HIGH PEAK POWER MICROWAVE PULSES AT 1.3 GHz: EFFECTS ON FIXED INTERVAL AND REACTION TIME PERFORMANCE IN RATS

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The animals used in this study were handled in accordance with the principles stated in the Guide for the Care and Use of Laboratory Animals, prepared by the Committee on Care and Use of Laboratory Animals of the Institute of Laboratory Animal Resources, National Research Council, DHHS, NIH Publication No. 85-23, 1985; and The National Animal Welfare Act of 1966, as amended.

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The current safety standards for radiofrequency and microwave exposure do not limit the peak power of microwave pulses for general or occupational exposures. To determine whether high peak power microwave pulses can alter known thresholds of behavioral disruption, four Long-Evans male rats were exposed to peak powers of 496.7, 336.7, and 146.7 kW in a waveguide exposure system while performing a time-related behavioral task. The task consisted of two components: a fixed interval schedule of reinforcement on one response lever and reaction time on a second lever. Responding on each lever was dependent on visual signals displayed through the translucent plastic levers. Trained rats performed the behavioral task during exposure to 1.3-GHz microwave pulses at a pulse repetition rate of 10 Hz. For the three power levels, the estimated average whole-body specific absorption rates (SAR) were 10.5, 6.3 and 3.5 W/kg. The corresponding peak whole-body SARs were 350.0, 210.0, and 11[illegible].7 kW/kg. Compared to sham irradiation,

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significant changes occurred in behavioral performance. Session time increased, response rates decreased, and reaction times significantly increased at whole-body SARs of 6.3 and 10.5 W/kg. Significant effects were not observed at 3.5 W/kg. The alteration of behavior in this study occurred at a whole body SAR between 3.5 and 6.3 W/kg, which is consistent with previous estimates of 4 W/kg as the threshold for behavioral alteration. The high peak power pulses used in this study did not alter this threshold, suggesting that the primary effect must be tissue heating.

SUMMARY PAGE

THE PROBLEM

Naval personnel are frequently exposed to microwave radiation from guidance, communications, and weapons-systems operating at various frequencies and power densities. In recent years, the development of new systems with very high peak power microwave pulses and other unique characteristics has caused increased concern for the safety of personnel working in and around such microwave environments. In earlier studies, behavioral performance of laboratory animals has been a sensitive test for the effects of microwave exposure. To determine the effects of high peak power microwaves, laboratory rats were exposed inside of a waveguide exposure apparatus while performing a vigilance task. The exposures were conducted using microwave energy pulsed at low pulse repetition rates to produce three average whole-body specific absorption rates (SAR) near a previously determined threshold (4 W/kg) for behavioral change.

FINDINGS

When exposed to microwave pulses, the rats required more session time to earn a daily ration of food pellets. During microwave exposure, the response rate on the observing lever decreased significantly, and reaction times on the food lever increased significantly as compared to sham exposure sessions. These effects were observed at whole-body specific absorption rates (SAR) of 6.3 and 10.5 W/kg but not at 3.5 W/kg. The corresponding peak whole-body SARs were 350.0, 210.0, and 116.7 kW/kg.

RECOMMENDATIONS

The results of this study agree very well with a whole-body average SAR of 4 W/kg deemed necessary (1) for microwave absorption to produce alteration of behavioral performance. The presence of very high peak SAR in the rat due to the pulsed microwave parameters used here did not alter this threshold. However, further investigation is necessary and should focus on microwave pulses of shorter duration (<100 ns) and higher peak power.

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INTRODUCTION

Present safety standards (1,2) recommend limiting microwave exposure to 0.4 W/kg for whole-body specific absorption rate (SAR) and 8 W/kg for localized SAR. The standards, however, do not address limiting the peak power of pulsed microwave fields. Microwave fields with high peak powers and low pulse repetition rates may satisfy the currently accepted safe SAR limits. However the possibility of adverse health effects from pulsed microwave energy with very high peak power has caused some concern in occupational and military working environments. While some bioeffects, primarily the auditory effect, depend on pulsed microwaves, hazards associated with very high peak power microwave pulses are unknown. The auditory effect requires relatively little peak energy for its occurrence, yet radar and proposed directed energy systems are capable of producing peak powers several orders of magnitude above this level. The most widely studied pulsed microwave-induced bioeffect has been the auditory sensation caused by thermoelastic expansion of brain tissue and a propagating acoustic wave producing stimulation of hair cells in the cochlea (3).

Recent studies have investigated the microwave pulse parameters necessary to produce acoustic mechanical vibrations in brain tissue of several mammalian species (4,5). The concern over adverse health effects stems, not from the relatively low power microwave pulses necessary to produce auditory stimulation, but from very high peak power pulses capable of producing intense mechanical vibration in brain tissue. This concern appears justified because new devices with very high peak output powers are constantly being developed. While the mechanisms are as yet unknown, recent reports describe ultrastructural damage to cell membranes (6) and behavioral alteration (7) following exposure to high power microwave pulses.

A safety standard for exposure to high peak power microwave pulses can only be established from an extensive experimental data base. In a previous study, D'Andrea et al. (8) found no significant effects of 1.3-GHz pulsed microwaves on rhesus monkey behavior with a peak SAR in the head of 15 W/kg. The study reported here utilized a waveguide exposure system to achieve a much higher microwave peak power and peak SAR than that used in our previous study.

METHODS

SUBJECTS

Four male Long Evans rats obtained from the Charles River (Wilmington, MA) colonies served as subjects. The mean body mass of the rats during the experiment was 297 g ($\pm$ 4 g, SEM). The rats were fed a daily standard rodent laboratory diet (Purina #5001) in sufficient quantities to produce a normal-sized animal for that age and housing condition. Prior to training, the rats were fed a reduced amount of the same diet until their body mass was reduced by 10% of the previously determined ad-libitum weight. During the experiment, the rats were maintained at this weight except for periods where they were again free-fed for several days (5 to 7) to establish a new ad-libitum weight. This procedure resulted in healthy, well-conditioned animals that worked adequately on food-reinforced tasks. The rats were individually housed in the vivarium in stainless steel cages with tap water continuously available. Home cage temperature was maintained at 21-25 °C under a 12/12 h light-dark cycle.

APPARATUS

Waveguide Exposure System

Rats were unrestrained and irradiated in a straight section of waveguide, as shown in Figure 1, which was mounted within an anechoic chamber, as shown in Figure 2. The microwave exposure device was a rectangular WR-650 waveguide (16.6 cm deep X 44.5 cm long X 8.3 cm wide). The inner walls were lined with a 1-mm thick plastic sheet, which provided electrical insulation. A Plexiglas plate (5-mm thick) was inserted into the waveguide at the junction of the waveguide exposure chamber and the section of waveguide delivering microwave energy from the radar magnetron. The opposite end of the exposure waveguide was covered with a plastic grid (1-cm squares) and held in place with Velcro tape. The plastic barriers served to confine the rat within the waveguide exposure chamber. Two levers were constructed from extruded Plexiglas rod (5-mm in diameter) and projected 30 mm into the interior of the waveguide exposure chamber through holes (0.64-cm diameter) cut in the waveguide. The levers were designated "observing response lever" and "food-delivery lever" for clarification. The end of each lever was illuminated on the outside of the waveguide by pilot lamps (GE No. 757). Thus, the lighted translucent rods served both as response levers and visual discriminative stimuli. An auditory signal (Sonalert, 70 dBA) was mounted on the outside of the waveguide and turned on while the food delivery lever was illuminated. Microswitches (located outside the exposure waveguide) were connected to the levers to monitor behavioral responses on each lever. A pellet feeder, mounted above the waveguide exposure chamber, delivered 45-mg rat food pellets (P.J. Noyes Co., Lancaster, NH; Formula A) through a hole (1.3-cm diameter) in the waveguide above the food delivery lever to a plastic food cup mounted inside the exposure waveguide. Filtered air was delivered to the waveguide from an air compressor by Tygon tubing through a hole (5-mm diameter) in the waveguide above the right lever. Air flow delivered to the waveguide exposure chamber was 600 ml/min as measured by a flowmeter (Brooks, #R-2-15-B).

During the experiment, the waveguide exposure apparatus was connected to the waveguide inside the anechoic chamber using a standard cover flange (UG-148; see Fig. 2). The anechoic chamber exterior dimensions measured 2.45 m long, 1.94 m wide, and 2.43 m high. The interior of the chamber was completely lined with sheet metal, which was covered with 20.4-cm pyramidal absorber (AAP-8, Advanced Absorber Products, Amesbury, MA). Room air was circulated through the anechoic chamber at a rate of 28 m^3 per minute. The air temperature of the anechoic chamber was measured with a telethermometer (Yellow Springs, Model 401), which was located 30 cm above the distal end of the waveguide exposure chamber. Ambient temperature inside the anechoic chamber varied between 22-27 °C (mean 23.5 °C ± 1.2 °C SEM) and the average relative humidity varied around 50% (± 5%). The anechoic chamber was equipped with a speaker for white noise and a 25-W house light. A background white noise level of 68 dBA was measured inside the waveguide exposure chamber.

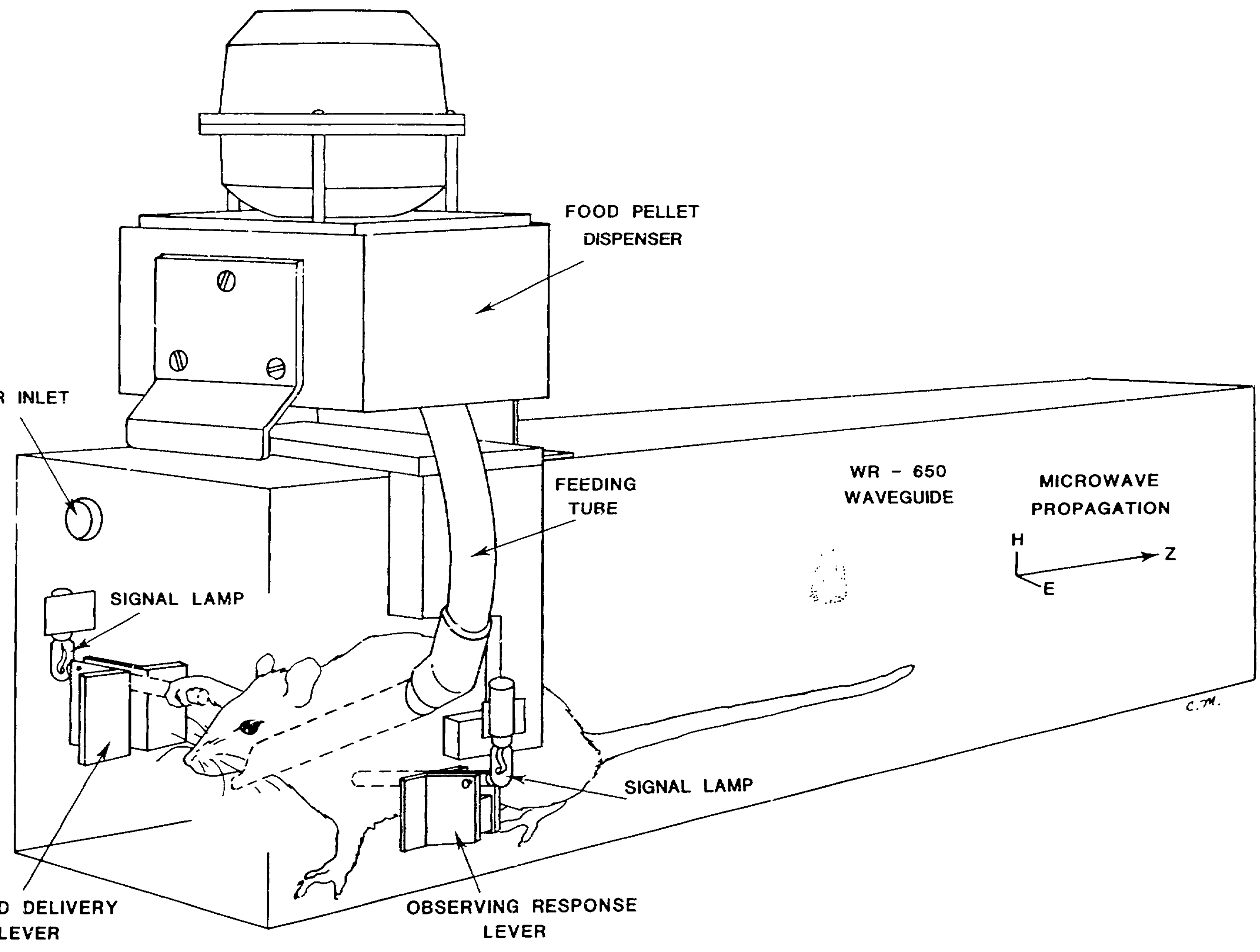

Figure 1. A schematic representation of the waveguide exposure apparatus.

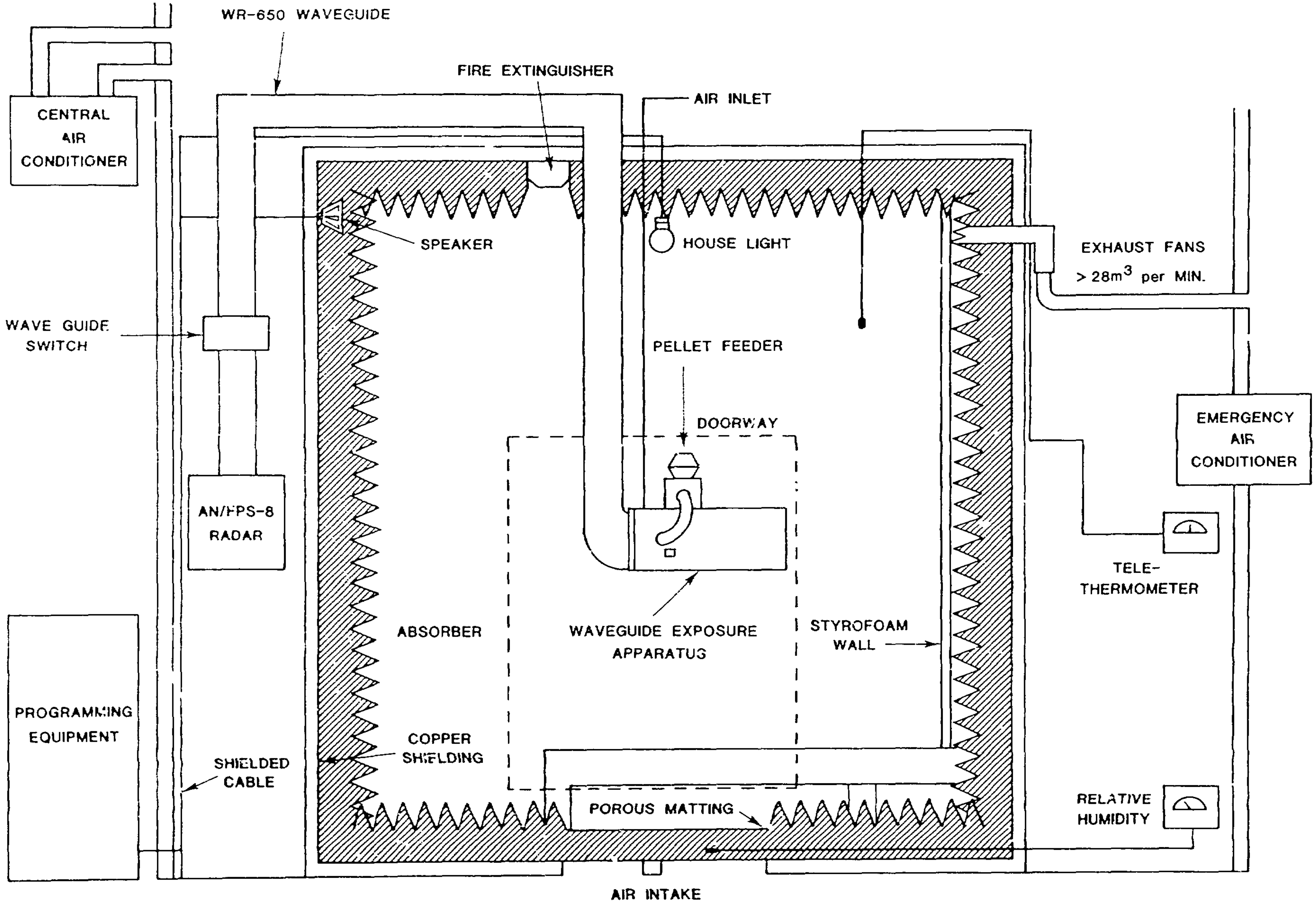

Figure 2. A schematic representation of the anechoic microwave chamber used to house the waveguide exposure apparatus.

Microwave Power

A military radar (AN/FPS-8) produced pulsed microwave radiation at 1.3 GHz. A pulse generator (Hewlett Packard 214A) was used to trigger the AN/FPS-8 magnetron at 10 pulses per second. The radar output was delivered to the exposure chamber via a circuit of rectangular waveguide (WR-650), which included a directional coupler (Raytheon No. FA595T) and waveguide switch (RCA No. SA-340/SPS-12). Average power in the waveguide was measured using a power meter (General Microwave, No. 470). Peak power in the waveguide was measured using the directional coupler, a crystal detector (Hewlett Packard No. 423B), coaxial attenuators (Weinschel Engineering No. 2), and an oscilloscope (Tektronix 7633).

Dosimetry

Estimates of whole-body SAR were made using a rat-shaped mold filled with saline (0.09%). The mold was constructed by pouring polyurethane foam (2 lbs/ft^3 density) around a paraffin rat model, which was cast from an original that was sculpted from modelers clay. Dimensions for the rat model were taken from a 270-g male rat. The paraffin rat was then removed by sawing the mold in half. Once the halves of the mold were glued together by epoxy cement, the cavity was then filled with saline. Local SAR in the rat head was estimated by filling a second rat mold with muscle equivalent m[illegible]ial using a formula from Chou et al. (9).

P[illegible]DURE

Dosimetry

The rat model was placed inside the waveguide exposure chamber, and a field-compatible temperature probe (Vitek No. 101) was inserted in the center of the rat saline model or in the head of the muscle-tissue equivalent model followed by a 600-s microwave exposure. The saline-filled rat model was gently swirled after microwave exposure but before the temperature measurement was taken. The SAR was calculated using the following formula: SAR W/kg = cT/t where T is the temperature change in degrees Celsius, c is the specific heat in J/kg/ °C, and t is the exposure time in seconds.

Behavioral

Rats underwent initial conditioning in the waveguide chamber, placed on a countertop adjacent to the microwave chamber to improve observation of subjects. Each rat had approximately 40 countertop training sessions before the waveguide exposure chamber was mounted inside the anechoic chamber for approximately 30 additional training sessions. The behavioral task required the rat to depress the lighted observing response lever (left lever) after a 30-s fixed interval (FI 30 s) had elapsed. Left lever responses before the end of the 30-s interval had no planned consequences. The first lever press that occurred after the end of the 30-s period produced a tone (70 dBA) and lighted food delivery lever (right lever). Reaction time was measured on this second lever. A lever press emitted on the food-delivery lever within 2-s after onset of the light produced a food pellet. Responses emitted after the 2-s period did not produce a food pellet. Responses on the unlighted food delivery lever (incorrect responses during the FI 30 s period) produced a 10-s time out, during which food pellets could not be earned. Time out remained in effect until no responses on the food delivery lever had occurred for 10 s. Following food pellet delivery, the lever lights reversed, and the rat was required to respond on the observing response lever for the duration of the next FI. The cycle of responding on the observing response lever during the FI-30 s interval followed by a response on the food delivery lever was termed a "trial." During sessions in the anechoic chamber, each rat was allowed to complete 99 trials before being removed from the chamber. For purposes of data collection, each session was divided into 3 components of 33 trials each.

Microwave Exposure

Following the development of stable behavioral performance, the rats were exposed to pulsed microwaves while performing the behavioral task. Microwave pulses of 3 μ sec in duration were delivered at 10 pps. Exposures at peak waveguide powers of 496.7, 336.7, and 146.7 kW were given by varying the high voltage to the radar magnetron. Microwave exposure commenced during session component two after the rat had completed 33 trials and continued until the start of component three (completion of 66 trials). If the rat ceased responding during radiation exposure, microwaves were discontinued after a total exposure duration of 20 min. During a sham exposure session, the radar was operational but the energy delivered to the waveguide was redirected from the antenna, using the waveguide switch, to a waveguide resistive load located outside the anechoic chamber. During baseline sessions where neither microwave exposure nor sham exposure was given, the radar was placed in the standby mode of operation. A repeated measures experimental design was used where the order of the microwave exposures and sham exposures was given randomly for each rat. Dependent variables collected for each session included session duration, observing-lever responses per minute, latency on the food-delivery lever, errors on the food delivery lever, and post-reinforcement pause time.

RESULTS

Dosimetry

The estimated peak and average SARs in both rat models are shown in Table 1.

TABLE 1. Magnetron Voltage Waveguide Power and Mean Specific Absorption Rate.

Magnetron voltage	11 kV	10 kV	9 kV
Waveguide power			
average power W	14.9	10.1	4.4
peak power kW	496.7	336.7	146.7
Whole body SAR			
Saline rat model			
average SAR W/kg	10.5	6.3	3.5
peak SAR kW/kg	350.0	210.0	116.7
Head SAR			
Muscle phantom rat model			
average SAR W/kg	15.9	9.9	5.9
peak SAR kW/kg	530.0	330.0	196.7

Based on the measurements using the saline filled model, the average SAR varied between 3.5 and 10.5 W/kg. Measurements with the muscle-equivalent model showed SARs in the head region to be about 37% higher than the average whole-body SAR. This enhanced SAR in the head is very similar to measurements taken by D'Andrea et al. (10) comparing saline-filled models and rat carcasses exposed to microwave radiation at 915 MHz.

Behavioral

Cumulative response records of the FI responses on the observing response lever for a baseline and three microwave exposure sessions from rat no. 17 are shown in Figure 3. The observing response rate for the baseline session was steady with relatively few pauses. During the microwave exposure sessions, the magnetron was energized only during component 2 (trial 33 to trial 66) of the session (see Figure 3). Microwave exposure at a whole-body SAR of 3.5 W/kg had relatively little effect on the response rate. During microwave exposure at whole-body SARs of 6.5 and 10.5 W/kg, however, the response rate declined continuously during microwave exposure, and invariably, exposures at 10.5 W/kg resulted in a complete cessation of responding.

Each of the behavioral measures for microwave and sham exposure sessions was transformed to percentage of baseline scores using the session the day before exposure as baseline. The percentages of baseline scores for each dependent variable were then analyzed using a two factor repeated measures analysis of variance (11). Reliable effects were evaluated further with the Duncan range test to determine significant differences between means (11).

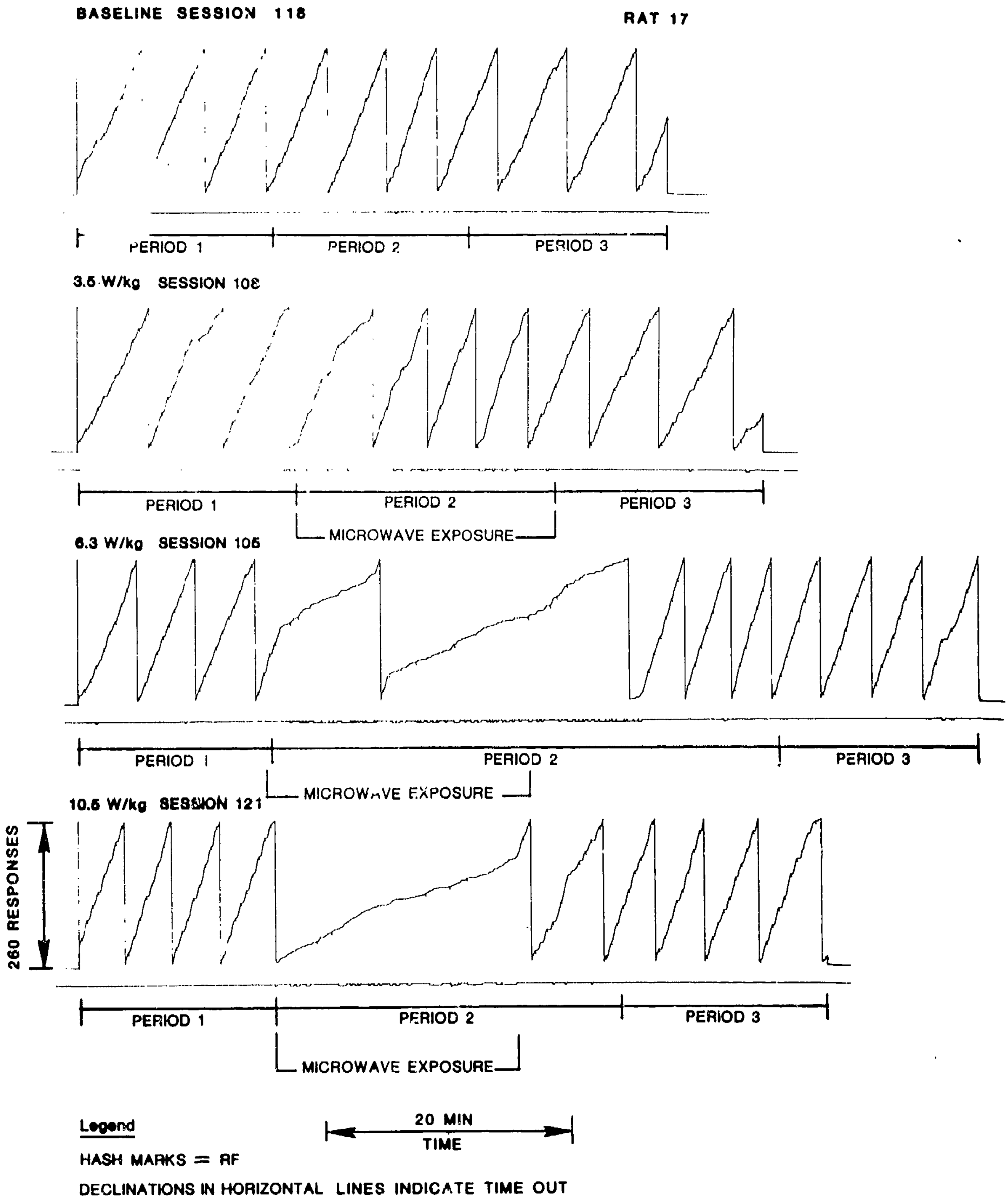

Figure 3. A series of cumulative records showing FI responses made by rat no. 17 during baseline and exposure sessions at whole-body SARs of 3.5, 6.3, and 10.5 W/kg. Time-out errors are shown on the horizontal line below each record.

The mean observing response rates for component 2 for microwave and sham sessions are shown in Figure 4. Microwave exposure at a whole-body SAR of 3.5 W/kg did not significantly alter the response rate. During microwave exposure at whole-body SARs of 6.5 and 10.5 W/kg, however, the response rate was reduced significantly from baseline and sham sessions. Overall, there was a significant interaction between SAR and the microwave and sham exposures ($\underline{F}(1,3) = 15.34$, $\underline{p} < .004$). The Duncan range test showed that the difference between microwave and sham exposure occurred at both 6.3 and 10.5 W/kg.

Increase in reaction time was SAR-dependent on the food-delivery lever for the microwave exposure sessions but not for the sham exposure sessions ($\underline{F}(1,3) = 36.79$, $\underline{p} < .009$). This result is shown in Figure 5 where, at a whole body SAR of 3.5 W/kg, the microwave exposures did not significantly alter reaction time as compared to baseline. At SARs of 6.3 and 10.5 W/kg, however, reaction time increased significantly during component 2 ($\underline{F}(2,6) = 8.79$, $\underline{p} < .02$). Like the FI response rate, reaction time on the food-delivery lever recovered during component 3 after the termination of microwave exposure.

The session duration required for rats to complete 99 trials also differed significantly between microwave and sham exposures as shown in Figure 6. Microwave exposures at 6.3 and 10.5 W/kg significantly increased the session duration as compared to sham exposures $\underline{F}(1,3) = 10.10$, $\underline{p} < .05$). The number of errors (responses on an unlighted food-delivery lever) and the post-reinforcement pause times were unaltered by microwave or sham exposure.

DISCUSSION

Exposure to microwave pulses delivered at a low pulse repetition rate produced several significant changes in rat behavior depending on whole-body SAR. A lack of effect at 3.5 W/kg compared to significant behavioral alterations at 6.3 and 10.5 W/kg confirms the validity of the previously determined 4 W/kg threshold SAR necessary to produce behavioral change. However, the high peak power microwave pulses per se used to produce the whole-body SARs (3.5 W/kg) appear to have no significant effect on behavioral performance. Otherwise, significant behavioral effects should have been observed at a whole-body SAR of 3.5 W/kg.

Presumably, acoustic mechanical vibrations were produced in brain tissue during pulsed microwave exposure, and rats experienced an auditory sensation. That this sensation did not disrupt a behavior requiring a visual discrimination is not surprising. Since the behavioral threshold of 4 W/kg did not appear to change, it is then reasonable to assume that the primary effect of the microwave exposures used in this study was to produce tissue heating the consequence of which produced the behavioral change. Nevertheless, absorption of microwave energy is dependent on several parameters including radiation frequency, orientation of field vectors, and size of the biological target. Further investigation should focus on these factors as well as the parameters of new microwave pulse sources such as pulses of shorter duration (< 100 ns) and higher peak power.

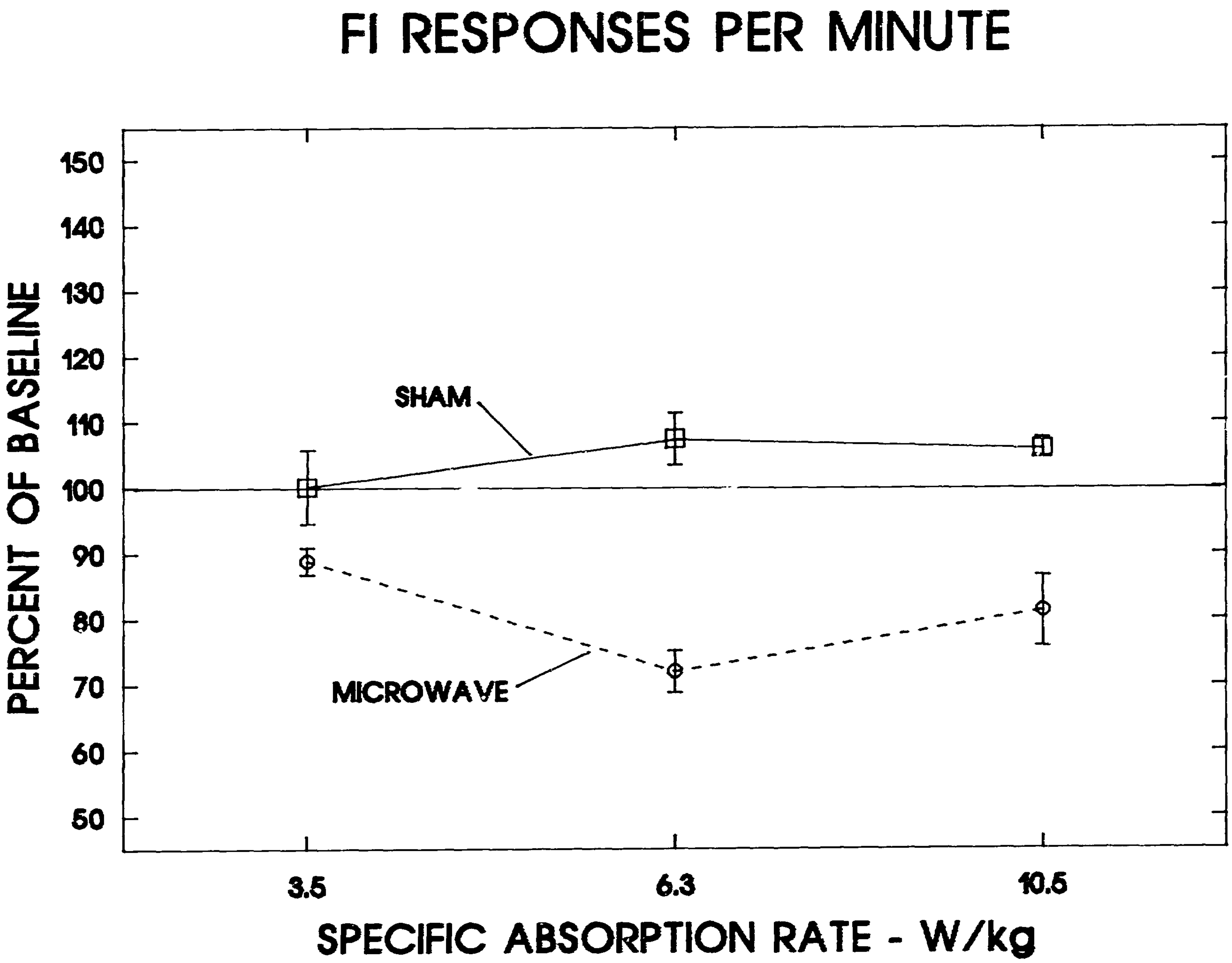

Figure 4. Mean correct responses per minute as a percentage of baseline performance for the FI schedule components during sham and microwave exposure sessions.

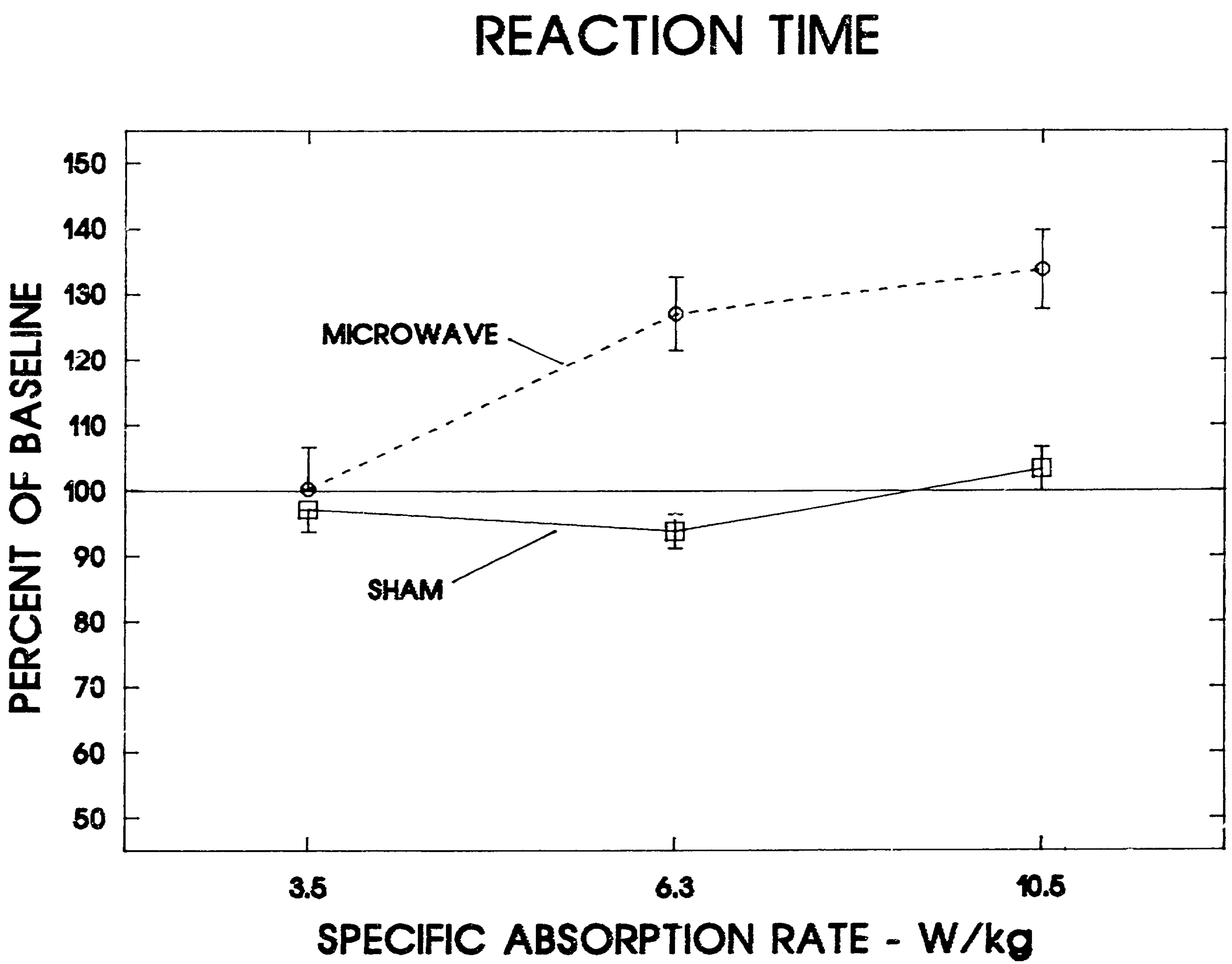

Figure 5. Mean reaction time on the food lever as a percentage of baseline performance during sham and microwave exposure sessions.

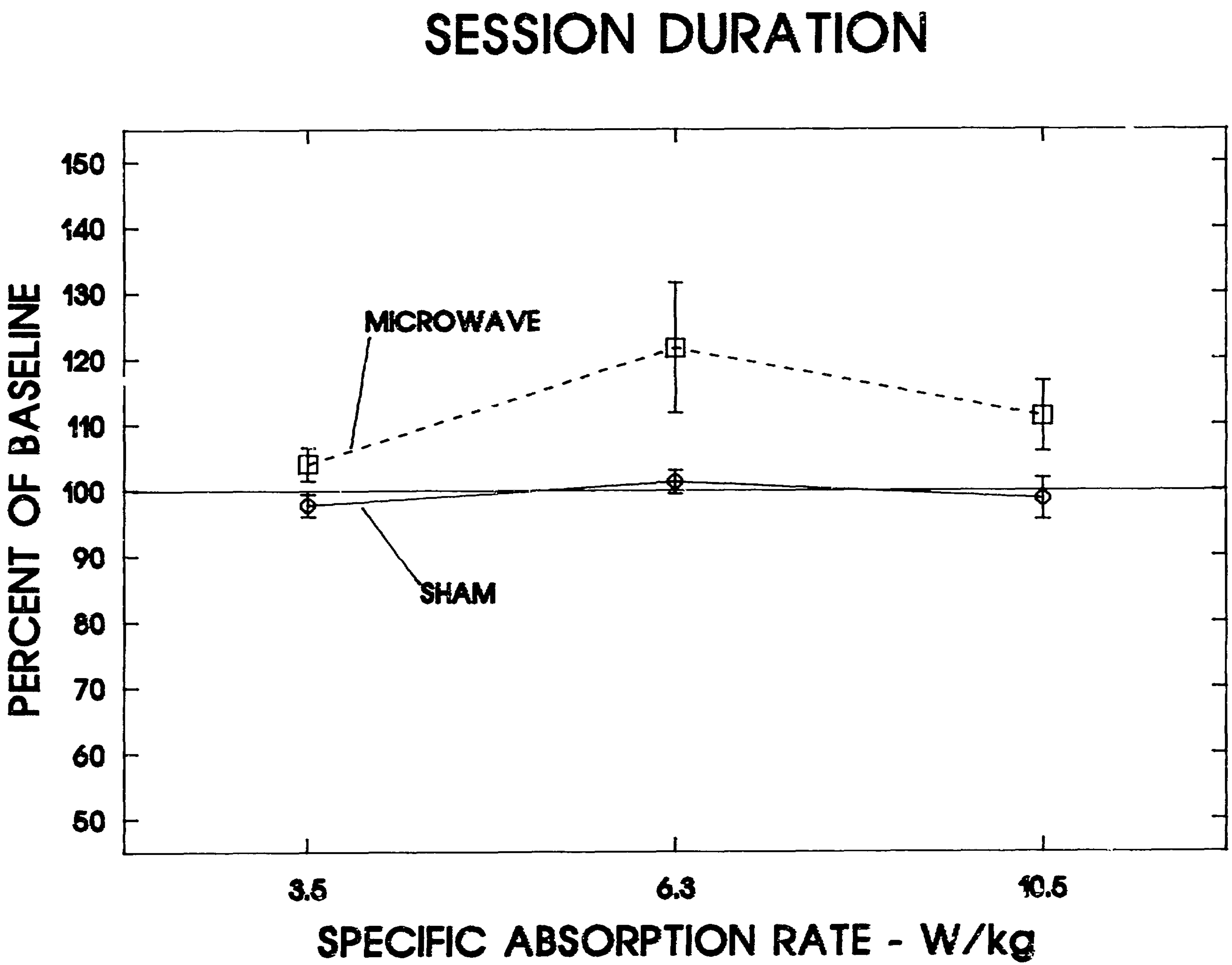

Figure 6. Mean session duration required for rats to complete 99 trials as a percentage of baseline performance during sham and microwave exposure sessions.

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