Effects of high-intensity microwave pulse exposure of rat brain

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Previous studies have indicated that auditory responses could be evoked in the head of animals exposed to 500-μs-wide or less microwave pulses of relatively small absorbed energies (5–180 mJ/kg). These studies were extended using an exposure system capable of locally exposing the head and especially the brain of the animal to a single 915-MHz pulsed magnetic field with sufficient intensity to produce a specific absorption rate level as high as 4×10^5 W/kg for any pulse width. When the animal was exposed to various pulse widths (1 μs to 360 ms) and power levels (2–10 kW), the animal displayed no reaction other than that due to the hearing effect until the peak absorbed energy density in the brain exceeded 28 kJ/kg, or an absorbed energy in the head of 680 J, regardless of peak power or pulse width. Thermographic and thermocouple measurements indicated a maximum temperature rise of 8°C or final maximum brain temperature of 46°–46.5°C at the reaction level. The reaction consisted of petit or grand mal seizures lasting for 1 min after exposure, followed by a 4- to 5-min unconscious state during which normal reflexes were displayed. There was a decrease in heartbeat rate in the exposed unanesthetized animals. After the period of unconsciousness the rats recovered without apparent effect from the exposure. Measurements indicated that the brain temperature returned to baseline level within 5 min after exposure and the animals began moving when the brain temperature returned to within 1°C of their normal values. These results would indicate that the thresholds for convulsions induced by short exposures of the brain to high energy pulses are dependent only on the deposited energy and temperature rise. Histological examinations of some of the animal brains indicated some demyelination of neurons 1 day after exposure and some microfocal glial nodules in the brain 1 month after exposure.

INTRODUCTION

Previous studies involving the exposure of the head of animals to microwave pulses have indicated that auditory responses can be evoked for relatively small absorbed energies of 5–180 mJ/kg corresponding to pulse widths of 500 μs or less [*Guy et al.*, 1975; *Chou and Guy*, 1979*a*]. These studies have been extended to include pulses of much greater width and energy in order to determine the effects other than microwave hearing. *Merritt et al.* [1977] conducted experiments in which they were able to produce convulsions and a state of unconsciousness (stun effect) in rodents exposed to a single microwave pulse of 0.1-s duration and a power density of 50 W/cm^2 of incident energy. In those experiments a temperature rise of only 2°C was measured in the brain, and a standard histological examination indicated no pathology attributable to the exposures. The purpose of the experiments reported here was to replicate the experiments by Merritt et al. for a number of pulse widths but, in addition, to determine the threshold for the effect observed by Merritt et al., in terms of the peak absorbed energy and the total absorbed energy in the head of the animal.

Several neurochemical studies exposing mice or rat brain to microwaves for 0.25 s to several seconds are reported [*Butcher et al.*, 1975; *Meyerhoff et al.*, 1979; *Modak et al.*, 1976; *Moroji et al.*, 1977; *Nordberg*, 1977]. In those studies, all animals were sacrificed immediately after exposure. In addition, there are studies on the microwave-induced convulsions [*Schrot and Hawkins*, 1975; *Phillips et al.*, 1975] by exposing the whole animal to intense microwave fields. Because of the different natures of the above mentioned studies, no comparison will be made with our observations.

METHODS

Electric field coupling. The initial exposure apparatus consisted of a circular waveguide with the animal's head placed in a region of high electric field

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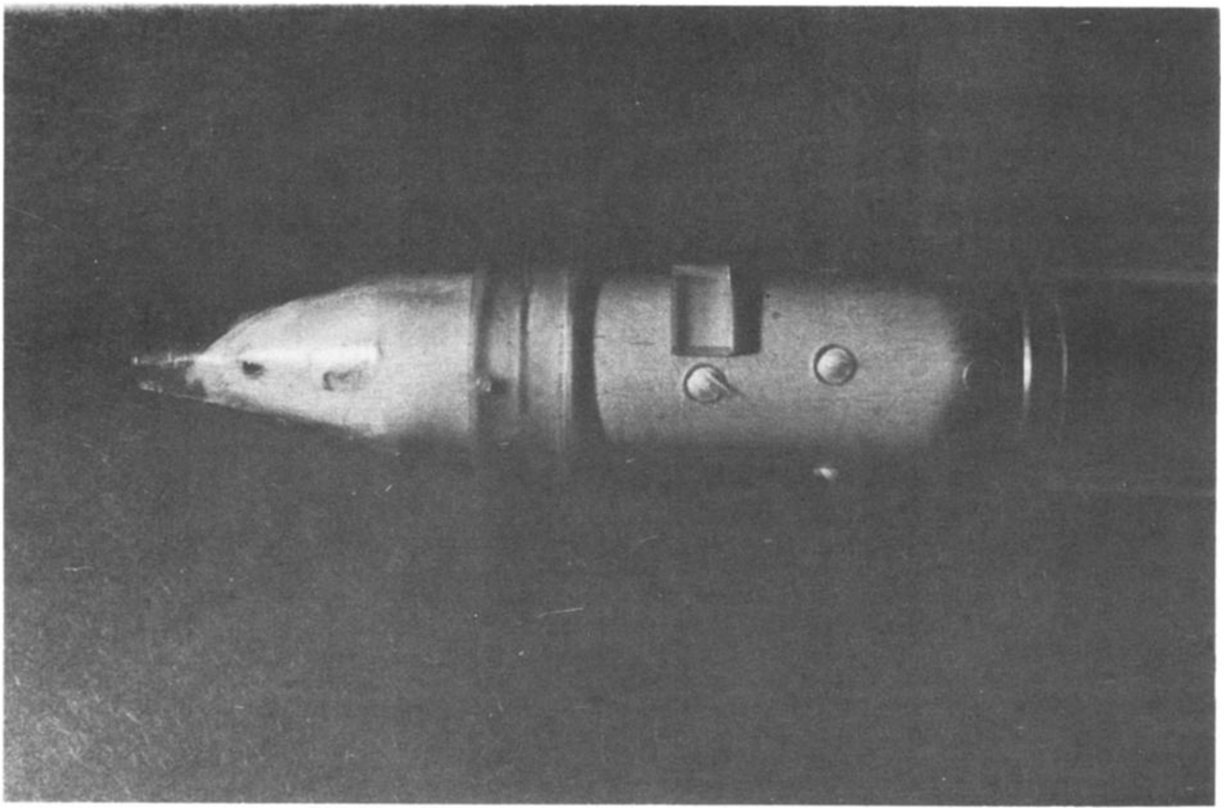

Fig. 1. Rat holder for use in the microwave stun effect study.

strength. The animal was immobilized by a plastic restraining device as shown in Figure 1. The device consisted of a 5.08-cm, OD, 0.19-cm, thick-walled tube with a cone at the end. The animal was placed within a tube, and a piston was used to push the animal toward the end so its head fit tightly into the cone. The piston contained a hole to allow the tail to protrude and a push rod for moving it forward to apply pressure on the animal. When the animal was in the proper position, the push rod was taped to the outer shell with masking tape to lock it into place. The animal was exposed in the exposure system shown in Figure 2. A detailed design of the feeding probe of the waveguide has been described previously [*Chou and Guy,* 1979*a*]. The acrylic tube holding the rat was placed in a hollow sliding metal tube of 6.55-cm, OD, and 0.2-cm thick walls which in turn was inserted into the exposure waveguide through an aperture with contacting metal fingers mounted at the periphery. The metal tube could be slid in and out of the exposure guide with the axis parallel to the electric field, as shown in the figure. The acrylic rat holder could, in turn, be moved back and forth to allow any desired portion of the animal to protrude into the exposure waveguide from the end of the hollow sliding metal tube. The volume of the exposed portion of the animal's head could be controlled by

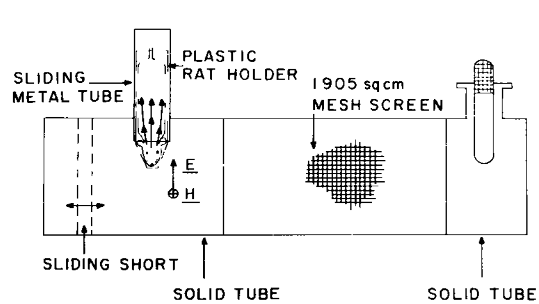

Fig. 2. Rat exposed to E field in cylindrical waveguide.

the relative position of the acrylic tube with respect to the metal tube. The waveguide fields could be matched to the head by setting the positions of a sliding short and the metal tube in the waveguide for minimum reflections back to the transmitter. The tapered end of the acrylic rat restrainer could be quickly removed after the rat was exposed, allowing the rat to be pushed out in the forward direction through the tube.

A number of thermographic studies were made on the heating patterns produced in a phantom rat composed of synthetic muscle tissue under different exposure conditions in the waveguide. Figure 3 illustrates the thermograms taken for a 0.1-s, 10-kW pulse exposure. Figure 3*a* shows a two-dimensional intensity scan taken over a plane parallel to the axis of the model of the head on the right-hand side. Profile single scans, vertical deflection proportional to temperature, were taken along the axis with the results shown below. The bottom horizontal scan in Figure 3*b* was taken before exposure, and the next scan above that was taken after exposure for the head penetrating 6 cm beyond the metal tube. The maximum heating which corresponded to a change in temperature as high as 21.6°C always occurred in the tissue adjacent to the edge of the metal tube. Unfortunately, with this type of exposure the body of the animal acted as a center conductor of a coaxial cable, and energy was transmitted back into the body as indicated by the increase in temperature along the body axis shown on the thermograms. These field lines are also pictorially represented in the sketch in Figure 2 and resulted in considerable waste of energy in heating up tissue outside the region of the brain. Also, the highest temperature did not occur in the brain.

Magnetic field coupling. The above problem was solved by redesigning the exposure system for expos-

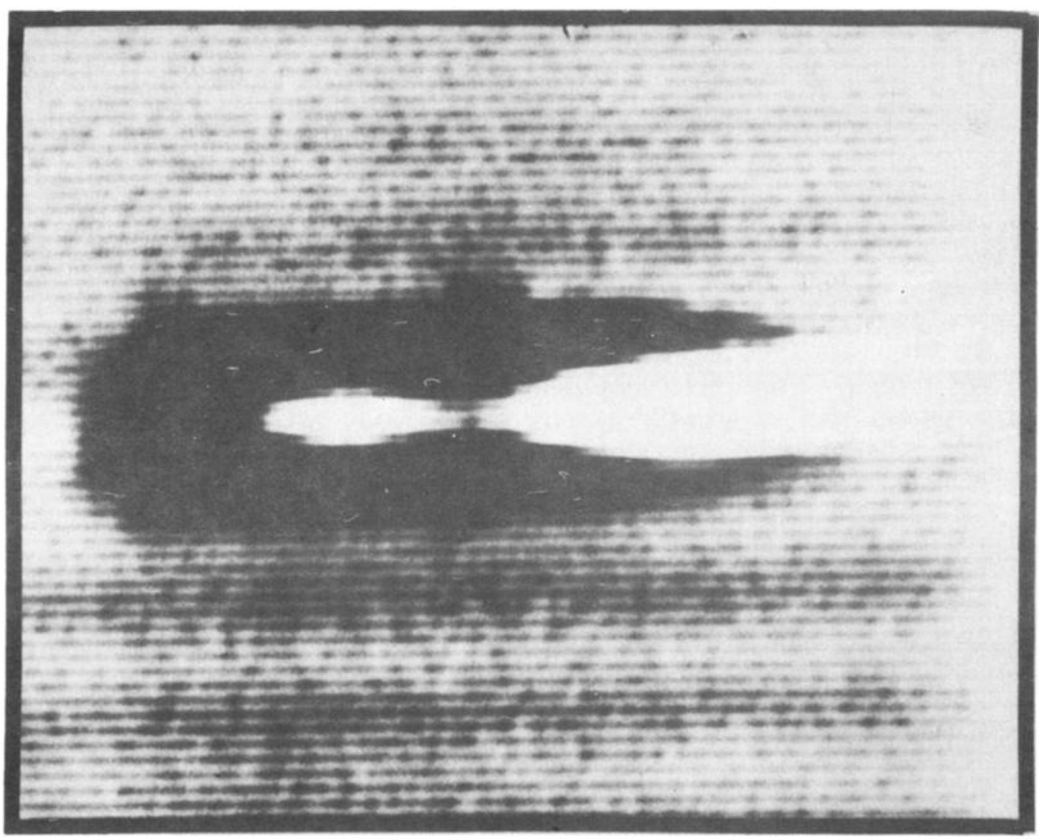

Fig. 3*a*. C scan thermogram showing the heating pattern in phantom rat exposed to *E* field in cylindrical waveguide.

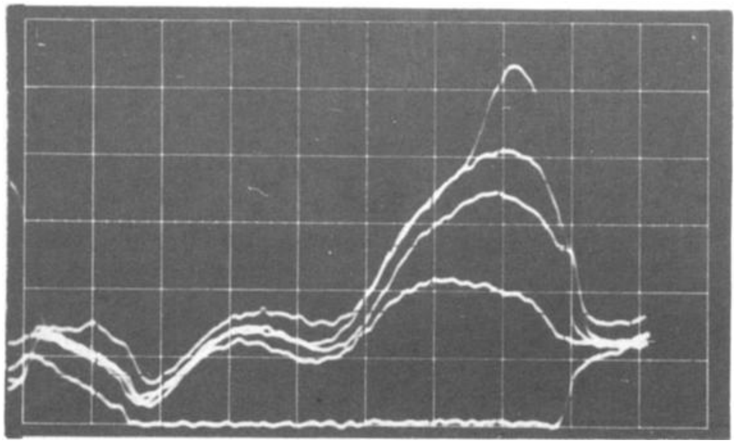

Fig. 3*b*. B scan thermogram along the center line of an exposed phantom rat at different head penetrations. From top to bottom, 2.5, 3, 4, and 6 cm (scale 4°C/division, 3 cm/division).

ing the head of the animal to magnetic fields, rather than electric fields, as shown in Figure 4. In the modification the aperture for inserting the animal was moved to the center of the sliding short so that the head could be inserted in a region of high magnetic field and low electric field. An impedance-matching probe was placed in the aperture previously used for inserting the animal in the electric field region, and the waveguide was lengthened so that the distance between the sliding short and the impedance-matching probe was near one-half wavelength. In this system the end of the metal tube was always placed flush with the sliding short, and the animal's head was inserted into the waveguide at any desired distance. The system was tuned for minimum reflections back to the source by proper positioning of the sliding short and the impedance-matching probe so that a high Q resonant cavity between the short and the probe was formed, allowing the animal's head to be exposed to a very high intensity magnetic field.

Dosimetry. During exposure the magnetic field would produce a circulating eddy current denoted by the arrows in the head of the animal in Figure 4. Since the eddy currents are produced only in the region of the magnetic field, energy was not wasted because of transmission into the body of the animal. Since the head of the animal is the shape of a semiprolate spheroid, one could expect a specific absorption rate (SAR) pattern similar to that measured for prolate spheroids exposed to magnetic fields. This was verified by thermographic studies of the SAR patterns generated in a phantom rat exposed in the metal tube, as shown in Figures 5*a* and 5*b* for 4-cm to 6-cm head penetrations. The thermograms illustrate the eddy current heating at the top and the lower part of the head with no observed heating in the unexposed portions of the body.

Figure 5*c* illustrates the profile thermograms taken along the region corresponding to the upper part of the brain in the phantom rat for head penetrations (right to left) 4, 6, and 8 cm into the exposure chamber. The bottom trace corresponds to the thermographic scan taken before exposure. Since there was some time lapse, however, between the time the animal was inserted into the tube and the time of exposure due to the delay for tuning and calibration, the body of the phantom rat had increased in temperature by 1.6°C, as shown in Figure 5*c*. Therefore to determine the temperature rise due to exposure, we must use the body temperature cor-

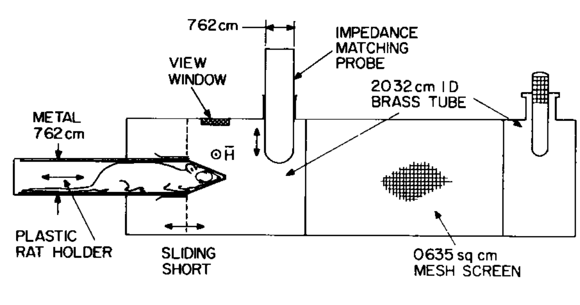

Fig. 4. Rat exposed to H field in cylindrical waveguide.

a)

b)

c)

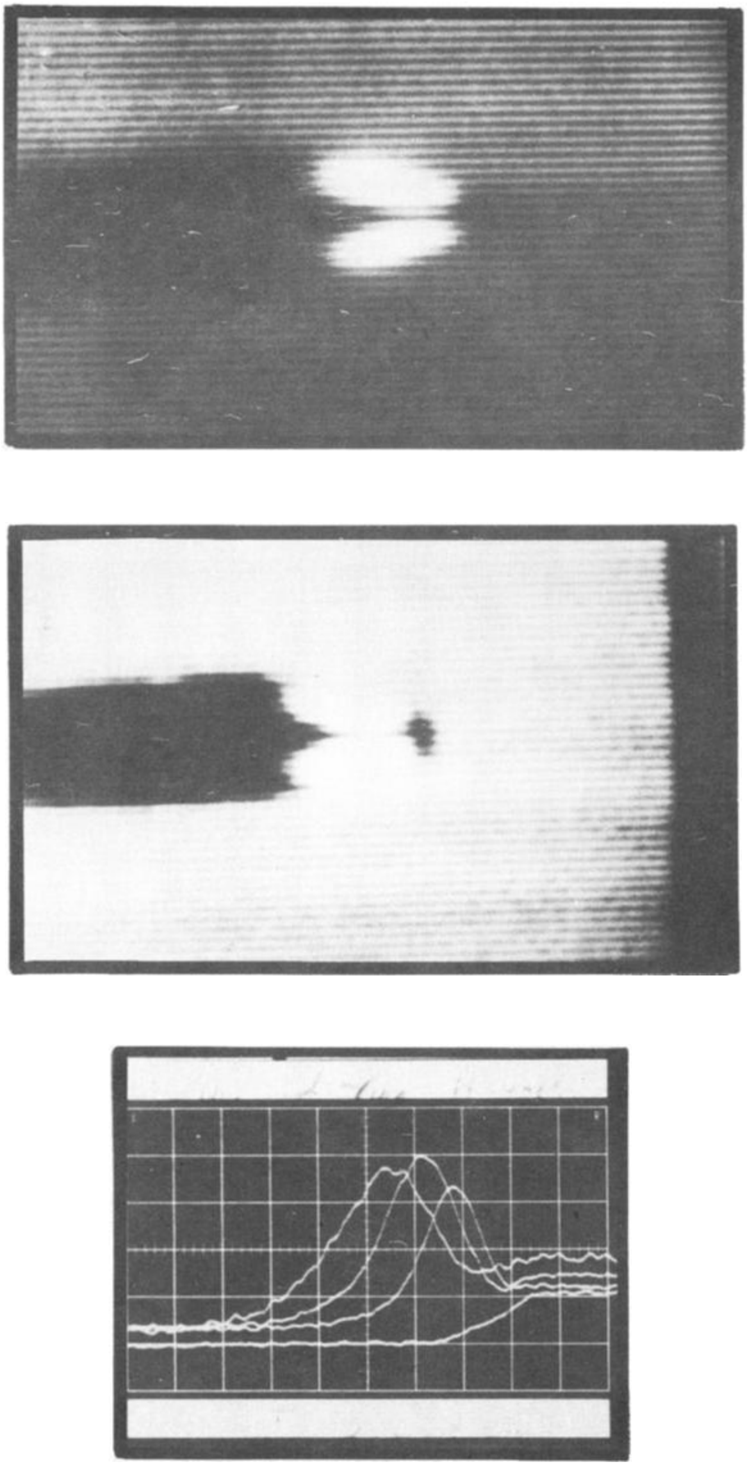

Fig. 5. (*a*) C scan thermogram of phantom rat exposed to 915-MHz magnetic field at 6-cm head penetration. (*b*) Same as Figure 5*a* except for 4-cm head penetration. (*c*) Multiple B scans showing that peak of heating pattern moves with head penetration. From right to left, 4, 6, and 8 cm (scale 4°C/division, 2 cm/division).

responding to the horizontal portions of the various profile scans at the left of the figure. By careful comparison of the thermographic heating patterns with the anatomy of the rat's head, it was found that a head penetration of 4 cm into the exposure chamber would insure that the top circuit of the eddy current pattern would pass directly through the brain of the rat with maximum temperature at the cerebrum. Note that from the previous picture this maximum temperature rise in the brain would be 12 °C for the 10-kW, 0.1-s pulse exposure and this would correspond to a maximum SAR of 4.17×10^5 W/kg, a total absorbed energy of 1000 J, and a peak specific absorption of 4.17×10^4 J/kg. The thermographic study was repeated on sacrificed rats with the results shown in Figure 6. In this case, the top of the figure shows the enlarged thermogram of the sagittal plane of the rat head, illustrating the localized heating in the brain and lower jaw region. At the bottom of the figure the profile scan shows a 12 °C temperature rise in the brain of the sacrificed animal in agreement with that obtained for the phantom rat head exposed with the same penetration of the waveguide.

RESULTS

Seventy female Wistar rats (220- to 250-g body mass) were exposed in the waveguide system, illustrated in the photograph in Figure 7, to various pulses of varying width and peak power to determine the threshold for the stun effect, i.e., the microwave-induced unconsciousness. The results shown in Figure 8 indicate that the threshold for the effect corresponds to a constant exposure energy of 680 J, regardless of the peak power and the pulse width, which we would expect if the effect is due to a temperature rise in the brain. Based on the thermographic data, this would correspond to a change in temperature of 8 °C, or a peak specific absorption of about 28 kJ/kg.

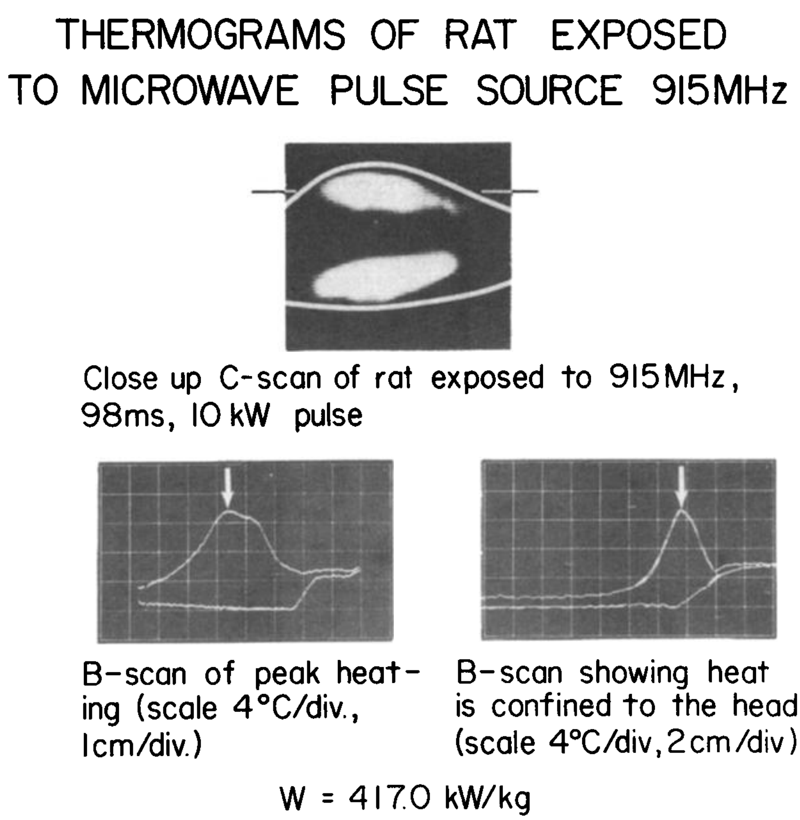

Fig. 6. Thermograms of rat exposed to microwave pulse source.

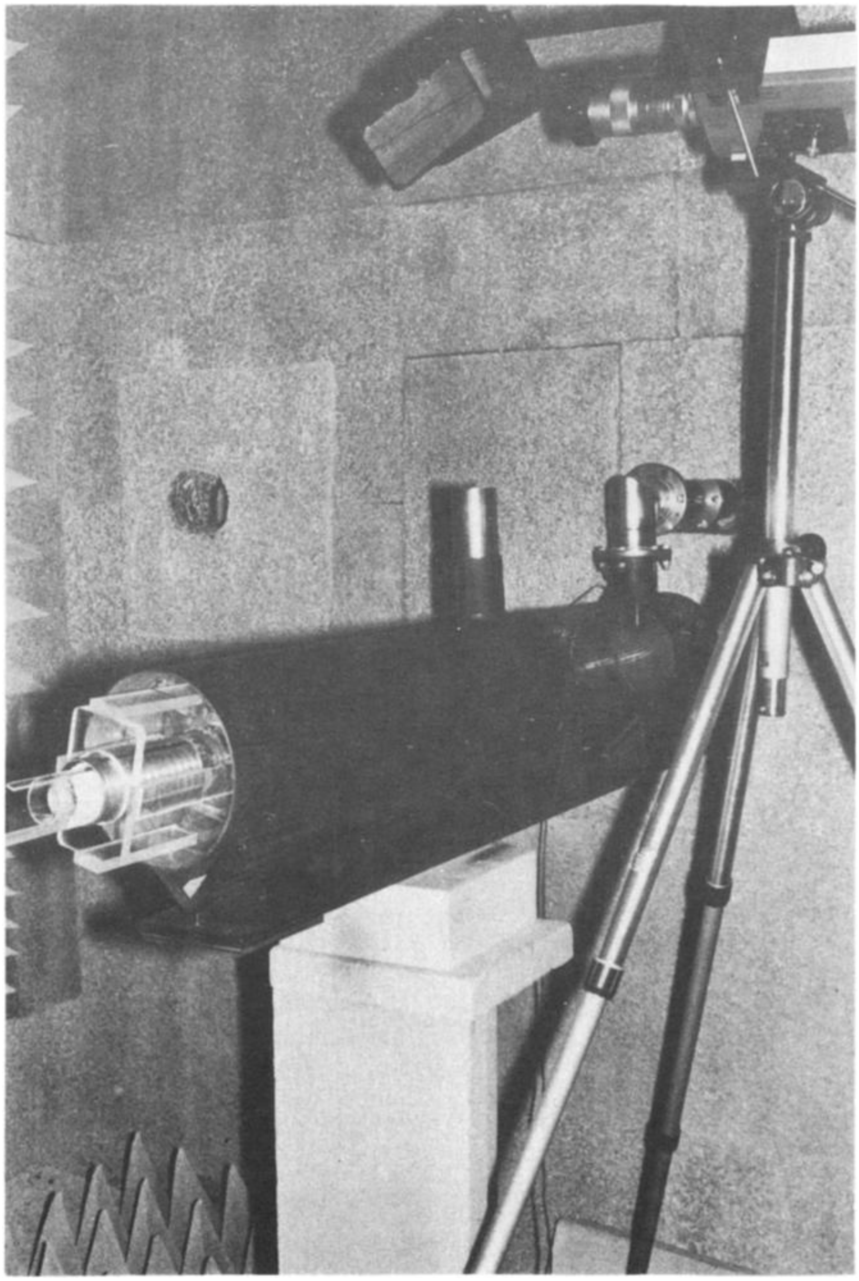

Fig. 7. Exposure for microwave stun effect.

Three different characteristics were observed in the rats after they were exposed to the microwave pulse. The rats exposed to pulses with characteristics corresponding to energy levels below the threshold curve appeared to be normal after exposure. Rats exposed to pulses with energies above the threshold curve generally displayed petit or grand mal seizures lasting for 1 min after exposure, indicated by their being rigidly stretched out and suffering violent spasms of twitching and jumping. After the seizure period they would lie quietly on their side in an unconscious state for a period of 4–5 min. When exposed to energy

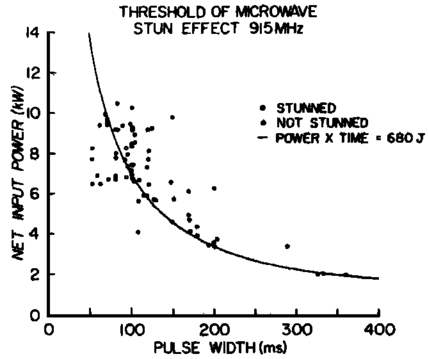

Fig. 8. Threshold of microwave stun effect, 915 MHz.

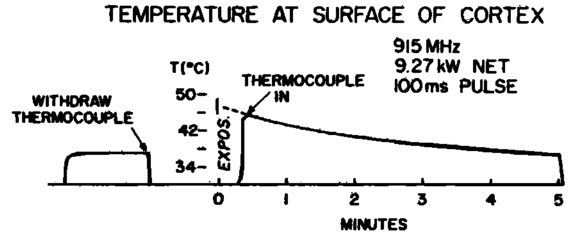

Fig. 9. Profile of temperature change at surface of cortex in rat exposed to 915-MHz, 9.27-kW, 0.1-s pulse.

levels corresponding to those slightly below or above the threshold curve, the animals sometimes were either normal or stunned, but displayed a lethargic and very slow moving characteristic. The period of unconsciousness seemed to increase with the amount of exposure energy above the threshold level. In all cases, when the rats were unconscious, they displayed normal reflexes.

A histological examination was performed on the head of five of the rats, three that were exposed to 10-kW, 0.1-s pulses, well above the threshold level, one that was exposed to 10 kW at 60 ms below the threshold level, and one control rat. Macroscopically, there was no observable difference among the five rats. Histological examination, however, on two rats (10 kW at 100 ms and 60 ms) indicated some unilateral focal (100-ms rat) and microfocal (60-ms rat) encephalomalacia. This was due to demyelination of neurons in dorsal frontal cerebral cortex 1 day after exposure. One month later the only pathological findings in two exposed rats were that the brains appeared swollen and in one rat a few microfocal glial nodules were present in the basal ganglia anterior to the optic nerves, while in another a single microfocl glial nodule appeared in the cerebral cortex.

The temperature increase in the brain as the result of the exposures and the cooling rate after exposure was measured in dead, anesthetized, and unanesthetized animals. This was done by implanting a polyethylene tube (PE90) at the surface of the cortex near the bregma area 4 cm from the nose (the region of highest energy absorption according to the thermograms) in five rats. In five other rats the tube was implanted 3 mm below the surface of the brain near the bregma area. The temperature was measured in the subjects by inserting a thermocouple through the tube such that its tip was imbedded in the region of highest energy absorption, both before and after exposure. A typical temperature pattern measured at the surface of the cortex is shown in Figure 9. In this case, as shown at the left of the figure, the cortex temperature was 37.6°C before exposure. The thermocouple was then withdrawn, the animal was exposed, and the thermocouple was reinserted to provide the temperature versus time measurement shown at the right of the figure. The exponential curve was extrapolated back to the time of exposure, which in-

TABLE 1. Brain temperature in rats before and after exposure to 915-MHz fields.

Subject	Physical state before radiation	Location of measurement	Net power (kW)	Pulse width (ms)	Preexposure (°C)	Temperature (°C) minutes postexposure 0	1	2	3	4	5
78120-1	awake	surface of cortex	9.4	100	37.7	49.0	43.5	41.2	40.0	38.8	38.4
78120-2	awake	surface of cortex	9.3	101	38.0	50.8	43.8	40.6	39.4	38.2	37.7
78120-3	awake	surface of cortex	10.3	100	37.7	48.0	43.8	40.6	39.4	38.6	37.6
78120-4	awake	surface of cortex	9.6	97	37.2	48.4	44.2	40.2	38.8	38.2	37.6
78120-5	anesthetized	surface of cortex	94	100	33.8	44.8	40.4	37.2	36.2	35.8	35.0
78120-3	awake	surface of cortex	9.3	100	37.6	47.8	43.6	41.0	39.4	38.4	37.5

Average total energy/pulse = 949.4 J. Average temperature rise = 11.13°C. Temperature rise/unit energy input = 1.17×10^{-2} °C/J.

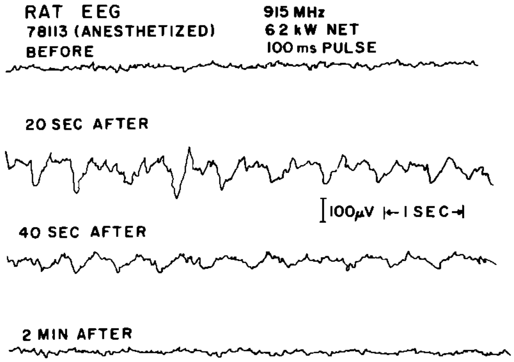

Fig. 10. Effect on EEG in anesthetized rat exposed to 915-MHz, 6.2-kW, 0.1-s pulse.

dicates a 10.2°C temperature increase to 47.8°.

Tables 1 and 2 illustrate the results for all of the measurements. In the unanesthetized animals the temperature returned to the baseline level within 5 min. Most of the animals began moving when the temperature returned to within 1°C of their normal temperature. The measurements indicate a mean surface temperature increase of 1.17×10^{-2} °C per joule of exposure energy and a mean temperature increase of 9.45×10^{-3} °C per joule of exposure energy at a depth of 3 mm into the brain. This would correspond to a total temperature change of 8°C at the surface (final temperature of 46°–46.5°C) and a change of 6.4°C at a depth of 3 mm (final temperature of 44.4°–44.9°C) at the 680-J threshold for the stun effect.

Electroencephalograms (EEG) and electrocardiograms (EKG) were measured in five animals using implanted carbon surface electrodes before and after exposure [*Chou and Guy,* 1979*b*]. Visual inspections of the EEG of unanesthetized animals did not show gross obvious amplitude or frequency changes after the exposure. It is possible to detect differences if a computer averaging technique or frequency spectrum analysis is applied. In an anesthetized animal, however, the amplitude of the EEG increased severalfold but recovered within 2 min after exposure, as shown in Figure 10. All of the unanesthetized animals showed bradycardia (decrease of heart rate) after exposure, whereas the one anesthetized animal exposed displayed tachycardia (increase of heart rate) after exposure. Table 3 illustrates the results on the heartbeat rate.

TABLE 2. Brain temperature in rats before and after exposure to 915-MHz fields.

Subject	Physical state before radiation	Location of measurement	Net power (kW)	Pulse width (ms)	Physical state after radiation	Preexposure (°C)	Temperature (°C) minutes postexposure 0	1	2	3	4	5
78113-1	anesthetized	3 mm in cortex	6.8	71	···	32.2	38.6	37.6	36.4	35.8	35.4	35.0
78113-2	anesthetized	3 mm in cortex	9.6	7.0	···	33.8	42.0	40.6	39.2	38.0	37.0	37.5
78117-1	unanesthetized	3 mm in cortex	9.4	98	stunned	37.9	44.6	42.4	40.2	39.2	38.6	38.4
78117-2	awake	3 mm in cortex	6.8	94	stun	39.0	45.6	42.2	40.6	40.0	39.6	39.3
78117-3	awake	3 mm in cortex	9.2	119	stun	37.7	47.4	43.2	40.8	39.8	38.4	38.0
78119-1	awake	3 mm in cortex	9.2	84	stun (died)	38.3	46.0	42.8	40.2	39.1	38.4	37.8
78119-2	awake	3 mm in cortex	9.4	80	not stunned	38.5	45.8	42.1	40.1	39.3	38.7	38.5
78119-1	dead	3 mm in cortex	8.9	84	···	32.4	40.2	39.2	38.3	37.3	36.4	34.8
78119-2	awake	3 mm in cortex			not stunned	39.2	46.2	42.6	40.6	40.2	39.8	39.6

Average total energy/pulse = 762.48 J. Average temperature rise = 7.49°C. Temperature rise/unit energy input = 9.45×10^{-3} °C/J.

TABLE 3. Effects on heart rate in rats stunned by microwaves.

Subject	Physical condition	Net power (kW) (0.1-s pulse)	Heart rate (beats/min) before	0 min	1 min	2 min	3 min	4 min	12 min
78113-A	awake	9.2	395	396	372				
79119-A	awake	9.1	408	402	378			402	390
79119-B	awake	8.84	392		312	336	372		
79119-C	awake	5.9	462				390		
79113-B	anesthetized	6.1	379	393				375	

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