of the applied EM field. Detailed values of the dielectric properties can be found in Schwan (1957), and in Johnson & Guy (1972).

### TISSUE GEOMETRY AND MASS

Reflection and transmission of EM waves occur at air-fat, fat-muscle, and muscle-bone interfaces. The amount of reflection depends on the impedance mismatch at the boundaries. Thickness of fat, curvature, and dimensions of the body, limbs, and head affect energy coupling to the tissue.

### TISSUE ORIENTATION AND FIELD POLARIZATION

It has been shown, both theoretically (Durney et al., 1978) and experimentally (Gandhi et al., 1977), that the absorption rate of EM energy by an exposed subject is maximal when the long axis of the body is parallel to the vector of the electrical field. For a rat-sized ellipsoidal model exposed to 10 MHz radiofrequency fields, the average rate of energy coupling when the electric-field vector is parallel to the long-axis of the model is about 20 times higher than that occuring when the electric-field vector is perpendicular to the body's long axis. This example illustrates that the rate of energy coupling in a freely moving rat exposed to a field at a constant power density of radiofrequency irradiation will vary about twentyfold depending upon the field-body orientation.

### FIELD FREQUENCY

In addition to the frequency dependence of the dielectric properties of tissue, the reflection (scattering) and the transmission (absorption) of wave energy by tissue also vary with frequency. For example, in an exposed head with a radius of 3 cm, the peak of energy absorption in the frequency range of 100 MHz - 10 GHz varies more than two orders of magnitude (Johnson & Guy, 1972). In another theoretical study, calculations of absorption in exposed ellipsoids showed that absorption increased proportionally with the square of frequency, reaching a maximum at whole-body resonance. At resonance the length of the long axis is approximately four-tenths of the wavelength in air (Durney et al., 1978).

### SOURCE CONFIGURATION

The configuration of a source of EM waves is irrelevant in the far field (field at a distance which is greater than $2D^2/\lambda$ from the radiating source, where D is the size of the aperature and λ is the wavelength in air) i.e, the field pattern is independent of the EM source. But in the near field, coupling of energy to a body is strongly dependent upon the shape and size of the source, since the electromagnetic field patterns in this region are determined by it.

## EXPOSURE CONDITIONS

The quantity of energy absorbed by the body is dependent upon whether that body is exposed in free space, on a ground plane, near metal reflectors, in a cavity, or in a waveguide.

## TIME-INTENSITY FACTORS IN EXPOSURE TO EM FIELDS

The intensity of an incident field and the duration of exposure are important parameters that determine the quantity of energy absorbed by tissues. When the intensity of the exposure is modulated in time, the rate of energy absorption is also amplitude modulated in the time domain.

## A UNIT FOR COMPARISON

Since coupling of energy to tissues is a complex function of many different variables, the intensity of an incident field (e.g., in units of $mW/cm^2$ or V/m) provides the investigator little insight into thresholds unless the other variables are known. Therefore, it is impossible to extrapolate the meaning of results from research on laboratory animals in predicting thresholds of human beings based solely on the power density or strength of the incident EM field.

A basic physical law (that of Grothus-Draper) is that a physical agent cannot have a physical effect if it is not imparted to a body. Consequently, the question arises as to the most suitable parameter(s) for the quantification of the interaction of EM fields with biological systems. Wacker & Bowman (1971) suggested the use of the square of the electric field or of energy density in a volume of tissues for quantification. Schwan (1971) proposed the use of induced current density in tissue. A simpler alternative is to use the strength of the electric field in the tissues. Yet another alternative is the mass-normalized rate of energy absorption, the dose rate, which was introduced into microwave research in the late 1960's (Justesen & King, 1970; Justesen, 1975). Many investigators now rely on the dose rate as a measure, which has also been termed "absorbed power density" (Johnson & Guy, 1972) and now is officially referred to as the Specific Absorption Rate (SAR) by the National Council of Radiation Protection and Measurements (NCRP, 1981). Technically, it makes no difference which of the above parameters is chosen, as they are all related by simple equations:

$$SAR = \frac{1}{10^3} \frac{\sigma}{\rho} E^2 \, W/kg \tag{1}$$

$$E = \left[ \frac{\rho \times 10^3}{\sigma} SAR \right]^{\frac{1}{2}} \, V/m \tag{2}$$

$$j = \left[ \sigma \rho x 10^3 SAR \right]^{\frac{1}{2}} A/m^2 \tag{3}$$

where E is the electric field, j is the current density, ρ is tissue density in $g/cm^3$, and σ is the conductivity of tissue in S/m. What is essential is the quantification of EM fields in the exposed tissues. The SAR has been widely adopted as a unit of quantification by researchers studying the biological effects of EM fields. The American National Standards Institute (ANSI, 1982) recently revised the 1974, frequency-independent 10-$mW/cm^2$ safety standard to a frequency-dependent standard by which limits on power densities vary from 1 to 100 $mW/cm^2$. The steps taken by the ANSI C95.4 subcommittee were:

(1) to determine whole-body SAR levels in which acute adverse biological effects occur in animals. It was consentually agreed, after an intensive review of the literature, that the threshold level of harm—as determined by behavioral testing—lies near 4 W/kg. This literature review included subjects ranging from quail embroys to primates and EM frequencies ranging from 0.147 to 9.6 GHz;

(2) to apply a safety factor of 10 for human beings (i.e., 0.4 W/kg);

(3) to determine the theoretical "worst case" power density of incident radiation that would result in a whole-body SAR in humans of 0.4 W/kg;

(4) to present the resulting, frequency-dependent guide on limits of exposure.

Figure 1 graphically portrays the 1982 ANSI frequency-dependent safety standard for human beings at frequencies from 300 kHz to 100 GHz. It should be interesting to point out to psychologists that the ANSI (1982) standard states "the most sensitive measures of biological effects were found to be based on behavior."

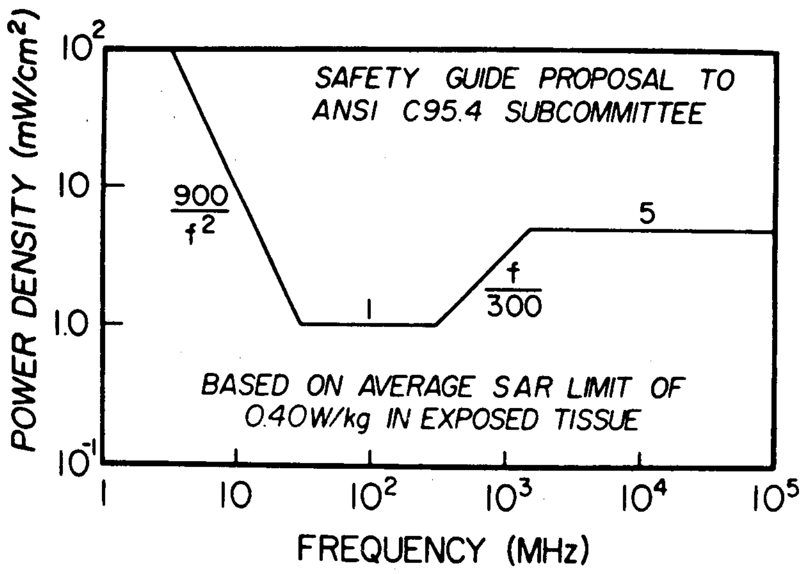



Figure 1. ANSI 1982 safety standard for electromagnetic radiation.

## MEASUREMENT OF SAR

The SAR can be easily measured from the temperature rise in tissues caused by a short exposure to high power EM fields. The equation for the SAR calculation is:

$$SAR \cong \frac{4186\, c\Delta T}{t} \tag{4}$$

where c, in kcal/kg °C, is the specific heat of the tissues under study, 4186 is the kilo-calorie-to-joules conversion factor, ΔT in °K or °C is the increment in temperature, and t the exposure duration in seconds. The symbol of approximation over the equal sign of the equation implies that accuracy is based on negligible loss of thermal energy by the irradiated body. Irradiation at a high power level (> 100 $mW/cm^2$) and for a short time (< 1 min.) exposures are necessary to accurately quantify the maximal short-term increase in temperature to preclude dissipation of thermal energy. The lower SARs used in most animal studies can be linearly extrapolated from the SAR measured at high power levels. For example, we measured a whole-body SAR in a rat of 60 W/kg exposed at 300 $mW/cm^2$. For a 0.5 $mW/cm^2$ exposure level used in a low-level study, the SAR in the rats was extrapolated to be (60/300) x 0.5 = 0.1 W/kg.

Several microwave-transparent temperature probes are commercially available for single-point measurements in a biological body (Bowman, 1976; Rozzell et al., 1975; Wickersheim & Alves, 1979). Because of the inhomogeneous energy deposition in a body (the electrical "hot spot" phenomenon which can yield thermal hot spots), multiple probing is necessary in quantifying distributive SARs. The BSD-1000 hyperthermia machine uses eight probes and is an example of a system that can be used to determine SARs at multiple points. Also, Guy (1971) developed a thermographic technique for rapid measurement of the SAR on an internal plane of the cadaver of a mammal by a bisection process. The accuracy of this technique depends on the size of the animal, since heat loss between the time of exposure and taking of thermograms becomes relatively large for smaller animals. The whole-body-averaged SAR in animals can be determined by twin-well calorimetry (Phillips et al., 1975; Blackman & Black, 1977; Allen & Hunt, 1979). Two animals of similar body weight were killed and kept at the same temperature, then one of the animals was exposed to microwaves. Immediately after exposure, the two carcasses were placed in the twin-well calorimeter. The averaged SAR in the exposed animal can be calculated from the differential heat of the two animals. In contrast to the thermographic technique, twin-well calorimetry is a better method for smaller animals; the long heat diffusion time for larger animals creates problems in twin-well calorimetry because the larger subject animals lose heat so slowly that the measurement time can take several days to reach equilibrium. During this time, decomposition generates additional heat which introduces errors in SAR measurement.

Mistakes have often been made by investigators attempting to measure SARs in subjects exposed at low power-density levels, exposed over a long period of time, or both. Loss of thermal energy via blood flow and thermal diffusion will occur at low power levels; then the measured changes of temperature are low and do not reflect the actual energy deposition.

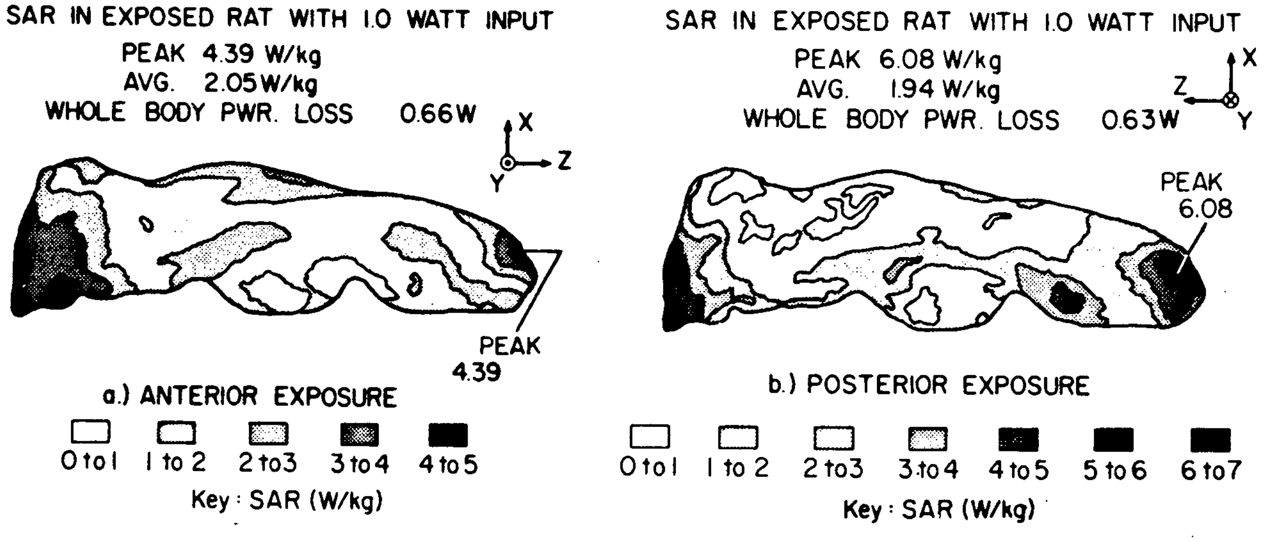
There is a misconception in some quarters about the validity of using the SAR in biological effects research involving both thermal and athermal ("field specific") effects. That is, since the SAR can be indexed by $\Delta T$, some investigators confuse measurement with mechanism. It should be emphasized that temperature measurement is not required in measuring the SAR. The SAR can also be determined by measures of the electrical field in a subject during exposure (to a weak or an intense incident field) by an electric-field probe. Measurement of $\Delta T$ resulting from a brief exposure to an intense field is merely a simple method of determining SAR, but has no implications as to mechanism of a field-body interaction.

## EXAMPLES OF INFRAHUMAN AND HUMAN EXPOSURE CONDITIONS AND ASSOCIATED DOSIMETRY

In this section, examples of the SAR distribution patterns that result from exposure of infrahuman cadavers and human models are presented to illustrate the distributive complexity of EM energy absorption by biological tissues.

### RATS EXPOSED IN A CIRCULARLY POLARIZED WAVEGUIDE

Figure 2 shows the SAR patterns in a 324-g rat exposed to the 2450-MHz, circularly polarized field of a waveguide (Guy et al., 1979). The upper pattern is for anterior exposure and the lower pattern is for posterior exposure. The patterns are different for different exposure orientations of the animal in the waveguide.

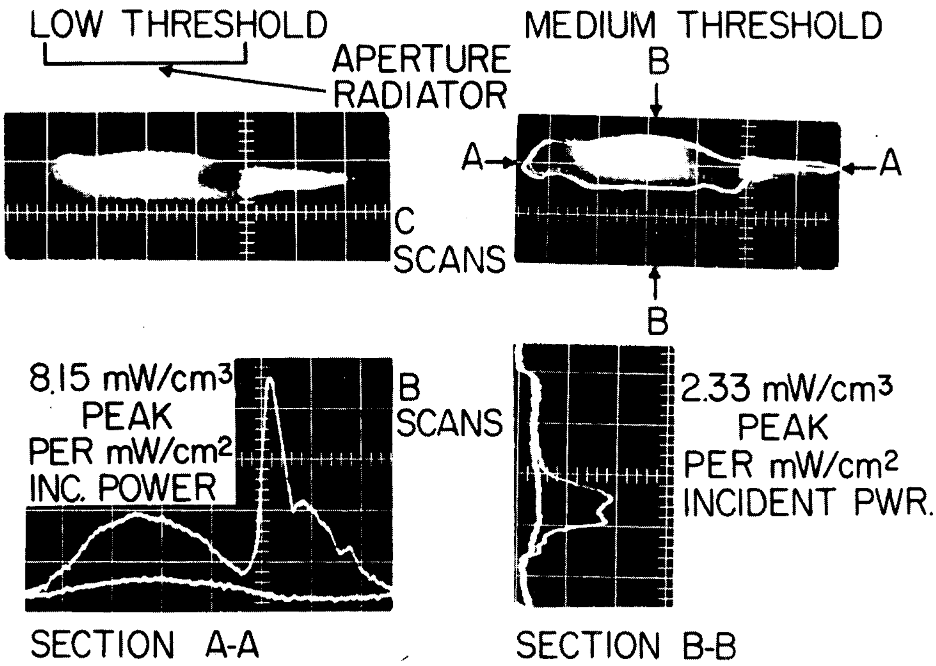



(2a) (2b)

Figure 2. SAR patterns in a 324 g rat exposed in a 2450 MHz circularly polarized waveguide

## RAT EXPOSED IN NEAR FIELD

Figure 3 shows the thermograms resulting from the dorsal exposure of a rat by a 13 x 13 cm 918-MHz applicator with the E-field-vector parallel to the body of the animal (Guy et al., 1978). The single A-A' scan reveals a high SAR at the base of the rat's tail. Although this exposure was used in a study of how microwave irradiation affected the behavior of a rat which performed on a fixed ratio schedule of reinforcement, the SAR in the head was quite small compared with that of the rest of the body.




RAT EXPOSED TO 918 MHz RADIATION

## BIRD EXPOSED TO FAR-FIELD MICROWAVES

Thermograms of the body surface were taken immediately after pigeon cadavers were exposed to microwave radiation. The feathers were plucked beforehand so they would not block infrared radiation by the body. Since feathers absorb very little energy, the change should have a negligible effect on the results. Figure 4 shows data based on the pigeon in a flying posture. Hot spots were observed in the neck and the wings, especially on wing tips where electric fields were nearly parallel.

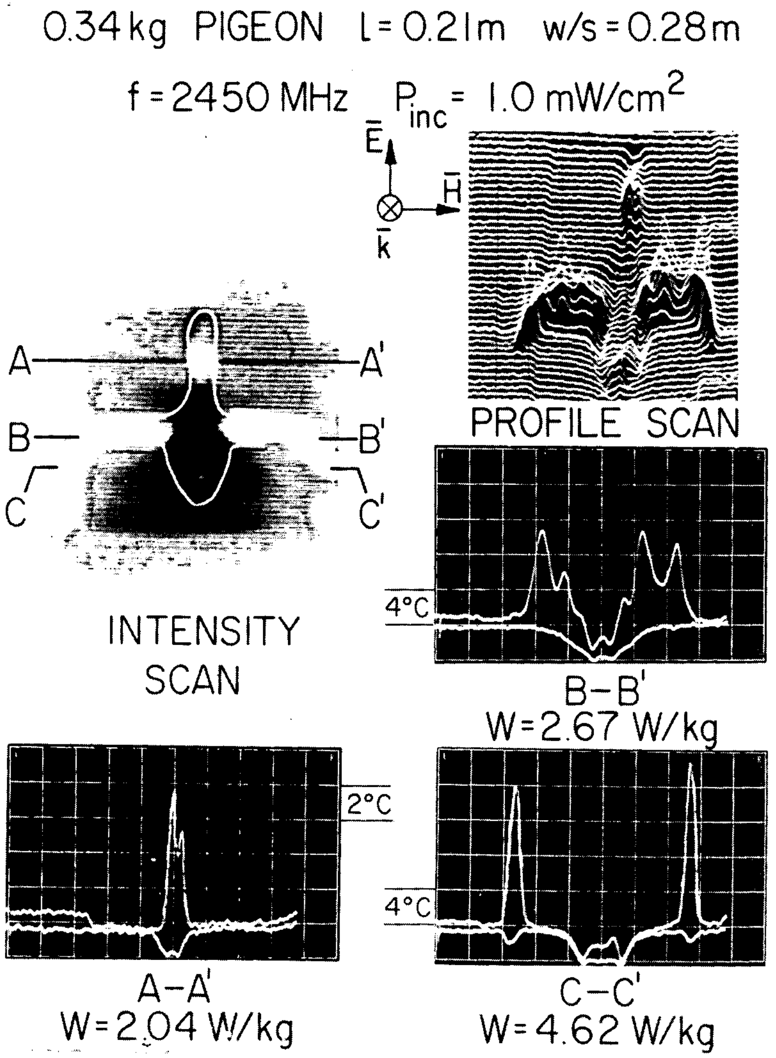
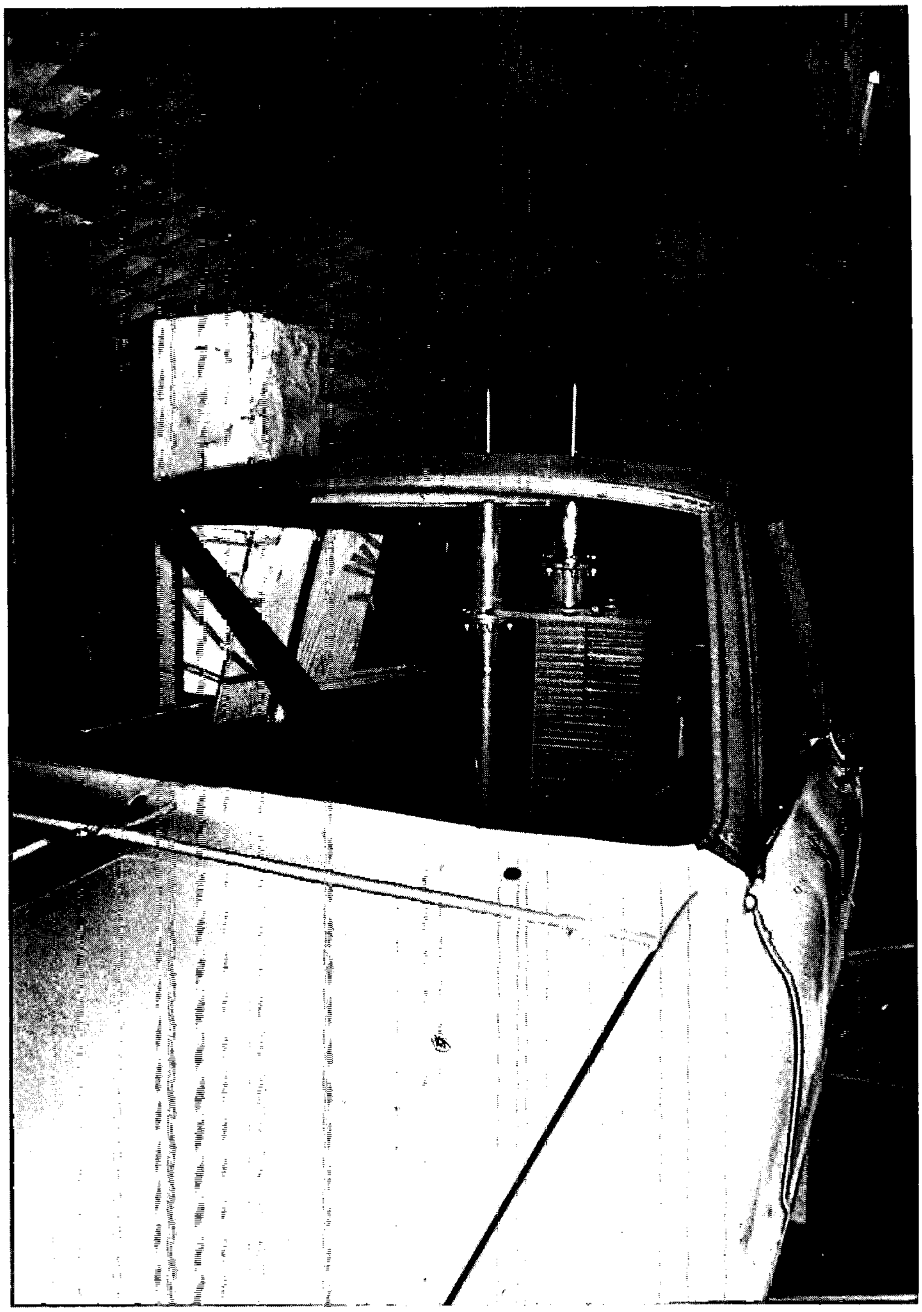



Figure 4. Surface thermograms of a plucked dead pigeon in flying posture exposed dorsally to 2450 MHz plane wave.

## FULL-SIZED HUMAN MODELS EXPOSED IN THE NEAR FIELD OF A UHF MOBILE ANTENNA

Full-sized human models were filled with high water-content, tissue-simulation material and were exposed to a 835-MHz (mobile-antenna) field (Fig. 5). The modified high-power antenna has the same radiation pattern as the Bell Laboratories' low power mobile antenna but safely handles the 10-kW CW input power. Figures 6 and 7 show the respective SAR patterns in a woman model (sagittal plane) and in a child model (horizontal plane at the eye level).



Figures 5. Photograph shows half of a full-sized woman model exposed to high power (10 kW) mobile antenna fields in an anechoic chamber for the quantification of energy absorption.

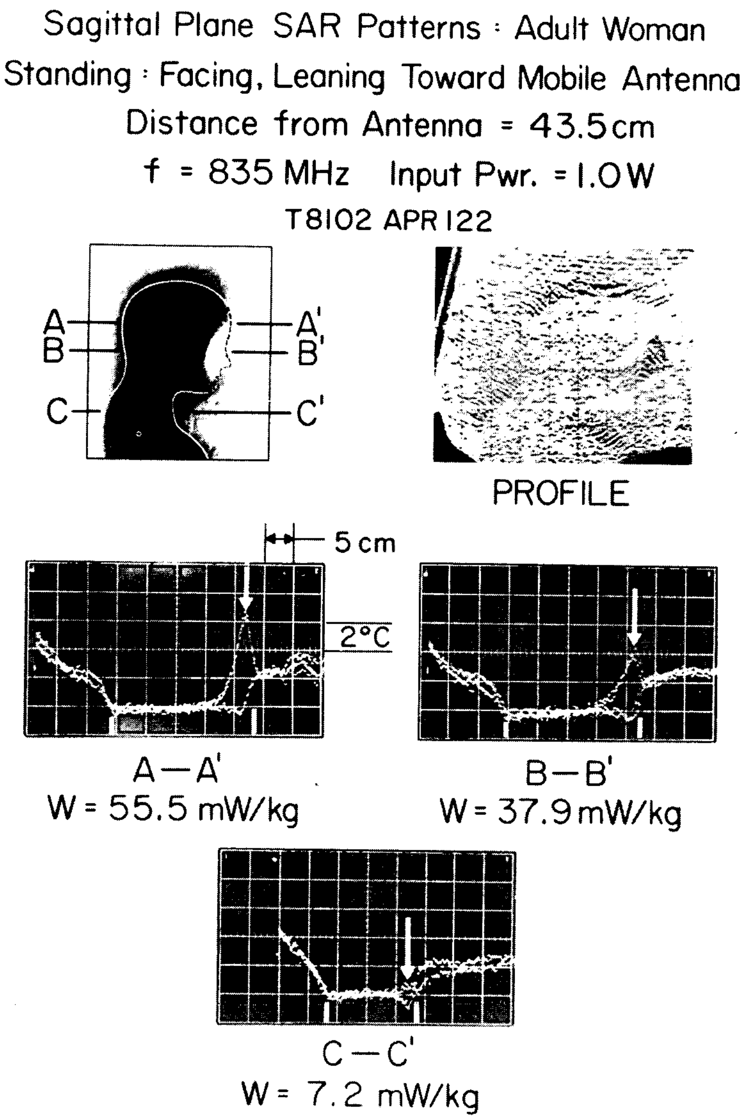



**Figure 6.** Sagittal plane SAR pattern in a woman model exposed to 835 MHz UHF fields from a mobile antenna at 43.5 cm away, normalized to 1 watt output power.

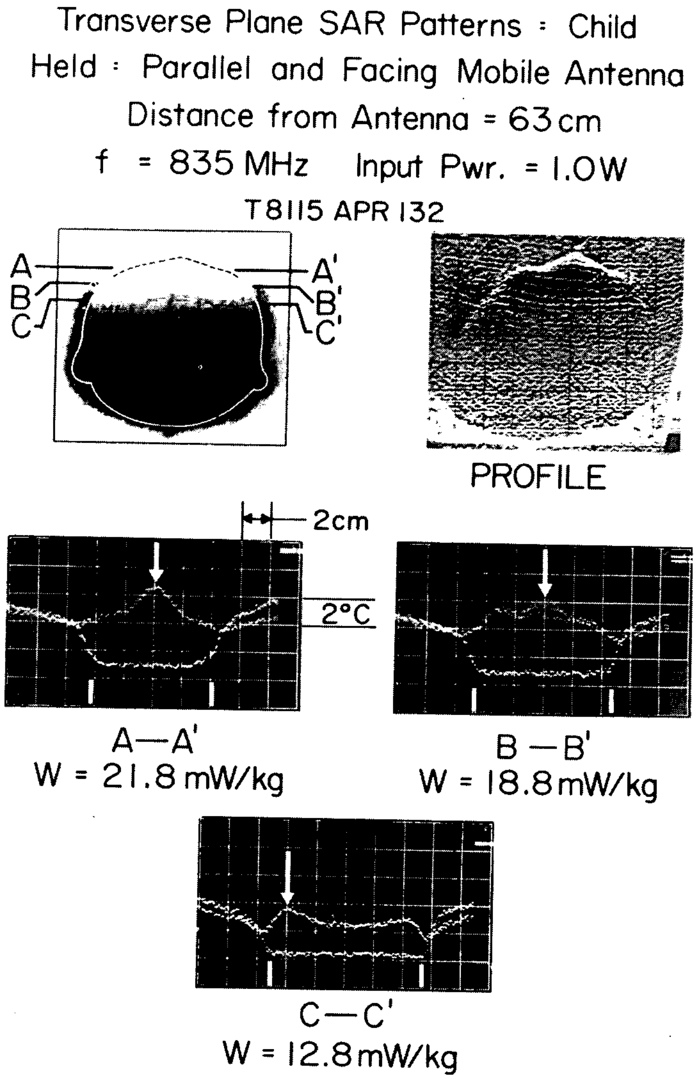



**Figure 7.** Horizontal plane SAR pattern at the eye level of a child model exposed to 835 MHz UHF fields from a mobile antenna at 63 cm away, normalized to 1 watt output power.

## SCALED MAN MODEL EXPOSED IN THE FAR FIELD

A reduced-scale Styrofoam hollow-man model (scale factor = 5.44) was filled with material of appropriately scaled electrical conductivity and then was exposed in an anechoic chamber to 2450-MHz fields to simulate exposure of a full-sized man to a 442-MHz field (Fig. 8). The thermographic results for the E polarization (E vector parallel to the body's long axis) are shown in Figure 9. The SAR patterns changed when the man model was exposed under different polarizations. For example, the high SAR in the neck region, as shown in Figure 9 for the E polarization, does not exist in the H polarization (where the H vector paralleled the body axis). The high SAR occurs in the groin area of man exposed to H polarization fields.

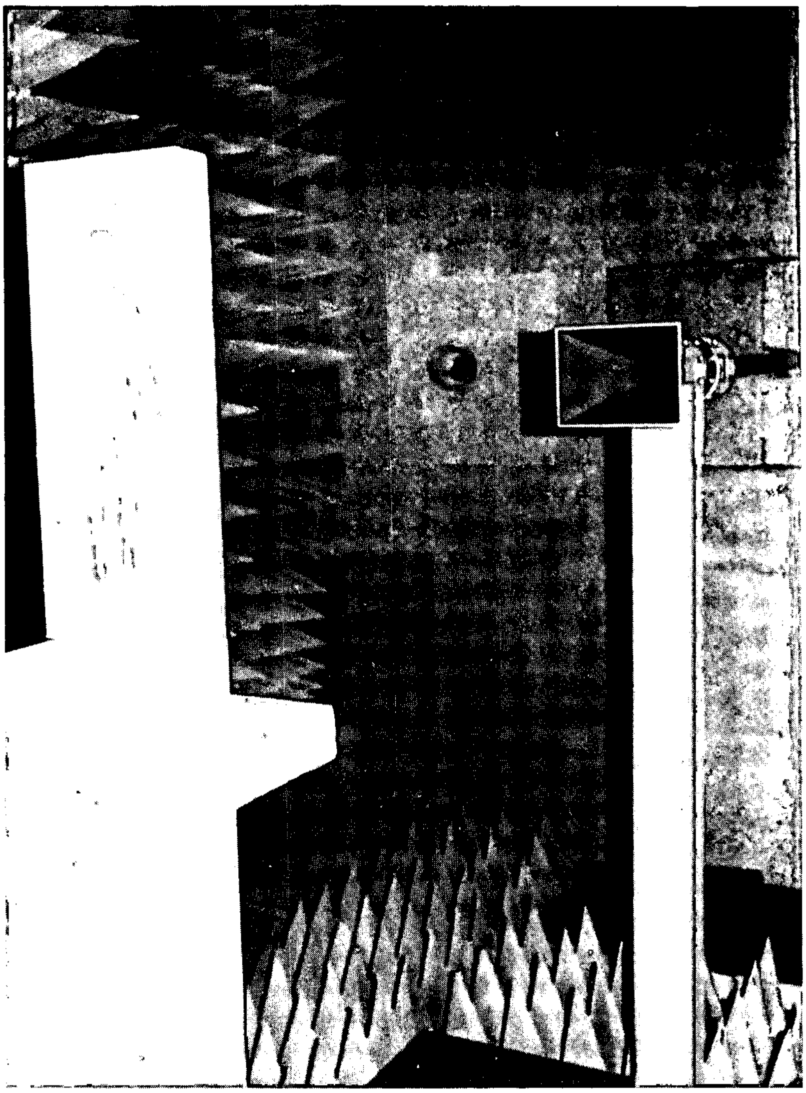


Figure 8. Scaled man model exposed in free space to 2450 MHz electromagnetic fields for the simulation of full-sized man exposed to 442 MHz.

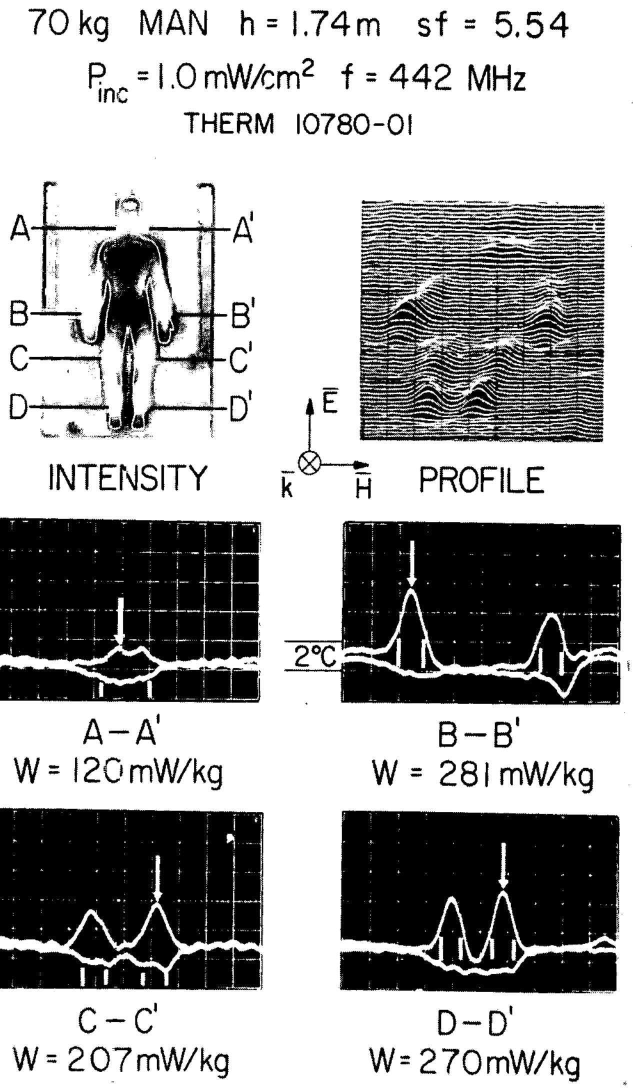



Figure 9. Thermographic results of a man exposed to 442 MHz electromagnetic fields, normalized to 1 mW/cm² power density (taken from the exposure of the model shown in Figure 8).

## DISCUSSION

Most research on infrahuman animals has the ultimate goal of applying the results for the benefit of human beings. Therefore, when effects are observed in animals, it should be discerned whether the effects can occur in exposed humans and, if so, under what conditions of exposure. Without quantification of the action of EM fields on biological tissues, it would be impossible to extrapolate the results to predict safe exposure levels for human beings. The SAR is now widely accepted by researchers in this field as a common unit for comparing and for extrapolating laboratory results in prediction of safe exposure levels for human beings. The techniques for measuring SARs are complicated and still primitive. Although whole-body-averaged SARs provide a first step in quantification, distributive SARs are also needed to make meaningful comparisons across species. For example, the SAR in the brain and spinal cord might be more appropriate than the whole-body SAR in determination of thresholds and mechanisms of combined microwave-and-drug effects on behavior.

Concerning the modulation characteristics of the applied EM waves, the SAR should also be modified to reflect the time-varying nature of the field. For example, the hearing of microwaves can occur to a single pulse (Chou et al., 1982). It is improper to quantify the effect by SAR as averaged over time. Instead, specific absorption (SA, the product of SAR and exposure time) for each pulse is more suitable for quantification. Another example of modulation is the effect of microwave exposure on $Ca^{++}$efflux (Bawin et al., 1975). This effect occurs only when the EM field is modulated, especially at 16 Hz. In this case a time-varying element of 16 Hz should also be specified.

The extrapolation of exposure time from animals to humans is not trivial. Tyazhelova & Tyazhelov (1980) presented equivalent intensities for different mammals. The basis for their calculation was to assume that the total energy absorbed in the lifetime of mammals is equal. This approach was used by Tyazhelova & Akoev (1975) for ionizing radiation. This approach requires that the effects be cummulative. However, there has been no evidence that nonionizing radiation is cummulative. Therefore, it is not appropriate to use this approach. Extrapolation of time requires the knowledge of mechanism of the effects. For example, the hearing effect mentioned above is shown to be caused by thermoelastic expansion for microwave pulses less than 50 µs. The same exposure time can cause auditory perception (different pitch) in both rats and humans, although the threshold intensity can be different. The SAR does not imply any mechanism of effect, therefore the questions on thermal time constant, animal response time, and scaling of a thermal effects are irrelevant. The general questions about using animal research to extrapolate to humans of different life span are discussed in a book by the National Research Council (1981).

There are several questions which should be discussed by the bioelectromagnetics community:

1. In the next revision of the ANSI standard, should local SAR be considered as the basis for extrapolation instead of whole-body SAR?

2. Should exposure methods be standardized so that the results of different researchers are easier to compare?

3. Should the SAR distribution for standard exposure conditions be documented so that other researchers do not have to repeat complicated dosimetric measurements?

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# MICROWAVE RADIATION DOSIMETRY: AREAS of RELATIVE CERTAINTY and UNCERTAINTY

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## INTRODUCTION

For biobehavioral experiments, the importance of proper knowledge of dosimetry cannot be overstressed for without this it would be similar to working with drugs research without knowing the amount of drug administered to the subject. That electromagnetic fields of a prescribed power density at a given frequency do not tell much about their biological efficacy is best illustrated by an example from Schrot & Hawkins' work (1977) on times to lethality of rats and mice at several frequencies for different polarizations of incident waves. Mice oriented along the electric field ($\vec{E}\|\hat{L}$) convulsed in an average time of 9 minutes for an irradiation power density of 150 mW/cm$^2$ at 985 MHz, while similar animals oriented along the microwave magnetic field ($\vec{H}\|\hat{L}$) lived through an observation time of 60 minutes without undue stress. For comparable convulsion times, power densities differing by 30:1 or more are not uncommon, and fairly small incident power densities may be considerably enhanced in their potency by the presence of reflecting surfaces (Gandhi et al., 1977), ground effects, and other animals nearby (Gandhi et al., 1979). Experiments in our laboratory (Gandhi et al. 1979) with six small-animal species, from 25-g mice to 2245-g rabbits, have shown mass-normalized specific absorption rates (SAR's) that vary from 1.85 to 67 mW/g (almost 37:1) for free-space 25 mW/cm$^2$, 2450 MHz, $\vec{E}\|\hat{L}$ irradiation. Including reflector, ground, and multi-animal effects, this spread in SAR's is likely to increase even further. In this paper we summarize the status of knowledge in the area of microwave radiation dosimetry particularly as it pertains to the laboratory animals. The knowledge about whole-body absorbed dose is on a relatively firm footing. Unfortunately, the same cannot be said about the distribution of absorbed energy (distributive dosimetry) where the knowledge is in a fairly primitive stage. We will also outline some of the reasons for lack of progress in the area of distributive dosimetry.

## AREAS OF RELATIVE CERTAINTY

A couple of excellent review articles are listed in the Bibliography (Gandhi, 1980; Durney, 1980). The whole-body absorbed dose is known for different exposure conditions for:

a. far-field irradiation conditions ($\vec{E}\perp\vec{H}\perp\vec{k}$) (Durney et al., 1978).

   where $\vec{E}$ and $\vec{H}$ are the electric- and magnetic-field vectors and $\vec{k}$ is the direction of propagation. For far-field irradiation conditions, generally valid for distances larger than 2 $D^2/\lambda$ where D is the maximum dimension of the radiating aperture and $\lambda$ is the free-space wavelength, the directions of the three vectors are perpendicular to one another.

b. different frequencies and polarizations of irradiation (Durney et al., 1978).

c. isolated animals and, to a lesser extent, for *regularly spaced* multiple animals.

It is generally true that even for far-field irradiation conditions, the whole-body-averaged SAR's are known for isolated animals or for animals that are separated from one another by two or more wavelengths.

d. near-field irradiation conditions with negligible coupling back to the source (Chatterjee et al., 1980).

e. near-field irradiation from simple dipole antennas (Karimullah et al., 1980; Durney et al., 1980).

The exposure fields are fairly complicated for regions in close proximity to the radiating sources, for distances less than 2 $D^2/\lambda$ or in the so-called near-field regions. For near-field regions the spatial variation of fields, both magnitude and phase, is very large and the various vectors are not directed perpendicular to one another.

In some near-field environments, the sources are tightly coupled to the subject, in which case the incident field itself is altered by the presence of the subject. In such cases the absorbed dose is difficult to calculate, being highly specific to the entire situation—the nature and location of the source and posture of the subject relative to it. Calculations for these cases have been made for simple monopole and dipole antennas (Karimullah et al., 1980; Durney et al., 1980). For a majority of situations, particularly those involving leakage fields, coupling back to the source may be neglected. A higher degree of generalization has been obtained for such near-field exposure conditions (Chatterjee et al., 1980; 1982).

From the foregoing it is clear that the absorbed dose is a sensitive function of irradiation frequency and exposure conditions. Even for a given irradiation condition, the absorbed dose is highly dependent on the body size and posture (such as is encountered with laboratory animals). In spite of these complexities, certain general conclusions have been drawn. These include:

a. Whole-body resonance frequency (Gandhi, 1980; Durney, 1980).Maximum absorption occurs for $\vec{E}\|\hat{L}$ far-field irradiation for frequencies such that the length (L) of the animal is on the order of 0.4λ or distributive dosimetry. Some of the reasons for less progress in this area are:

b. Absorption cross section at resonance (Gandhi, 1980). The absorption (electrical) cross section is larger than the physical cross section by factors of 2 to 5.

c. For a frequency (f), below-resonance, the absorption reduces as $f^2$ while post-resonance, whole-body absorption reduces as 1/f.

d. Near-field/far-field equivalence criteria have been developed for leakage-type near-fields (Chatterjee et al., 1982).

## AREAS OF LESS KNOWLEDGE

As previously mentioned an area of less knowledge is the distribution of absorbed dose or distributive dosimetry. Some of the reasons for less progress in this area are:

1. The dose distributions are highly variable with the irradiation conditions, body size, and posture; variable to a much larger extent than even the whole-body dose.

2. Experimental determination is tedious for all the conditions that one might encounter.

For experimental dosimetry, Guy (1971) has developed a thermographic camera to determine the temperature distribution for a given plane or over a given surface of the body as a result to exposure to far- or near-field type electromagnetic fields. Though primarily qualitative, the method offers the advantage of rapidly identifying regions of high SAR's. In living systems, the presence of blood flow, however, is likely to smear the so-called electrical hot spots. Thermal hot spots are therefore not necessarily apt to occur at these locations.

D'Andrea and colleagues (1983) have also done some work in this area with rats. They have used the semiconductor-sensor, fiberoptic, temperature probe (Insight Instruments Model TP-4) for temperature elevation measurements in the various parts of the body during irradiation.

3. The calculations use shaped, inhomogeneous block models which are expensive to run computationally. With the moment methods (Chen & Guru, 1977; Hagmann et al., 1979) that have been used, one solves for the unknown $\vec{E}$-fields (three components, magnitude and phase) in the N cells by solving a large set (3N x 3N complex) of simultaneous equations, which is quite time-consuming even with reasonably large computers. Three-dimensional, inhomogeneous models with 160-200 cells have typically been used for a man model as well as for a model of a rat (Hagmann et al., 1981; D'Andrea et al., 1981). With some ingenuity and considerable computation effort we have recently extended the moment method to man models with 626 to 1132 cells (DeFord et al., 1983) which, because of the larger body size, have also been found to be inadequate for a proper representation of the body (cell size to wavelength is still quite large and should preferably be on the order of 0.1 or less). We obviously need numerically efficient (therefore less costly procedures for accurate distributive dosimetry. Two numerical approaches that hold the most promise are the time-domain finite-difference method (Taflove, 1980) and a new method based on fast-Fourier-transform recently developed in our laboratory (Borup & Gandhi, 1983). The development of finely discretized, inhomogeneous, experimentally verified models is obviously of a great deal of interest for it would then be possible to obtain distribution of absorbed dose for the man models for the crucial regions such as the eyes, gonads, CNS, and so forth, and for rat models the distributions that will allow experimenters to focus on exposure conditions where the depositions are maximum in the critical organs.

## CONCLUDING REMARKS

Even though a great deal of much-needed progress has been made in the field of microwave-radiation dosimetry, most of it pertains to the quantification of whole-body-averaged SAR's at various frequencies and for different orientations of the animal relative to the incident fields. Distribution of absorbed energy is likely to be important for biobehavioral endpoints and yet there is little knowledge either experimental or theoretical that prescribes irradiation conditions where the SAR's are maximum in the critical organs of the exposed animals. It is true that distributive dosimetry by its nature is highly variable with every slight movement of the animal—a great deal more should nevertheless be done here to allow experimenters to focus on conditions of maximum absorption in the critical organs for study of the biological effects. The development of finely discretized, inhomogeneous, experimentally verified models for distributive dosimetry is therefore of great interest. Also needed are the inhomogeneous thermal models which will translate the absorption dose distributions into temperature increases for the various parts of the body.

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# COMPATIBILITY of BEHAVIORAL RESEARCH TECHNIQUES with MICROWAVE IRRADIATION: SOME INSTRUMENTATION-RELATED PROBLEMS that IMPEDE CREATIVITY

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## INTRODUCTION

The recent evolution of our area of endeavor into a recognized scientific society, the Bioelectromagnetics Society, has formed permanent relationships among microwave engineers and research psychologists. These relationships are necessary because research using microwave irradiation is hardware intensive and forever will be. Good behavioral research in this area can only come of close interactions between the psychologist who sets the behavioral objectives and the engineer who produces an irradiation system that will achieve those objectives. In a few instances, we see evidence that the psychologist and engineer are a single individual and as such have produced high-quality behavioral research results. This report will focus on typical instances where the state-of-art technology in electromagnetic (EM) and EM-compatible instrumentation fail to produce an experimental system that meets all of the research objectives. Also to be presented, consistent with the theme of "future directions for research," are several suggestions for alleviating some of the restrictions placed on the kinds of experiments that can be conducted with microwave (or radio wave) irradiation.

## INSTRUMENTATION-RELATED PROBLEMS IN BEHAVIORAL BIOEFFECTS RESEARCH

Inspection of the behavioral research results presented at the annual meetings of the Bioelectromagnetic Society held thus far show a wide spectrum of experimental configurations. Many types of animal subjects have been used, but the rat is the most common. There is no typical experiment within this category of research, but a common feature is the use of some form of directed ELF, radio wave, or microwave energy to which the animal behaviorally reacts according to the various contingencies arranged by the investigator. Technical problems are usually encountered in making the irradiation system compatible with the behavioral contingencies, and several of those problems will be discussed in this section. The brief list of problem areas is meant to be only a representative sample rather than a comprehensive summary.

Central to nearly every study is a determination of the absorption or the rate of absorption of EM energy (SAR) in the subjects (1). In earlier years, a simple measurement of the incident intensity of irradiation in the absence of the animal was all that was usually given, but much more sophistication is required today in the dosimetric analysis of bioeffects research. Unfortunately, reliable SAR data is not easy to obtain and cannot be measured with a simple probe and meter since SAR is related to actual tissue absorption. How much more simple it would be if the behavioral psychologist could obtain dose rate information from straightforward meter measurements rather than the tedious calorimetric, thermometric, or approximate techniques required today.

Compounding the difficulty in SAR determination is animal movement during irradiation. Behavioral experiments often use animal movement or generalized motor activity as a dependent variable. It is well known that changes in orientation of the animal have profound effects on SAR (2); thus, irradiation experiments that produce large and frequent movements of the subjects substantially increase the difficulty of accurate SAR determination. This represents an example of when a creative experiment involving many locations or postures of an animal within a particular irradiation system could not be conducted because of the difficulty in describing the temporal absorption of the subjects. Without the important dosimetric information, no dose-response or threshold information (in terms of SAR) could be obtained.

Another problem is perturbation of the incident irradiation by the required experimental apparatus. Behavioral research often used certain direct electrical connections to animals to monitor neural activity, motor activity, or physiological parameters. Here again, those studying EM-induced effects are encumbered by the fact that metal wires cause great perturbations in the localized irradiation parameters such that wires, in general, cannot be connected to animal subjects during irradiation (3). A researcher, therefore, wanting to monitor an animal's EEG, ECG, and behavior parameters such as simple task performance or response rate during microwave irradiation would be stymied by this present incompatibility, and many creative experiments cannot be conducted. Some success has been reported with the use of conductive, nonmetallic electrodes, in the place of ordinary wire (4), but the success is of limited value, because the high-resistance conductors are not always compatible with the available electronic instrumentation and because the high-resistance conductors tend to be very noisy during animal movement, usually the result of A-C line interference (5).

Other, less serious, problems hamper the simple implementation of behavioral techniques in microwave experiments. These include multiple subjects in close proximity to each other (6), the noise and vibration produced by powerful microwave and radio wave generators and amplifiers, and so forth. These latter types of problems are usually solved through the application of good engineering principles and close attention to small details.

## SUGGESTED AVENUES TO OVERCOME INSTRUMENTATION-RELATED PROBLEMS

Solutions to the types of problems listed in the previous section can be subdivided into several categories according to how the solutions might be produced. First, some solutions will be obtained through normal progress in electronic technology in general, such as miniaturization, new materials, etc. Second, I consider it highly probable that some solutions will be attained through an interactive process between commercial suppliers and an organized body of behavioral researchers in bioelectromagnetics. Third, this body of behavioral researchers in bioelectromagnetics could, by itself and in the process of appropriate evolution, produce solutions to some of these problems.

To examine these avenues of solutions, first consider how future advances in technology might produce an easy-to-use SAR meter. I envision a small, computer controlled device with a sensor to acquire a sample of the incident microwave or radiowave field intensity at all of the locations to be occupied by the animal. Information on species-specific parameters such as size and weight would be keyed into the device along with information as to frequency and posture and/or polarization of the animal with respect to the incident irradiation. An internal program would use the various input parameters along with a stored data base of up-to-date dosimetric information to yield SAR directly. A simple device, based on a single sample of the internal field intensity is being developed now. Consider next how technological advances can help solve problems of field perturbation by apparatus. The optical cables now employed in our area to telemeter rather slow signals as a field strength and temperature information from irradiated regions (7-9) someday will be able to transmit other types of data such as EEG, ECG, and heart rate. Tiny (and perhaps absorber-coated) transducers on the bodies of irradiated animals will be used with the optical cables such that virtually any kind of monitoring will be possible without the use of metal wires.

For the second source of solutions, consider how instrumentation-related problems might be solved by an interactive process between commercial suppliers and an organized body of behavioral researchers in bioelectromagnetics. I feel that an active cooperation between these groups is highly desirable for two principal reasons. First, the area of bioelectromagnetics research is relatively young and the present market for microwave-compatible instruments is small. There is therefore no established interest in this area by the commercial suppliers. Second, microwave materials technology and microwave instrumentation capability have been and are rapidly developing areas. Possible application of some new microwave product to behavioral research might be overlooked because the product was originally developed as a part of an advanced weapon system or satellite system. Without cooperation and interaction, technology innovations in microwave apparatus and materials cannot be utilized by the behavioral researchers in bioelectromagnetics. The specific type of future cooperation or the benefits in terms of products to be expected is highly speculative, but past developments of specific pieces of equipment can provide a useful history. Two examples of such apparatus are pertinent.

The first devices are the miniature implantable field probes first proposed by the Center for Devices and Radiological Health (formerly the Bureau of Radiological Health) (7,10). I have followed this development and, at various times, have attempted to procure the probes with only a fair amount of success. The development of these probes has been hindered by the lack of a widely accepted specification generated by a consensus of the potential users of the devices such that even medium-scale commercial production could not be initiated. The second example of specially designed bioeffects apparatus is the circularly polarized waveguide irradiation system developed (and produced in some quantity) in the laboratory of Dr. Guy and coworkers at the University of Washington (11,12). The specifications of these systems were published along with detailed dosimetric analyses of a rat subject. As a result, the circularly polarized waveguide system has seemed to become the system of choice for several experiments currently underway using devices actually built by Guy and his colleagues or patterned after principles of his original design. Much can be said in favor of this method of proposing or introducing specialized apparatus for bioeffects research. It would appear that many obstacles to behavioral bioeffects research related to apparatus could be overcome through a process similar to that just described.

As a third avenue of solutions to these problems, consider how an organized body of researchers in behavioral bioelectromagnetics could, of itself, produce solutions. Suppose such a body would actively pursue reduction of the instrumentation-related barriers to bioelectromagnetic research by actively interacting with materials specialists, microwave device suppliers, and instrument makers. Suppose further such a body would regularly meet in an open forum to identify significant areas needing more attention or to cite other areas needing replication of results or perhaps not needing so much attention. Such increased communication among researchers would produce many desirable effects, the least of which would be promotion of better work. Perhaps the ultimate contribution of the organized body of researchers in behavioral bioelectromagnetics would set forth standards and specifications for the critical experiments in this area, those involving human subjects.

In conclusion, there are significant instrumentation-related problems that limit the types of behavioral experiments that can be conducted during microwave irradiation. Because of the relatively young age and small size of bioelectromagnetics research area, makers of commercial instruments and microwave components see no large market for irradiation-compatible apparatus. Therefore progress in solving instrumentation-related problems has been slow. Normal growth in our technological base will solve some of these problems, but faster solutions and better research will result if apparatus specifications and/or designs are published and made easily available such as the circular waveguide system.

Even greater results are possible through the efforts of an influential group of behavioral researchers in bioelectromagnetics. In the future, this group could serve as a catalyst among researchers and engineers to promote application of new materials and devices in novel behavioral irradiation experiments using methods previously unsound because of past instrumentation incompatibility.

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