ACKNOWLEDGMENT

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Effect of 2450-MHz Radiation on the Rabbit Eye

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***Abstract*—The cataractogenic effects of near-zone 2450-MHz radiation in rabbits are presented. The power deposition pattern inside the eyes and head of rabbits has been determined using a thermocouple technique. It was found that a peak absorption of 0.92 W/kg occurred between the lens of the eye and the retina for each milliwatt/square centimeter incident. Time and power-density studies indicated a cataractogenic threshold of a 150-mW/cm² incident, or 138-W/kg peak absorption behind the lens for 100 min. The threshold time decreased with increasing power density. Agreement between *in vivo* intraocular temperature measurements and finite-element computer predictions reinforces the suggestion of a thermal mechanism for microwave-induced lens opacities.**

INTRODUCTION

PRODUCTION of lens opacification in the eyes of laboratory animals by exposure to microwave radiation has been known to occur since 1948 [1]–[3]. However, the exact conditions under which these changes exhibit themselves are often subjects of discussion. While it is generally known [4]–[6] that acute exposures to high-power continuous-wave radiation cause various degrees of lens opacities at a number of frequencies, there remains the question of whether chronic exposure to low power densities or pulsed radiation of low average power is significant in the induction of cataracts. Absorption of microwave energy in the eye and consequent conversion into heat has been thought of as the principal mechanism responsible for the cataractogenic effect. However, recent reports [4],[5] suggested that some factors other than the thermal one might be responsible. These reports allude to formation of lens opacities in animals receiving repeated exposures of microwave radiation at levels believed to produce insufficient temperature rise. A large portion of past investigations were characterized by lack of quantitative rigor and produced few results useful for the purpose of scientific extrapolation to human exposures. It is essential that quantitative relationships between the physical variables of microwave radiation and the biological changes in the eye be determined in order for the animal data to be of use in predicting safe levels of human exposure.

Extending the concept of quantitative measurement of the actual fields or absorbed power in the affected tissue structure relative to the incident radiation, we have established the microwave field and power patterns both inside and outside the rabbit's head and eyes by special measurement techniques while the animals were exposed to near-zone 2450-MHz radiation from a corner reflector (dia-

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thermy *C* director). Time and power threshold for cataractogenesis in rabbits exposed to the above conditions has also been clarified. *In vivo* experiments and computer modeling have been applied to study the intraocular temperature during microwave irradiation. The good agreement between these two approaches reinforces the suggestion of a thermal mechanism for microwave cataractogenesis.

EXPERIMENTAL

The subjects were 107 New Zealand white rabbits of both sexes weighing 3.5–4.4 kg, and were eight months old when they were initially involved with these experiments. Seven animals were used for the dosimetry studies, nineteen were used for retrolental temperature studies, and the rest were divided into groups of not less than three for each determination of time and power threshold for microwave cataractogenesis. The basic experimental arrangement was the same for all parts of this study. The rabbits were placed in an acrylic box with the head and hind legs outside (Fig. 1). The box contained extra openings for ventilation. The head was fixated by a specially constructed acrylic restrainer. The animals were exposed in a microwave anechoic chamber to the near zone of a 2450-MHz corner reflector (diathermy *C* director) with horizontal polarization. The distance between the crossing point of the dipole feed and the corneal surface of the eye was 5 cm. The incident power density at the same position as the right eye of the rabbit was measured with a Narda 8100 electromagnetic radiation monitor with the box and head restrainer in place, but the animal absent. The power delivered to the corner reflector antenna was monitored continuously with a dual directional coupler and Hewlett-Packard 430C microwave power meters.

A. Dosimetry—Absorbed Power Distribution

The absorbed power distribution along the anterior–posterior axis of the eye and extending to the head was determined by measuring the temperature rise in the tissue, which is proportional to the absorbed energy, due to a short exposure to high-intensity radiation. The absorbed power density (PD) in watts per kilogram can be obtained from a knowledge of the tissue specific heat c, density ρ, temperature rise ΔT, and the duration of exposure t from the expression $PD = 4186\ c\rho\Delta T/t$. The animals were prepared with an initial dose of acepromazine (0.4 cc) and sodium pentobarbital (Nembutal, 10 mg/kg) given intravenously via a marginal ear vein. After 15–20 min, an ear vein was cannulated and surgical anesthetic level maintained throughout the experiment by periodic injection of sodium pentobarbital. Rectal temperatures and pulse rates were monitored with a Yellow Springs telethermometer and a Hewlett-Packard 7807C cardiac monitor, respectively, throughout the experiment and recorded before and after each exposure.

The surgical procedures involved retraction of eyelids by passing silk sutures through the lids and fastening the sutures to the head restrainer. The eye was kept immobilized by silk traction sutures under the superior and inferior rectus muscles. A hollow glass probe (1.4-mm OD) of known length was inserted through a corneal hole obtained by removing a 1-mm corneal button. To prevent collapse of the anterior chamber after trephining a corneal, and subsequently a lenticular hole for the thermocouple probe, a finely drawn-out glass pipette attached to polyethylene tubing was inserted into the chamber where it it came to rest just anterior to the superior iris (Fig. 2). The polyethylene tubing was connected to a bottle of 5-percent dextrose in 0.9-percent NaCl solution hanging on a stand such that the resulting hydrostatic pressure was sufficient to reform the chamber after insertion of the thermocouple probe.

Preliminary experiments indicated that if a hole was drilled through the entire lens thickness in one stage, the lens would become rapidly hydrated and swollen, and would almost eliminate the anterior chamber and thus significantly alter the ocular dimensions. If only the anterior half of the lens was first drilled, no significant change in anterior chamber depth occurred. Consequently, when the anterior capsule of the lens was reached during the experiment, a tunnel for passing the thermocouple probe was drilled in two stages. The interval between the initial and final drilling stages was 25 min. The drill consisted of a 15-gauge ground-down needle stock (1.4-mm OD) coated with stopcock grease for lubrication. Drilling was found to be necessary in such mature animals because the

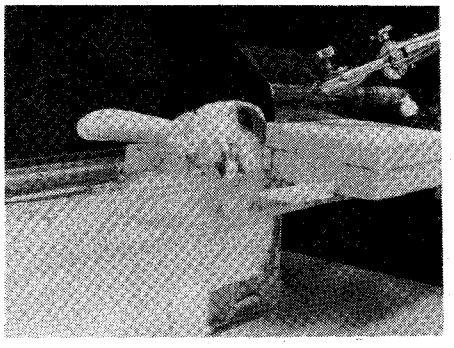

Fig. 1. Rabbit under microwave exposure.

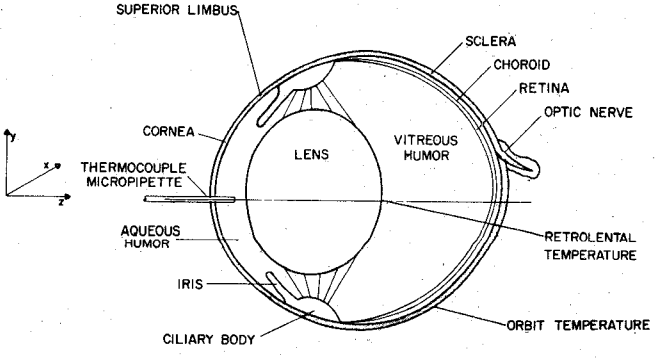

Fig. 2. Vertical section of a rabbit eye showing the thermocouple probe.

lens was too hard to allow passage of a needle without dislocating the lens from its normal position.

A fast-reacting, iron–constantan thermocouple was passed into the probe and the intraocular temperature was measured at increasing depths of 2-mm increments, each taken just prior to and just after a short exposure (20 s) of a known level (540 mW/cm²) of high-intensity microwave radiation. The measurements in the rabbit head extending beyond those of the eye were conducted at 3-mm intervals immediately after sacrifice. An intraperitoneal injection of euthenol solution was used to sacrifice the animals.

The ocular dimensions were determined by enucleating and freezing the fellow eye after completion of each experiment. The fully solidified eye was bisected sagittally resulting in a nasal and a temporal half. Anterior–posterior measurements were made of the corneal thickness, anterior chamber depth, lens, and the distance between posterior lens capsule and retina. These were used as a guide in gauging the location of the probe in the other eye, since passage of the probe into the lens prevented direct visualization of its tip.

The absorbed power patterns resulting from the dosimetry measurements are shown in Fig. 3. In all cases, the absorption reached peak values within the vitreous body, about 1.5 cm behind the cornea, and had a mean of 0.92 W/kg for every milliwatt/square centimeter incident. During the dosimetry runs the rabbits generally showed an increase in rectal temperature of 0.97°C and an increase in pulse rate of approximately 30 percent. The uncertainty associated with using thermocouples immediately after cessation of microwave radiation to measure the true temperature rise was established to be small, as shown in Fig. 4. The result was obtained using the computer model to calculate the temperature elevation from dosimetry measurement and follow the postirradiation temperature decay on the computer.

B. Retrolental Temperatures

Rabbits were anesthetized with sodium pentobarbital and acepromazine administered intravenously with periodic supplements of sodium pentobarbital during the surgery and measurement sessions. The animals were placed in the acrylic box. Following removal of a 1-mm hole through the upper sclera, a glass thermocouple holder (probe) similar to that employed in the dosimetry studies was inserted 4 mm behind the superior limbus. The glass probe was oriented under direct visualization to lie just behind the posterior pole of the lens. Orbital, rectal, and ambient temperatures, as well as respiratory rates and ambient percent humidity, were monitored throughout. Microwave irradiation at a predetermined level was performed at 5-min intervals, pausing momentarily for introduction of the thermocouple into the probe. After a 2–3-s stabilization, the temperature was recorded and the thermocouple withdrawn. The process was repeated until the desired length of exposure was realized.

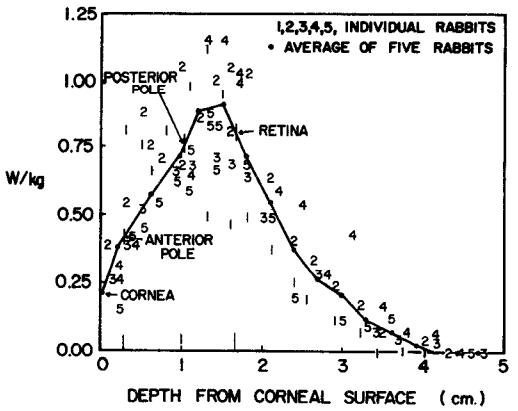

Fig. 3. Absorbed power distribution in the rabbit's head and eye exposed to 1-mW/cm² microwave radiation.

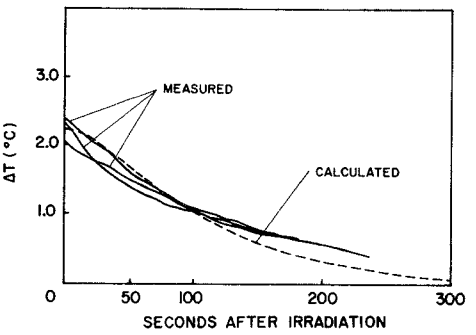

Fig. 4. Measured and computed temperature decay as a function of time following cessation of microwave irradiation.

The actual peak temperature in the vitreous body behind the lens reached in three different radiation conditions was determined and is shown in Fig. 5. These are for 100 mW/cm² incident for 60 min, 200 mW/cm² for 35–40 min, and 300 mW/cm² for 30–35 min. The absorbed power, as determined from Fig. 3 is, respectively, 90, 180, and 270 W/kg. Each power level reached its own specific temperature plateau after 15–20 min due to the gradual increase of body-core temperature. The temperature for the 100 mW/cm² ones stayed consistently at 41°C, while that for 200 and 300 mW/cm² all surpassed 41°C. The baseline orbital temperature in each case was practically identical with the rectal or core temperature (Fig. 6), but after the first 5 min of irradiation, the former followed the intravitreous temperature rise more closely. The orbital temperature, however, never rose as high as the vitreous. This presumably is because of the greater blood flow and hence greater heat-regulating capacity of the orbit. It is interesting to note that rabbits exposed to 200 and 300 mW/cm², without surgical manipulation of the eye or ocular temperature probing, all developed lens opacities while those exposed to 100 mW/cm² remained unaffected (see Part C).

C. Cataractogenic Time and Power Threshold for an Acute Single Exposure

Eighty-one rabbits, averaging 4.0 kg, were used to determine the cataractogenic threshold for near-zone

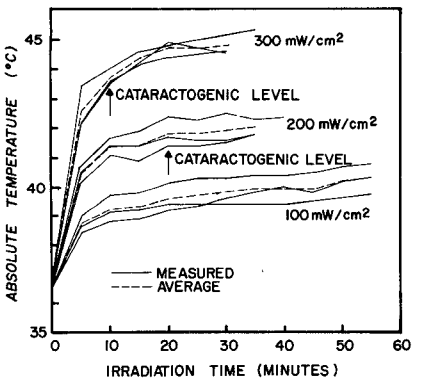

Fig. 5. Measured retrolental temperature in rabbits exposed to near-zone 2450-MHz microwaves.

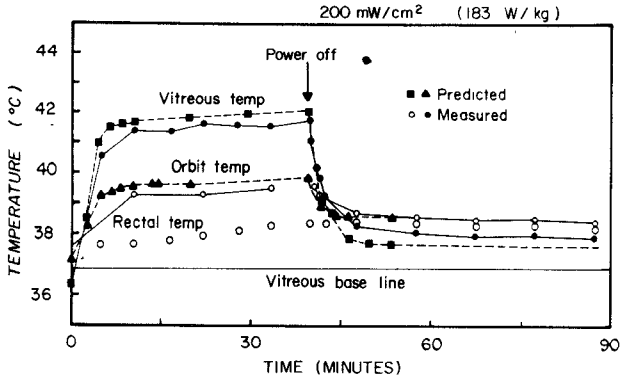

Fig. 6. Comparison of measured and predicted temperature changes in rabbits exposed to microwave radiation.

2450-MHz radiation. Prior to radiation, both eyes of the animals were examined, following pupillary dilation with 1:1 mixture of 1-percent cyclopentolate and 10-percent phenylephrine, using a Nikon slit lamp and an American Optical opthalmoscope. Any rabbits with general or ocular abnormalities were excluded from the study. Intravenous acepromazine and sodium pentobarbital were used for sedation. The animals were placed in the acrylic box and were irradiated in an anechoic chamber. The right eye was irradiated, while the left eye served as a control. Both low and high power densities at various exposure durations were used. The rabbits' eyes were examined with the slit lamp immediately after irradiation and periodically thereafter. Any abnormalities were recorded using a camera attached to the slit lamp and by hand sketches.

Depending upon the level of exposure, varying degrees of injection, tearing, pupillary constriction, and anterior-chamber turbidity were noted immediately following the exposure. These changes were transient and disappeared by the second day following exposure. Changes in the lens were usually detectable on the first or second day postirradiation.

At the lower exposure levels, mild and often reversible changes were observed. These consisted of a milky band (single, double, or triple) in the posterior cortex, close to the posterior capsule and extending to the equator. This banding was visible only with the slit lamp. In addition, a chain of vacuoles or small vesicles formed in the area of the posterior suture. At higher levels of irradiation, more advanced and permanent cataractous changes were noted. These changes consisted of more pronounced banding, an increase in the number of vacuoles with a definite well-circumscribed opacity forming in the posterior cortex, which was easily seen with an ophthalmoscope. Occasionally, large vesicles were seen in the equator of the lens, and, in a few cases, the posterior cortical opacity was found to involve not only the equator, but also extended from the equator to the anterior subcapsular cortex. As a rule, however, the cataracts were confined to the posterior cortical area. Only at relatively high levels would the entire lens become involved in the cataractous process. Examination of the fundi showed no abnormalities. The left, or control eye, aside from a transient pupillary constriction immediately following exposure, remained normal.

The time and power threshold resulting from these experiments is shown in Fig. 7, along with Carpenter's [4] and Williams' [7] curves. Each point on the chart represents 3–6 animals. It can be seen readily that our threshold curve follows Carpenter's very closely. The maximum absorbed power shown on the right-hand side is slightly lower than the incident power density in numerical value. Note that the minimum cataractogenic power density was found at 150 mW/cm² for 100 min, which represents a maximum absorbed power of 138 W/kg.

COMPUTER MODELING

A. Intraocular Temperature

The temperature distribution of an intact eye in the rabbit under microwave irradiation was modeled numerically using a finite element of rectangular and triangular annular regions shown in Fig. 8. The model incorporates into it various cooling mechanisms such as conduction, evaporation, and radiation [8]. The calculations were based on a spatially constant specific heat equal to that

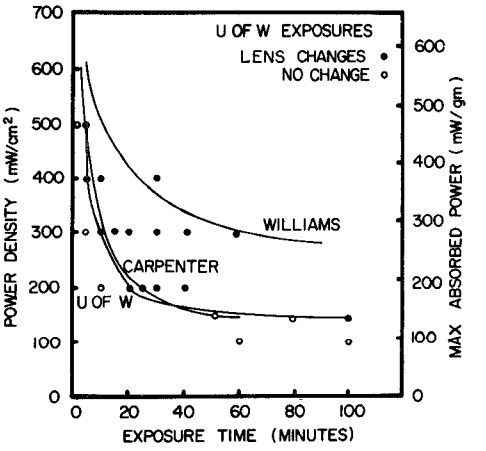

Fig. 7. Time and power-density threshold for cataractogenesis in rabbits exposed to near-zone 2450-MHz radiation.

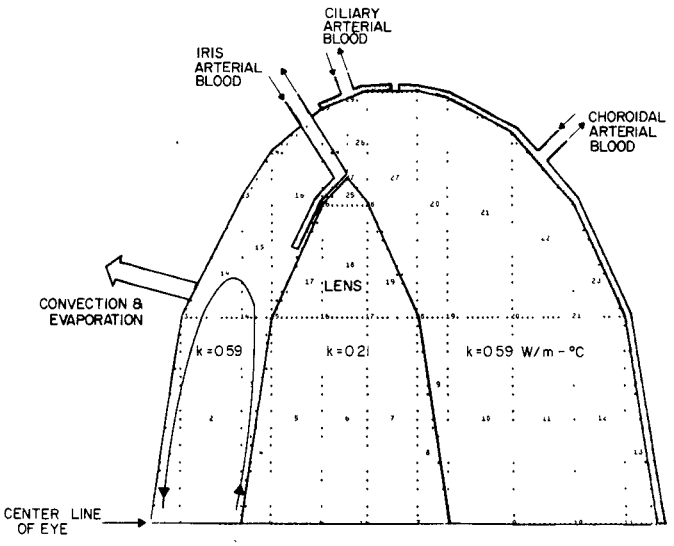

Fig. 8. Computer model of the upper half anterior–posterior section of rabbit eye showing various thermal regulating mechanisms.

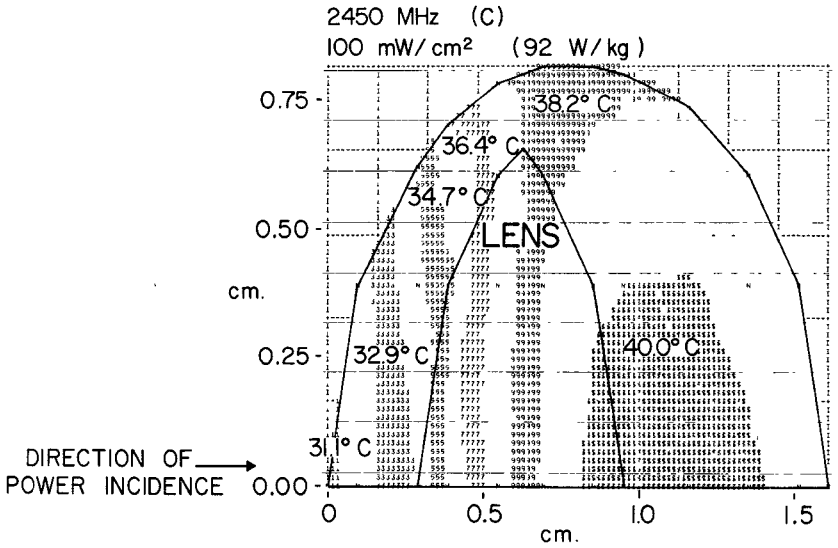

Fig. 9. Computer-predicted intraocular temperature in the rabbit exposed to 100 min of near-zone 2450 MHz at 100 mW/cm².

of a saline solution, a vitreous-humor thermal conductivity of 5.94 mW/cm/°C as measured in the beef eye [9], and a lens thermal conductivity of 2.13 mW/cm/°C obtained by finding the ratio of the electrical conductivities. The aqueous-humor conductivity was 5.94 mW/cm/°C. These conductivities were checked by calculating the eye temperatures in a nonirradiated eye with an orbital temperature of 37.8°C reported in the literature [10], and excellent agreement was obtained at all points along the pupillary axis. A blood supply rate of 1.7 cc/min is assumed for the vascular bed of the eye which includes the iris, ciliary body, and the choroid [11]–[13]. The predicted temperature distribution depends also upon the specific orbit temperature and upon the heat-transfer rate at the corneal surface. The orbit temperature is assumed to be 39°C, and the heat-transfer values due to convection and radiation were taken to be 1 and 0.6 mW/cm²/°C, respectively. Evaporation heat loss was assumed to be 1.2 mW/cm²/mW/kg. An average ambient condition of 25°C and 35-percent humidity was taken as the standard. Calculations were made for several exposure levels using the above conditions, and the measured absorbed power distribution shown in Fig. 3.

Calculations for 2450-MHz induced temperature distribution in the eyes of rabbits were performed for incident radiation levels of 100, 150, 200, and 300 mW/cm², applied for 100, 100, 30, and 20 min, respectively. The resulting banded isotherms over an anterior–posterior section are shown in Figs. 9–12. In all cases, the highest temperatures are localized on the center line near the posterior surface of the lens. The 100 mW/cm² case showed slight elevation over the 39°C blood temperature, whereas the 150, 200, and 300 mW/cm² produced temperatures of 40.0, 42.4, 42.8, and 45.8°C, respectively. These results were in complete agreement with the measured retrolental temperature rise.

The transient temperature rises in the eyes were also obtained from the computer model. Fig. 6 illustrates that

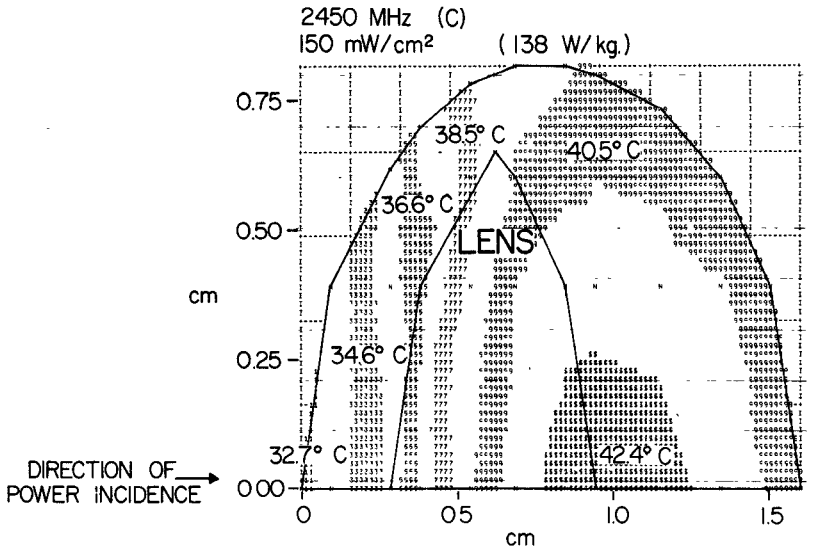

Fig. 10. Computer-predicted intraocular temperature in the rabbit exposed to 100 min of near-zone 2450 MHz at 150 mW/cm².

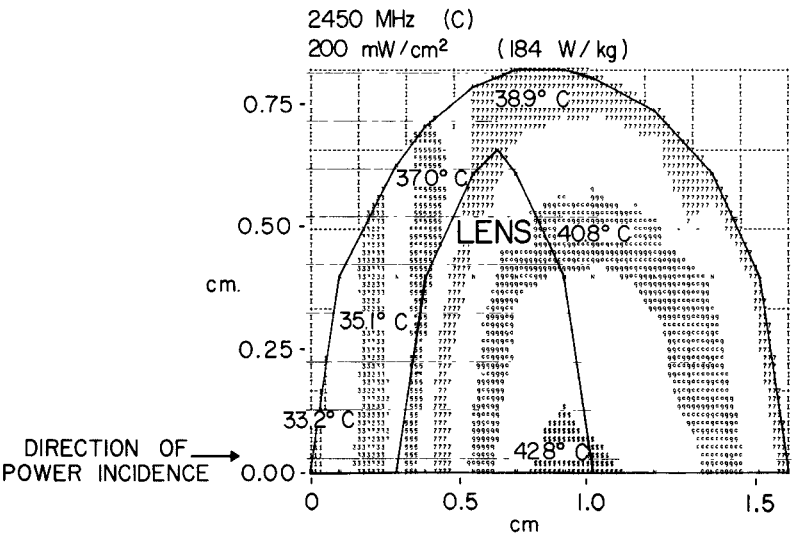

Fig. 11. Computer-predicted intraocular temperature distribution in the rabbit exposed to 30 min of 200-mW/cm² near-zone 2450-MHz radiation.

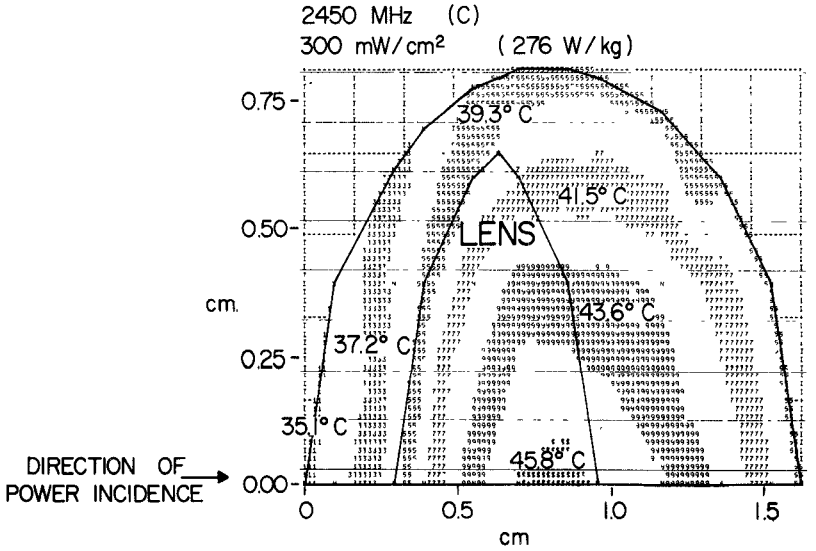

Fig. 12. Computer-predicted intraocular temperature distribution in the rabbit exposed to 20 min of 300-mW/cm² near-zone 2450-MHz radiation.

there was good agreement between the predicted and measured temperature changes.

CONCLUSIONS

The absorbed power distribtuion pattern in the eyes of rabbits exposed to near-zone 2450-MHz radiation has been derived from thermocouple measurements. The results indicated that the absorption increased steadily until a peak of 0.92 W/kgm for each millwatt/square centimeter incident was reached in the vitreous body (just behind the lens) and then fell off rapidly as the depth increased, thereby suggesting the lens may be the most susceptible or critical part of the eye to near-zone 2450-MHz radiation. This contention was strongly supported by our time and power-density threshold studies. Following irradiation, irreversible changes in the lens were seen in the posterior cortical area only. All other changes in the eye were transient and disappeared by the second postirradiation day. Our time and power-threshold curve agreed closely with that of Carpenter. The minimum cataractogenic power density was 150 mW/cm^2 for 100 min, which corresponded to a maximum absorbed power density in the vitreous body of 138 W/kg.

Comparison of the measured and computer estimate of peak retrolental temperatures and consideration of the overall results of cataractogenic threshold revealed a possible threshold cataractogenic temperature around 41°C in the eye. This points to a localized heating mechanism responsible for the microwave cataractogenic effects. However, the validity of this observation needs to be carefully examined, and the possibility of some nonthermal interaction of microwave radiation with the lenticular structure should not be casually discarded.

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