Glaser

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Effect of Microwaves on the Eye

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Abstract—The utilization of microwave energy to produce an acute effect on the eyes of rabbits was experimentally investigated using both CW and pulsed power at 5.5 GHz. When present, lens opacities were developed within four days after exposures of sufficient intensity and duration; three minutes at the one-watt level were found to exceed cataractogenic threshold, while at the 1/2-watt level no acute effect was observed following a two-hour exposure.

The method consisted of placing the anesthetized animals so that the exposed eye served as the termination of a length of waveguide, permitting conventional microwave instrumentation to be used for measurement of power entering the eye. The development of a device to channel the microwave power from the relatively large waveguide cross section through a small aperture for delivery into the eye of the animal was a necessary preliminary to the carrying out of this work.

Threshold curves were determined for both CW and pulsed (0.001 duty cycle) power and no substantial difference was found to exist. Thus, the average power level rather than the peak power was the determinant of injury.

As a by-product of the work, the exposure technique may serve as a useful tool for inducing cataracts. This may be of value in ophthalmic research, since other current methods for producing cataracts involve use of toxic agents.

FOREWORD

THIS ARTICLE describes a continuing experimental study of microwave cataractogenesis by a team with Dr. M. M. Zaret as principal investigator. This investigation, appearing deceptively simple to execute, incorporates the rather extensive efforts of many microwave, biological, and medical personnel of the Zaret Foundation and the Department of Electrophysics of the Polytechnic Institute of Brooklyn.

INTRODUCTION

The response of the living organism to RF radiation [1] generally, and to microwave power [2]–[4] in particular, has been the subject of considerable study. From this work, it is known that exposure to microwave power has a harmful effect when the intensity and duration of irradiation have been properly selected. Of special interest in this paper is a form of eye injury where the normally transparent lens becomes opacified.

Viewed from the present, it appears not at all strange that eye injuries should occur; in fact, it is almost obvious, a consequence of the avascularity of many parts of the eye and the known capability of microwave energy for heating living tissues. However, until it was discovered by Daily *et al.* [5] and Richardson *et al.* [6] that microwave power (2.45 GHz, CW) can produce cataracts in animals, it was by no means evident that this would occur. Subsequently, this conclusion was verified and quantitatively supplemented by Richardson *et al.* [7], who showed that 10-GHz pulsed power produces cataracts in the rabbit lens; by Williams *et al.* [8] and Carpenter *et al.* [9], who established time-power-density cataractogenic threshold levels at 2.45 GHz (CW) for the rabbit; by Carpenter and associates [10], [11], who established time-power thresholds at 8.236 and 10.05 GHz (CW); and by others. It is the purpose of this paper to complement existing data by reporting the results of an investigation of the acute effects produced by CW and pulsed 5.5-GHz irradiation on the lens of the rabbit eye.

In humans, cases of microwave-induced cataract are well documented [12]–[14]. Early stages of this lens opacification process are termed incipient cataract, a condition which may lie dormant for long periods of time without materially reducing visual capability. Eventually, the opacification spreads through the lens substance and becomes denser. This results in the loss of useful vision at which time the condition is recognized clinically as a cataract.

Ultimately, microwave-induced cataracts result in blindness. Therefore, interest in the potentially hazardous effects [15] of microwaves is a natural consequence of their wide use in radar, communications links, industrial processing, and now even in the home for ovens.

Human [16]–[18] and rabbit [19], [20] eyes exhibit a general similarity of anatomy which is represented in Fig. 1. This permits utilization of the rabbit for a general qualitative study such as this. With reference to Fig. 1, light enters the eye through the cornea, is transmitted through the aqueous fluid, passes through the pupillary opening in the iris, through the lens and the vitreous body, and through the inner layers of the retina to the photosensitive cells that initiate neural transmissions to the brain. Opacification of the lens is therefore seen to interrupt the free transmission of light through the eye.

A description is given of the method and equipment used to irradiate the eye. Technical aspects of an adaptor used to channel power from the relatively large waveguide cross section through a small circular aperture into the eye of the experimental animal are discussed.

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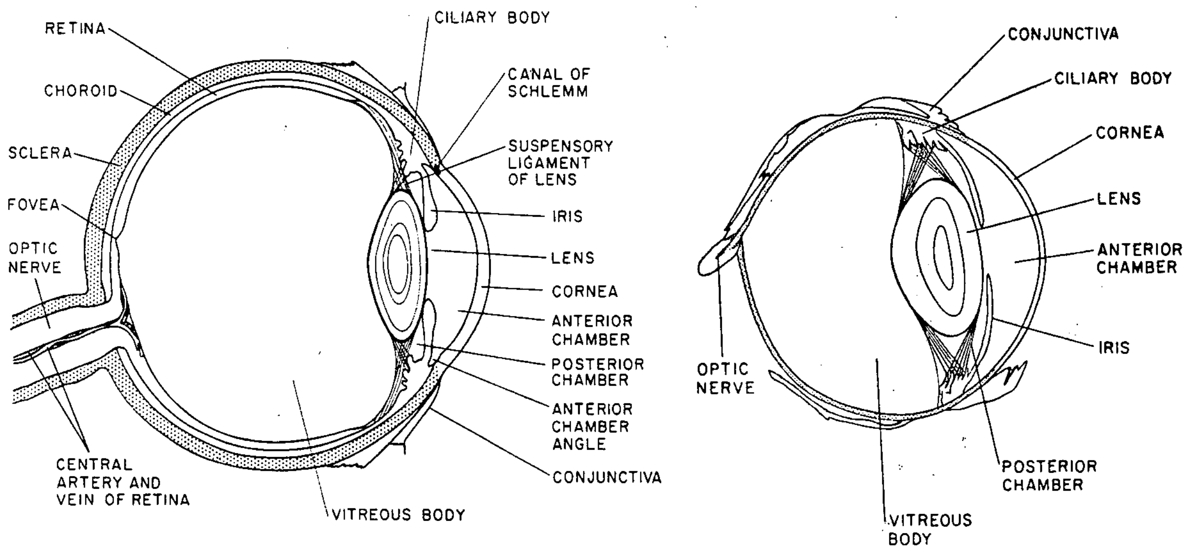


Fig. 1. Cross sections of (a) the human eye and (b) the rabbit eye.

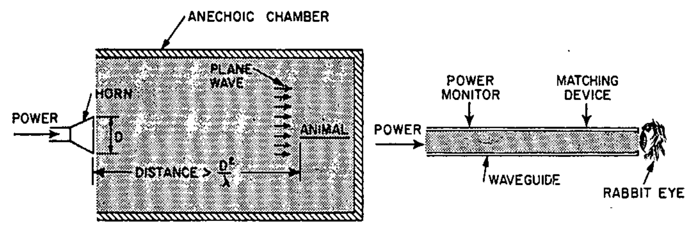


Fig. 2. Two possible methods of microwave irradiation. (a) Free-field method. (b) Closed-waveguide system.

The results of CW and pulsed exposures are presented and compared. Briefly, our work showed that

1) an acute lens injury, when produced, was almost always apparent by the fourth day following the exposure
2) no significant difference between the effects of CW and pulsed power was observed.

General Method of Irradiation

The technique employed was the "closed-waveguide" system originated by Carpenter and associates [10], [11]. This consisted of using one eye of an anesthetized animal as the RF termination for a length of waveguide [Fig. 2(b)]. By so doing, standard microwave instrumentation could be used to determine exactly how much power actually entered the eye of the animal.

Initially, attempts were made to conduct the exposures by placing a metal plate with a centered $\frac{1}{2}$-inch-diameter hole directly at the end of the waveguide, as suggested in Fig. 2(b); the animal was positioned so that the exposed eye was placed in the aperture and an E-H tuner was used for matching purposes.

Certain difficulties were encountered with this method, however. Very large reflections were observed (the standing wave ratio was about 30), making the setting of the tuner critical, and the transmission loss was large (about 3 dB). Also, during the actual exposures, slight movements of the rabbit's eye made it necessary to continuously retune the device. As a result, the transmission losses were variable, so that there existed considerable uncertainty about the value of the power level. In view of these difficulties, it appeared that a less abrupt method of terminating the waveguide was required.

Transition from Waveguide to Rabbit's Eye

For the purpose of achieving a more gradual transition from the waveguide to the animal's eye, i.e., one having lower reflections and consequently easier to match, the adaptor shown in Figs. 3 and 4 was finally developed. It is seen to consist of two sections, the first of which is a transition from *C*-band waveguide (RG-49/U or WR-187, with 1.872-inch by 0.872-inch inner dimensions) to ridged guide. The second is a length of circular waveguide. Both portions use Stycast[1] inserts of relative dielectric constant 12. The function of the dielectric taper and of the ridged guide is to concentrate the energy, normally distributed over a large cross sec-

[1] Manufactured by Emerson and Cuming, Canton, Mass. It has very low losses at microwave frequencies (loss tangent is about 0.001).

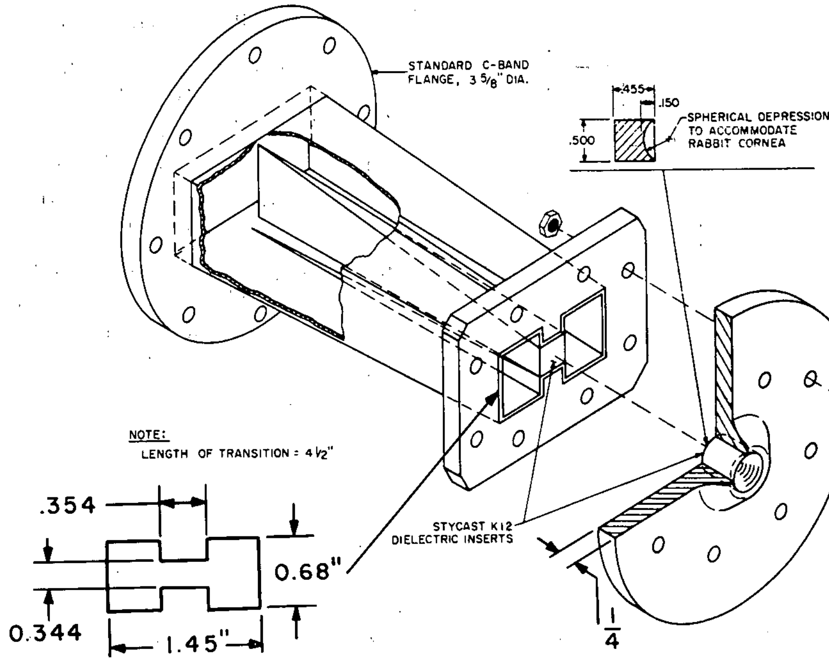


Fig. 3. Drawing of transition from waveguide to rabbit eye.

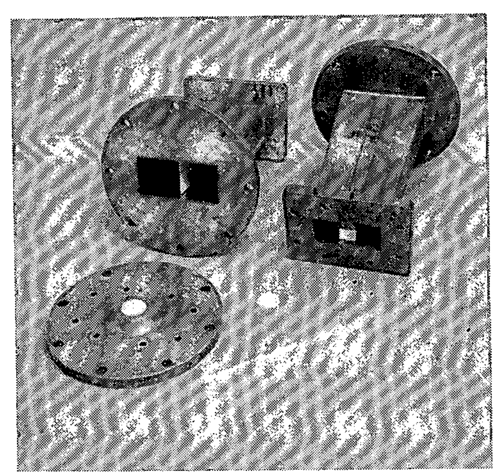


Fig. 4. Photograph of transition from waveguide to rabbit eye.

tion in the rectangular waveguide, into a relatively small cross section. The circular waveguide then provides a good mechanical way of irradiating the animal's eye through the $\frac{1}{2}$-inch-diameter aperture. The sketch shows that the end of the circular waveguide has a spherical depression to accommodate the cornea of the rabbit's eye, and protrudes beyond the adaptor and the bony orbit within which the rabbit's eye is recessed.

An important property of the transition is its effectiveness in matching the eye to the waveguide, measured without using a tuner. The degree of success achieved in this respect is shown by the curve in Fig. 5. Although the data were taken with a rabbit eye that had been fixed in formaldehyde, there is very little difference between these values and standing wave ratios obtained when terminated with a rubber sac filled with physiological saline, or with ordinary tap water, or when terminated with the eye of a living animal.

A second important characteristic of the transition is the power loss that occurs during transmission. The most direct experiment to make involves a measurement of the power entering and leaving the transition. This was actually done [21] at 5.5 GHz in the following way. The transition was terminated with a small rubber sac filled with water, to simulate the eye of an animal. The power entering the transition was measured using a thermistor detector. The temperature rise of the rubber bulb was observed. Using a second (dummy) identical rubber sac in an identical thermal environment, dc power was used to heat it to exactly the same temperature existing in the microwave-heated sac. This dc power was then taken to be identical to the microwave power leaving the transition. The result obtained for the transition loss was 0.28 dB.

Another method of loss measurement, less direct but much easier to make, takes advantage of a result rigor-

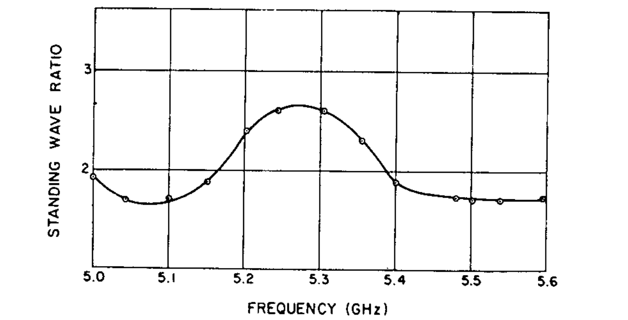


Fig. 5. Effectiveness of transition in matching waveguide to eye.

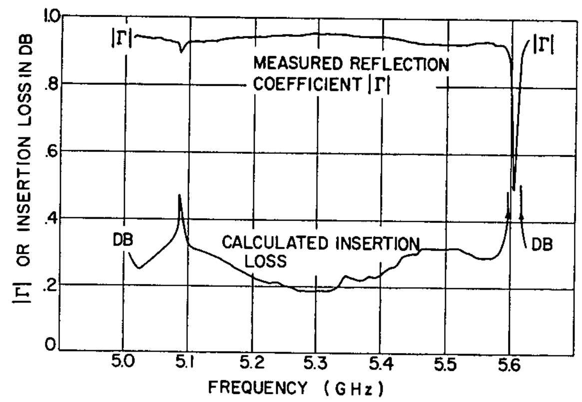


Fig. 6. Test of transition losses.

ously applicable to a length of uniform waveguide. The attenuation experienced by a wave transmitted through the guide into a matched load may be related to the standing wave ratio r observed when the waveguide is short-circuited at its output end:

$$\text{attenuation} = 10 \log \frac{1}{|\Gamma|}, \quad |\Gamma| = \frac{r-1}{r+1}.$$

For the complicated transition actually used, this method represents more of an intelligent estimate than an accurate measurement. However, since the attenuation is relatively small, an error as large as 30 percent is not a serious one. In Fig. 6, the reflection coefficient $|\Gamma|$ and the corresponding attenuation are plotted; the deviation of $|\Gamma|$ from an ideal value of 1 is a qualitative measure of the transducer loss, and the attenuation values may be taken to be fair quantitative estimates of the transducer loss. By inspecting the figure, it is seen that the transmission loss is of the order of 0.3 dB except at 5.6 GHz. At this frequency, it is believed, resonance in a higher mode (not identified) was excited within the transmission. In fact, at 5.1 GHz, this may also be true except that the coupling to this spurious mode was very much looser. Parenthetically, it is noted that it is of the utmost importance that the sharp edge at the beginning of the dielectric taper (see Figs. 3 and 4) be maintained, for if it is broken, the spurious modes are excited very strongly with consequent high losses within the transition.

Preparation of the Animal for Exposure

Immediately before exposure the rabbit was examined to determine whether both eyes were normal. Next, the rabbit was anesthetized by administering, intramuscularly, a tranquilizer (sparine or promazine HCl, 20 milligrams per kilogram of body weight) followed about 15 minutes later by diluted sodium pentobarbital (35 mg/kg) administered intraperitoneally. If necessary, a 15-mg/kg booster was given in the ear vein. The left eye was taped open and a few drops of Barnes-Hind wetting solution applied to prevent drying of the cornea.

Details of the Exposure Technique

The rabbit was positioned so that the cornea of the left eye was in contact with the transition when the latter was mounted in the equipment arrangement shown in Figs. 7 and 8. The slide screw tuner in front of the transition was adjusted for unity standing wave ratio. Microwave power was then increased to the desired dosage level and the duration of the exposure carefully timed. The power level was continuously monitored by a thermistor mount and power meter attached to the output arm of a directional coupler. Calibration was performed before the start of the test.

After the exposure, the rabbit's eyes were reexamined for immediate effects. Subsequently, the animal was examined the fourth day after exposure, and at weekly intervals thereafter for a period of about one month.

Results of Microwave Exposure

Acute inflammatory reactions of the cornea, conjunctiva, iris, and/or ciliary body were observed in many and probably produced in every exposed rabbit eye. Although such reactions were frequently severe immediately following irradiation, they had usually subsided by the fourth day.

Acute lens injury, on the other hand, runs a different and more prolonged course. Ordinarily, the initial phase of hydration begins several hours after exposure and last for about a week. During that period, opacification, if it is going to occur as part of the acute process, becomes evident. Therefore, by the fourth day following irradiation, almost all of the cases where opacification is going to occur as part of the acute lens injury can be recognized because the inflammation of the other ocular tissues has subsided sufficiently to permit detailed examination of the lens.

Occasionally, lens opacification cannot be observed or does not appear for another week or two. Therefore, the rabbit lenses were examined weekly for three additional weeks. The endpoint observation was the presence or absence of lens opacification, no matter how minimal, during the four-week period following exposure. Opacification occurring during this interval con-

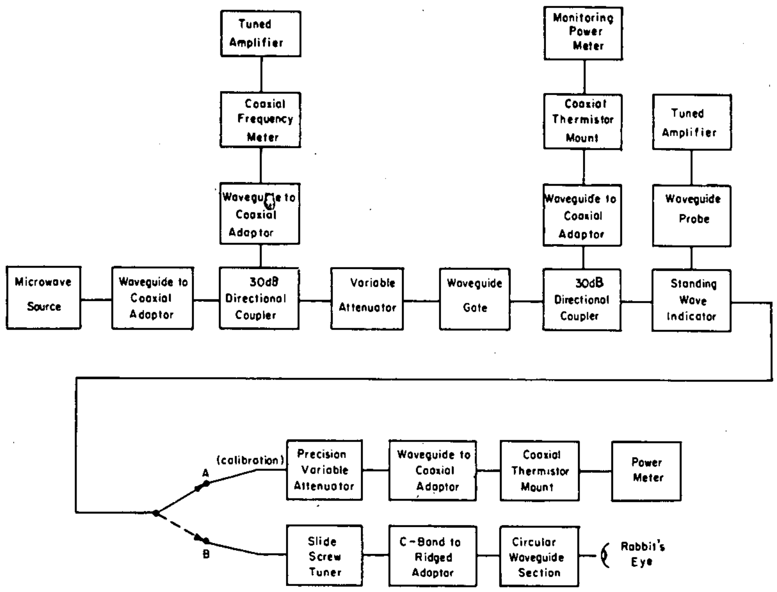


Fig. 7. Block diagram of equipment arrangement for microwave irradiation of rabbit eye.

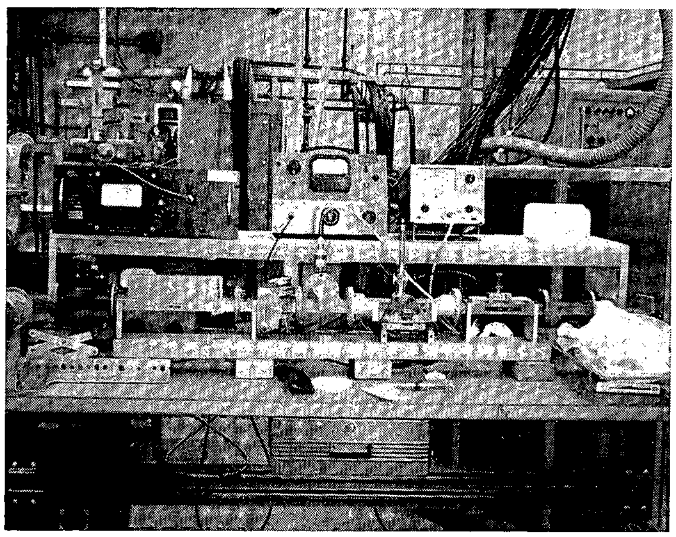


Fig. 8. Exposure of left eye of rabbit to 5.5 GHz.

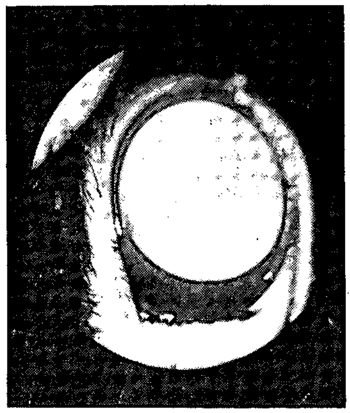
stitutes permanent, irreversible, acute lens injury. Almost invariably, such opacification was present in the anterior portion of the lens. As such, it would obscure the presence or absence of opacification at deeper levels within the lens. Gradations of lens injury are demonstrated in Fig. 9.

The data obtained for 100 exposures to pulsed microwave radiation (5 μs, 0.001 duty cycle) are presented in Fig. 10, a graphical display of the average power intensity and exposure duration required to produce lens changes at a 50-percent probability level. Fig. 11 is a similar graph depicting the results of 62 exposures to CW microwave radiation. For clarity, each graph is divided into shaded and clear areas to distinguish between regions in which the probability of lenticular change exceeds or is less than 50 percent.

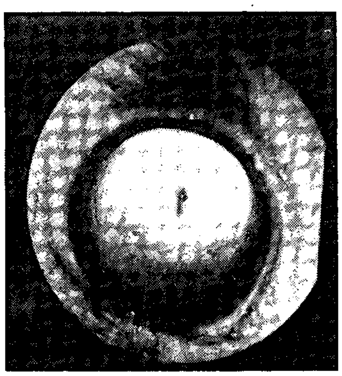
Close inspection of Figs. 10 and 11 reveals that the boundaries between the clear and shaded sectors are to some extent arbitrary. Consequently, despite the difference between the two thresholds as drawn, it appears reasonable to conclude that for the exposure conditions utilized, the threshold values for continuous and pulsed radiation are not significantly different from each other when exposure is expressed as average power. (See Fig. 12.)

Discussion

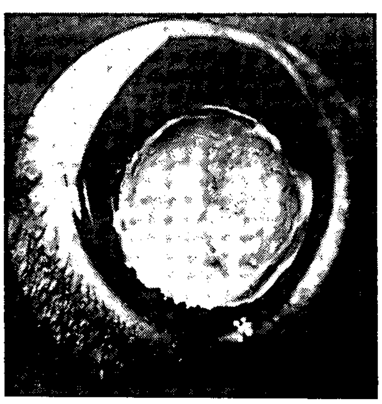
The adaptor utilized to channel power from the relatively large waveguide cross section into a match with the entrance geometry of the eye of the experimental animal may prove to be useful for investigators wishing to induce cataracts by nontoxic means.



(a)



(b)



(c)

Fig. 9. Gradations of microwave-induced lens injury. (a) Normal rabbit lens. (b) Minimal. (c) Extensive.

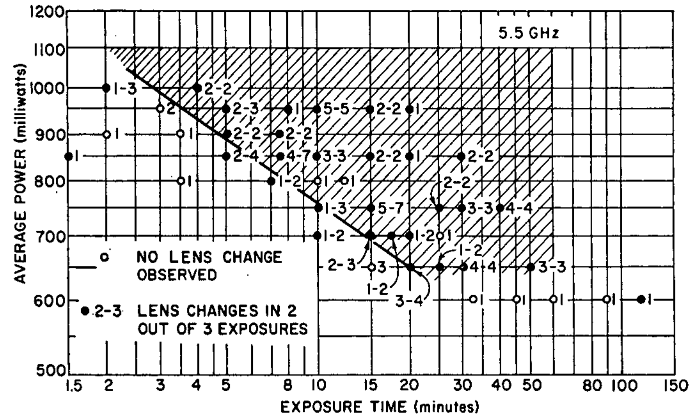


Fig. 10. Results of pulsed microwave exposures.

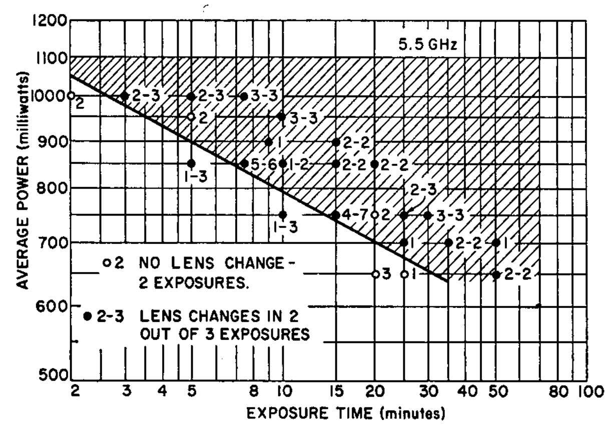


Fig. 11. Results of CW microwave exposures.

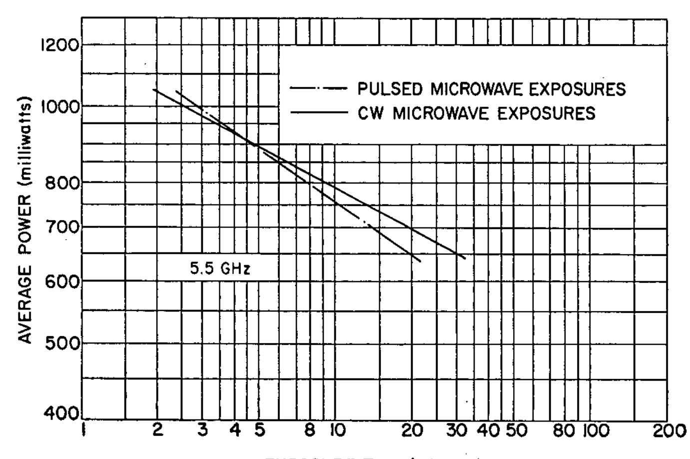


Fig. 12. Comparison of 5.5-GHz pulsed and CW thresholds.

Regarding the experimental results, several items require amplification. The first concerns definition of the threshold value for an acute injury of the lens. Irreversible opacification, as the selected endpoint, is an observable loss of transparency in at least a portion of the lens and it represents an objective determination. No attempt was made to evaluate reduction of visual acuity which is purely subjective. Therefore, although this endpoint is readily determined by an observer, it cannot be directly related to the clinical condition termed cataract.

Another factor to be considered is the acute nature of these experiments. For this reason, extrapolation cannot be made to conditions of subacute, intermittent, or continuous chronic exposure, nor to the delayed appearance of lenticular opacification.

An additional factor for consideration is the utilization of a 50-percent probability curve. As with other biological reactions, there are individual variations among animals which give rise to the well-known biological bell curve. The selection for our threshold criterion of values where there is a 50-percent probability of inducing a lenticular opacification represents a recognition of biological variability.

By applying the 50-percent probability value and examining that portion of the logarithmic graph where the intensity-duration function is linear, it is evident that, at 5.5 GHz, the dose of microwave radiation required to produce an acute lens injury is based upon average rather than peak power.

It is of interest to note that the threshold curves for 5.5 GHz generally resembled those obtained previously at 8.2 and 10.0 GHz with CW power by Carpenter and associates [10], [11] using the closed-waveguide technique.

At this point, it is pertinent to discuss, in a conceptual way, the relationship between thresholds derivable from closed-waveguide exposures and those determined from free-field exposures. In the former, one measures the power that actually enters the eye of the animal. In the latter, before the animal is placed in the far field of the transmitting antenna, the power density is measured using a receiving antenna of known gain. Unfortunately, as soon as the animal is inserted into the field, the power density contours are changed [11]. This means that it is no longer correct to determine the power incident upon the eye by multiplying the measured power density by the cross-sectional area of the eye. Also, reflections from the eye reduce the power dissipated within it. Thus, power dissipated within the eye is an unknown quantity, and direct comparison with closed-waveguide results is not possible without additional information. Finally, in the free-field case, heating of the animal by the incident radiation may affect the cataractogenic effectiveness of the power entering the eye.

To make things worse, *all* of the time–power–density thresholds so far reported [8]–[10] were established with the animal located in the *near* field of the transmitting antenna, making even more questionable the evaluation of power dissipated within the eye of the animal from these data.

Data concerning the relative effectiveness of CW and pulsed power were reported earlier by Carpenter [10] for a duty cycle of 0.05 at frequencies of 2.45 and 9.375 GHz, and were inconclusive in establishing any clear difference between the two types of power. Our results at 5.5 GHz showed that there was no detectable difference in the effect of CW and pulsed power for a 0.001 duty cycle. Therefore, it appears that the earlier results of Carpenter are not inconsistent with our own. Our investigation could not be extended to duty cycles below 0.001 because of electrical breakdown within the transition.

Our observations at 5.5 GHz of consistent involvement of the anterior portion of the lens are the same as those reported for other closed-waveguide irradiations at 2.45, 8.236, 9.375, and 10.05 GHz [10], [11]. This is to be contrasted with the results of "open" near-field experiments in which posterior lens opacities have been reported at 2.45 GHz [5], [6], [8], [9] and 10.165 GHz [11], and anterior lens opacities at 10.0 GHz [7].

Another pertinent comment is that the animals were deeply anesthetized during irradiation, a condition necessitated by contact of the cornea with the transition. Under these circumstances, the cataractogenic effectiveness of the microwave energy may be different from that observed for a wakeful animal positioned far from the source, or at least not in intimate contact with it.

In conclusion, the method used here is believed to be both accurate and reproducible. However, it is important to realize that the conditions of the experiment were carefully controlled and quite different from those of a free-field irradiation, a more natural situation. The relation between the two remains to be determined. Also, comparative data at other frequencies must be evaluated in order to determine the relative biological effectiveness at different portions of the spectrum. Nevertheless, it is hoped that the data presented here will contribute, eventually, toward better understanding of the mechanism of injury to the eye by microwave energy.

Acknowledgment

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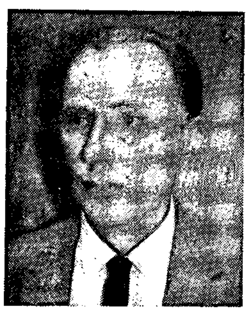

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