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"MICROWAVE CATARACTS - A CASE REPORT REEVALUATED"

Frederic G. Hirsch, M. D.*

*Assistant Director of Research, Lovelace Foundation for Medical Education and Research. This investigation was supported in part by General Research Support Grant FR-05531-04 from the General Research Support Branch, Division of Research Facilities and Resources, National Institutes of Health.

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I. INTRODUCTION

In 1952 Dr. John T. Parker and I reported on a case of bilateral cataracts which occurred in a technician who operated a radio frequency power source whose output was in the microwave portion of the electromagnetic spectrum.[1] At the time, for a number of reasons, it was not possible to publish a meaningful estimate of the magnitude of his exposure, so that the indictment of microwave radiation as etiologic in the case perforce rested on circumstantial evidence. In the first place, much of the data on which an estimate of dose rested was at that time subject to security restrictions. A second, and more important reason was our inability (at that time) to determine dosage due to the rudimentary state of the body of knowledge of the impact of microwave energy on biologic systems. Now, after seventeen years have gone by, the first impediment has been removed, and the second has profited by the research of many workers in the United States, the United Kingdom, and the USSR. Indeed the bibliographic reference file which I have maintained since I first became interested in the subject now contains hundreds of entries.

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I am continually amazed at the continued interest in this case over the past seventeen years and into the present. It seemed useful, therefore, to take advantage of this forum, provided by the Blue Grass Chapter of the Health Physics Society, for a reevaluation of the case utilizing the freedoms resulting from the lifting of security restrictions and taking advantage of the present state of the art. In doing so my purpose is threefold. First, I would like to present my own evaluation and some unpublished studies which make that evaluation possible. Second, by presenting the data on which dosage calculations can be made, others can make their own estimations and decide for themselves whether or not my conclusions can stand critical scrutiny. Third, I think it will be of interest to present the ophthalm. findings as of the present time and to equate the changes with the passage of seventeen years.

II. HIGHLIGHTS OF THE CASE HISTORY

The patient was a 32-year-old white male electronics technician who operated a microwave RF power source for a year prior to the onset of his visual disturbance. For the immediate three days prior to the onset of symptoms he had worked the apparatus on a more or less continuous basis during most of each working day with the antenna horn arranged in a peculiar geometry with respect to his head. This period of increased risk amounts to something approximating 24 hours with intervals of 16 hours separating each 8 hour period at risk. Figure 1 diagrams his relationships to the output of the power source.

It will be apparent that the limited space available placed the patient's head in close proximity to the radiation coming out of the horn antenna for

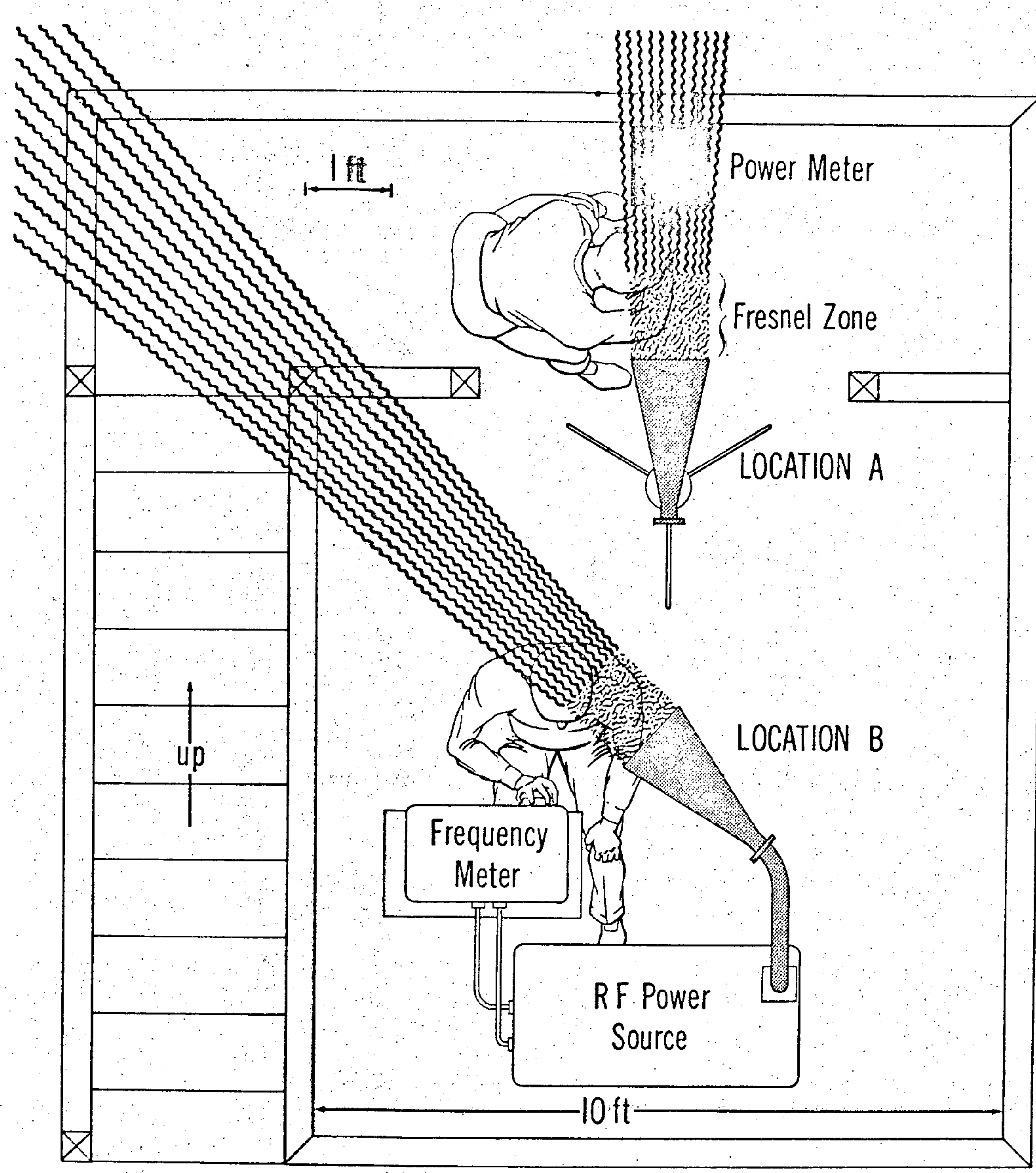

Figure 1. Plan view of test tower platform.

what must have been a good share of the time. When the antenna horn was in its usual configuration as shown in position A, he had to cross in front of the beam many times during the course of his activities; and, as was noted in the original report, he had the habit of sticking his hand into the ope end of the antenna horn to gauge from the heating effect on his hand whether or not the source was radiating power. However, it was probably the exposure incurred in the three days when he worked in position B that caused his lesions to develop. He was aware of a sensation of heat on his head, but was not uncomfortable. He did notice that his eyes were somewhat "blood shot" at the end of each working day. His visual disturbances developed quite suddenly during the night two days after the last working day. Please note that the left side of his head is closest to the antenna horn. As will be pointed out the lesions in the left eye were substantially more severe than in the right.

In October of 1951 he was first seen complaining of blurred vision which had developed between retiring on Sunday night and awakening on Monday morning. He was found on examination to have moderately advanced bilateral cataracts, chorioretinitis in the left eye, and numerous opacities in the vitreous humor of the left eye. The nature and extent of the left retinal lesions found are shown in Figure 2.

Figures 3 and 4 are histologic sections which show changes in the lenses at a time later than the original examination. These are quite identical to those reported by others in cases of cataracts resulting from radiant energy, notably Duke-Elder.[2] The large swollen "foam cells" are characteristic. The left lens was completely cataractous at the time of

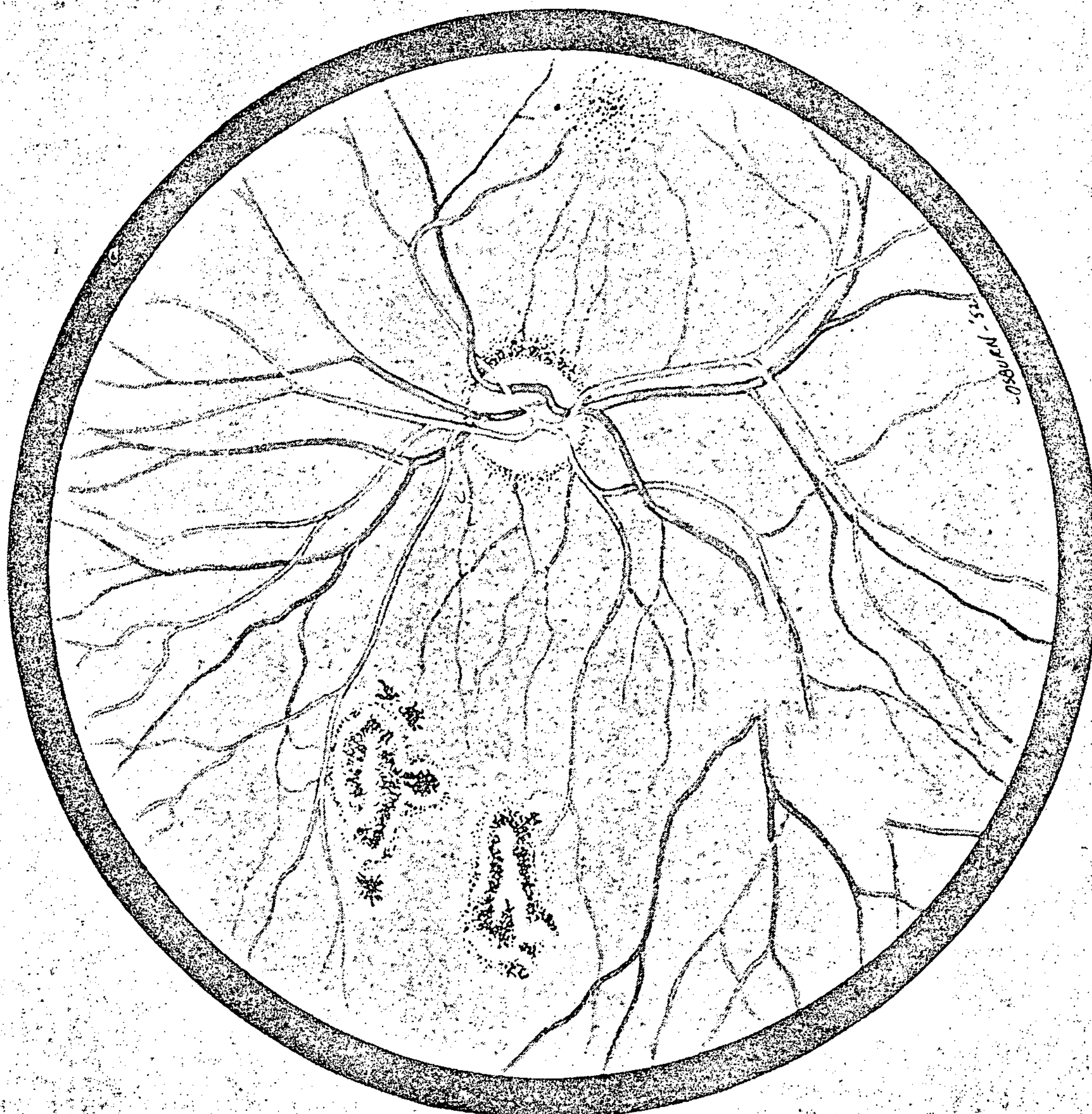

Figure 2. Artist's rendition of left fundus showing pigmented lesions of retina and choroid which are surrounded by pigmentation, and oedematous areas in retina.

Figure 3. Histologic section through the left lens. Posterior capsule is at the bottom of the picture.

Figure 4. Histologic section through the left lens taken near attachment to ciliary body.

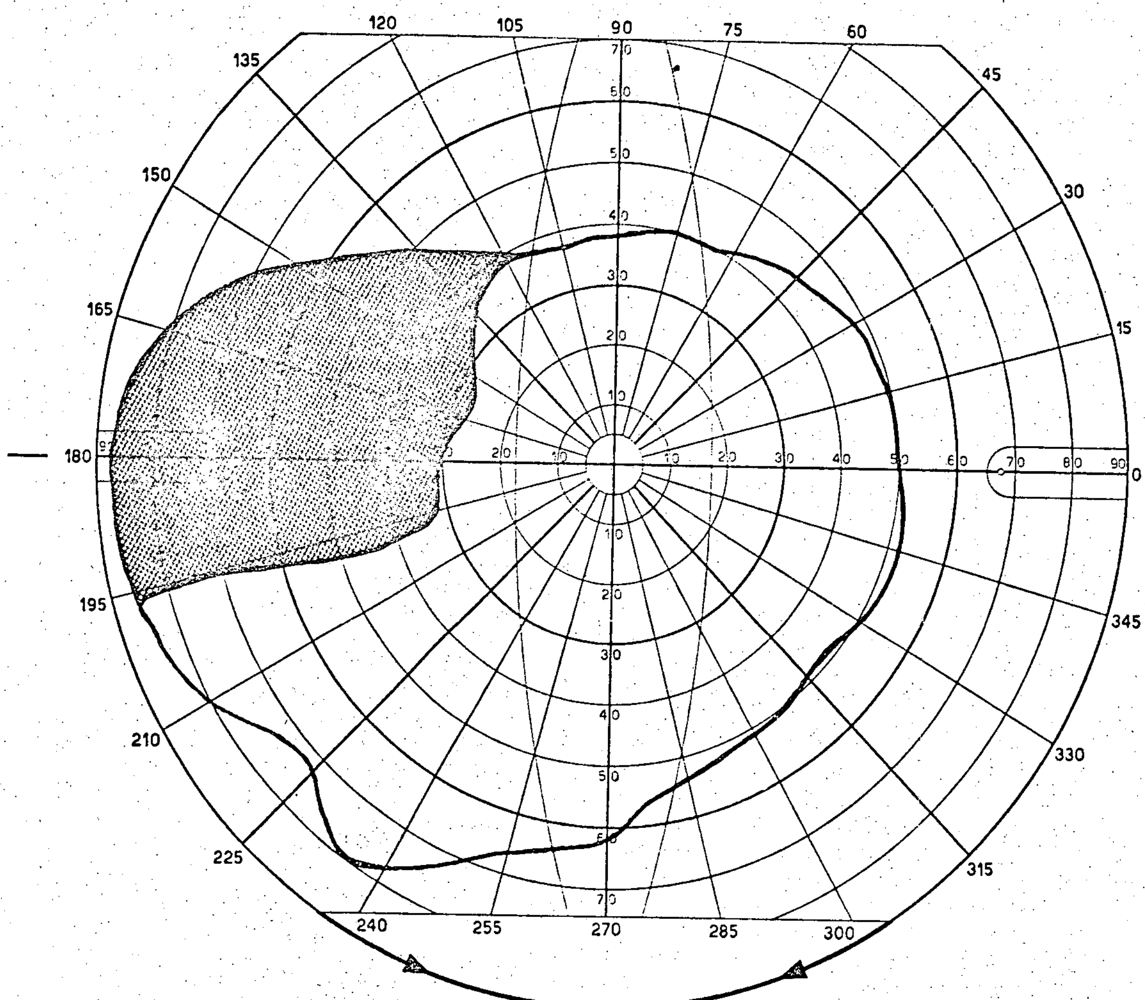

Figure 5. Scotoma produced by chorioretinal lesions in left eye.

its removal in March 1953. The retinal and vitreous lesions stabilized with the passage of time and treatment by cortico steroids. He was fitted with an appropriate contact lens and has functioned since without significant visual handicap, although he has a troublesome chronic uveitis, probably associated with a small amount of retained lens material. A recent followup examination established that the cataract in the right lens has remained stable over the past fifteen years. That is to say, it has neither progressed to complete opacification nor has it regressed to any apparent degree. At the present time the retinal lesions can still be seen, and they cause scotomata as can be seen by the visual field map which is shown in figure 5. Figure 6 is a recent photograph of the left fundus showing the present appearance of the old lesions. How much of the present activity of the chorioretinitis is due to the radiant energy he received many years ago versus that caused by his persistent uveitis is conjectural. My own feeling heavily indicates the latter.

III. ESTIMATE OF DOSAGE AND ITS RATIONALE

In order for radiant energy to produce a biological effect, mere exposure to it is not enough. The energy must be absorbed in sufficient quantity to produce functional or structural change in a tissue or organ, whether it be simply by producing damaging temperature elevations or whatever else. My purpose in that which follows is only to establish that in this instance sufficient energy was absorbed, and I shall not consider the possible pathophysiologic mechanisms. I will use the heat developed only as an index of absorption of energy, because whatever else happens, when an eye absorbs radiant energy heat is produced and to submit that the amount of temperature rise in a tissue is directly proportional to the energy absorbed seems to be altogether reasonable.

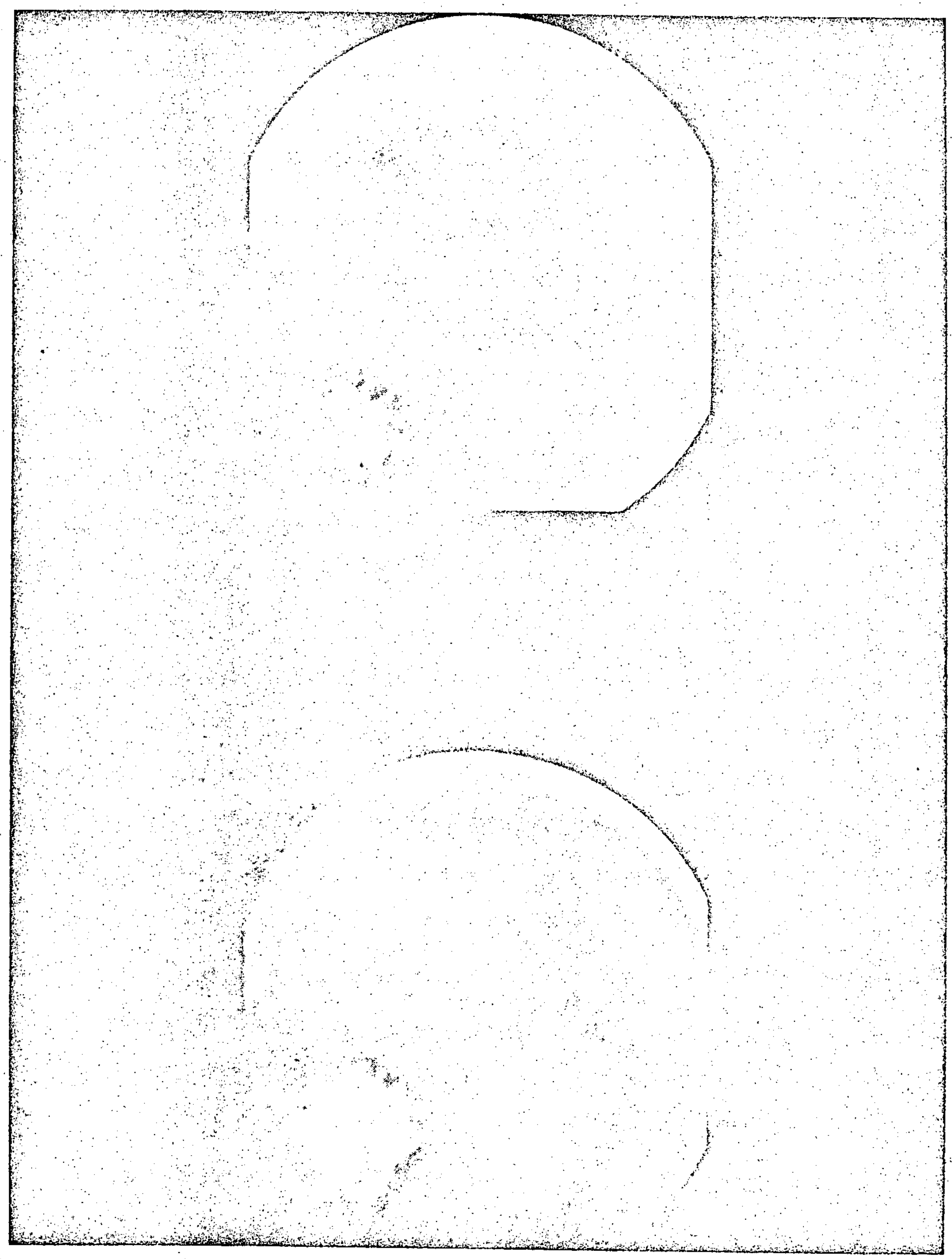

Figure 6. Fundus photographs of left retina showing chorioretinal lesions after 15 years.

The RF power source in this case was a "C" band magnetron which was connected by wave guides to a standard "S" band rectangular horn antenna. The output of the oscillator was at a frequency between 5000 and 4000 Megahertz corresponding to a wavelength between 6.0 and 7.5 cm. The apparatus was operated on a 50 percent duty cycle with a peak power output of 500 Watts, and an average power output of 250 Watts. The peak power density in a plane at the rim of the horn was 0.9 Watts/cm^2. The area of the aperture of the horn was 120 $in.^2$ or 792.5 cm^2. The effective area of the antenna was 550 cm^2. The gain factor of the antenna was 123. These parameters are shown in Table I.

An RF power source such as this has certain characteristics which are germane to our present considerations and which are shown diagrammatically in Figure 7. There is a zone extending from the rim of the horn out into space which is commonly known as the "Fresnel" or "Near Field" Zone. The dimensions of this Fresnel Zone depend on the area of the antenna, the peak power, and the wave length of the radiation. The intensity of the radiation is not uniformly distributed, but is more intense in the center of the beam than at the edges. Further, there are finger-like concentrations of intensity distributed throughout, with those in the center being more intense than those at the edge as diagrammed in Figure 8. The radiation in the Fresnel Zone is roughly collimated to the dimensions of the horn and does not diminish in strength in this zone with increasing distance.[3,4]

TABLE I. PARAMETERS AFFECTING DOSE CALCULATIONS

1. Magnetron (C Band). Wave guides to a standard "S" band horn. Duty cycle 50%.

2. Wave length -- 6.0 to 7.5 cm.
   Frequency – 5000 to 4000 megahertz/sec.

3. Maximum peak power -- 500 Watts.
   Average power – 250 Watts.
   Power density at plane of rim of horn = 0.9 W/cm^2

$$\frac{\text{Power}}{\text{Effect area}} = \frac{500W}{550\ cm^2} = 0.9\ W/cm^2$$

4. Area of horn – 10" x 12" or
   25.4 cm x 31.2 cm (120 in^2 or 792.5 cm^2)
   Effective area of horn = 550 cm^2 (10" x 8.5")
   Gain of antenna – 123

$$G = \frac{4\ \pi}{\lambda^2} \times A\ \text{effective} = \frac{12.6}{56.25} \times 550 = 123.02$$

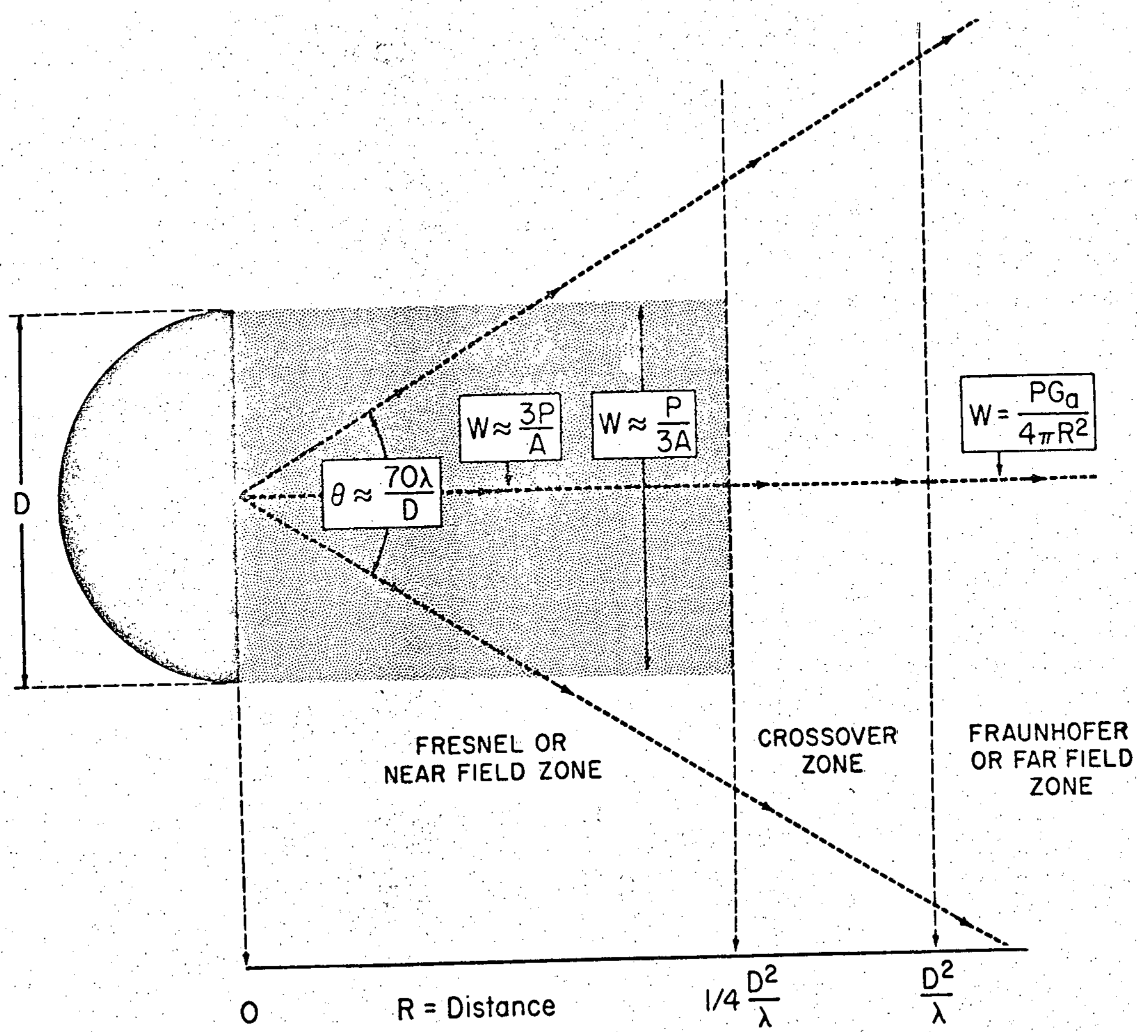

Figure 7. An output diagram of a typical antenna radiating into free space illustrating the various radiation zones. Not to scale.

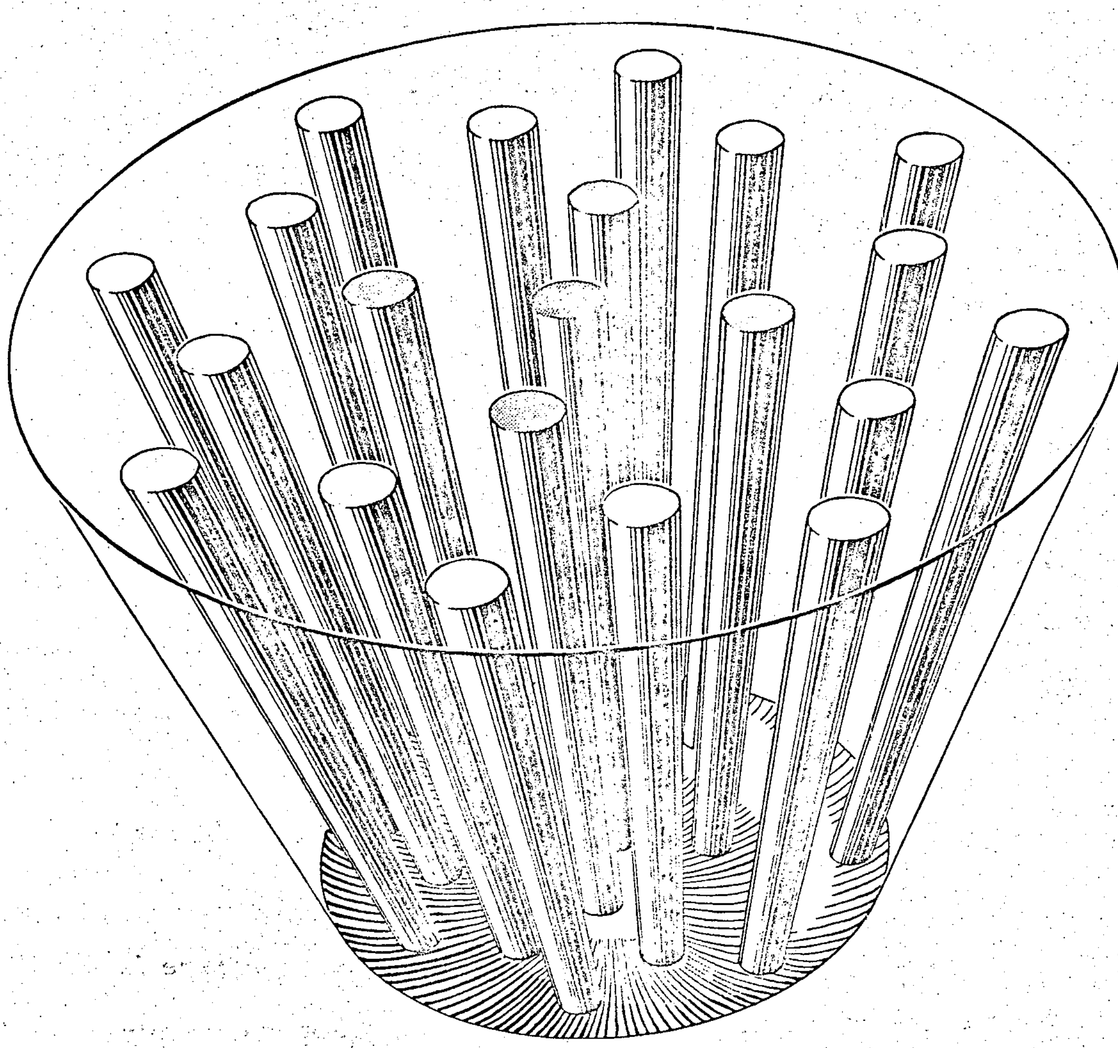

Figure 8. A diagrammatic representation of the finger-like projections of energy concentration in the Fresnel zone of a radiating antenna. The shading represents relative intensities, the blacker, the more intense.

The length of the Fresnel Zone can be estimated by the equation:

1. $$R = \frac{1}{4}\left(\frac{A}{\lambda}\right)$$

where:

R = Length of Fresnel Zone in feet.

A = Area of antenna horn in sq. ft.

λ = Wave length in feet.

In the case in point, the area was 0.83 ft.^{2}, and the wave length was 0.2 ft. so:

$$R = 0.25 \times \left(\frac{.833}{.23}\right) = 0.905 \text{ feet or about 30 cm.}$$

This means that the patient operated in the Fresnel Zone whenever he was within 1 foot or 30 cm of the front of his antenna.

As previously mentioned the power intensity in the Fresnel Zone is unevenly distributed. At the center axis the intensity is approximated by the equation:

2. $$W_c = \frac{3P}{A}$$

where:

W_c = Power density at center axis. (W / ft.^{2})

P = Power in Watts.

A = Area of the antenna horn in square feet.

At the edges of the horn the power density is approximately given by the expression:

3. $$W_e = \frac{P}{3A}$$

where:

W_e = Power density at the edges of the Fresnel Zone.

In this instance we obtain values for the center axis and edge powers as follows:

$$W_c = \frac{3 \times 250}{.833} = 900 \text{ Watts/ft.}^2$$

$$W_e = \frac{250}{3 \times .833} = 100 \text{ Watts/ft.}^2$$

In summary, whenever the patient was a foot or less in front of the horn and six inches or less to one side of the center axis of the horn, he was in the Fresnel Zone where the field was between 100 and 900 Watts/sq. ft.

Extending from the far end of the Fresnel Zone out into space the radiated energy becomes more coherently organized. This is known as the "Fraunhofer Zone" or "Far Field." Between these two zones there is a "Crossover Zone" for which there is no satisfactory mathematical expression. The intensity of the radiation available for absorption in space in the Fraunhofer Zone can be calculated by several equations one of which is shown in Figure 7. Since the case in point involves an exposure which took place in the "Fresnel" and "Crossover" zones for the most part, no more consideration will be given to the "Fraunhofer" zone.

One is probably justified in assuming that one can use Fresnel Zone calculations for as much as a foot in front of the antenna horn in estimating this patient's exposure. Certainly it can be said that the field in front of the horn extending almost to the hand rail of the platform was well above the accepted 0.01 W/cm^2. This becomes apparent when one uses Bovill's equation[5] for calculating safe distances in the Fraunhofer zone:

4. $$R = (P_w \times G_a / 4 \times L)^{\frac{1}{2}}$$

where:

R = So-called "safe-distance" (cm).

P = Radiated power (Watts).

(continued)

G_a = Antenna gain

L = Maximum permissible exposure level (10m W/c

Substituting the appropriate numbers in Equation 4 we have:

$$R = (250 \times 123/1.2566 \times 10)^{\frac{1}{2}} = 49.47 \text{ cm.}$$

So we can add the length of the Fresnel Zone (30 centimeters) to the length of the unsafe distance in the Fraunhofer Zone (49.5 centimeters) and find that the length in front of the horn where the patient was exposed to haza was about 80 cm or 2.6 feet. These calculations do not take into considerat the intensity or length of the Transition Zone. We know its intensity is somewhat less than in the Fresnel Zone and greater than in the Fraunhofer Zone, so something more must be added to this estimate of the hazard zone. I hav arbitrarily elected to add 0.4 feet which makes the hazard zone extend one yard in front of the horn.

In order for radiant energy to have a traumatic or biologic effect, absorption must take place. According to Maskalenko,[6] the absorption of radiant energy by tissue can be calculated using the expression:

5. $$P_{in} = P_{thru} \times e^{2\alpha z}$$

where:

P_{in} = Incident power (W/cm^2)

P_{thru} = Unabsorbed power which passes through.

$e^{2\alpha z}$ = Factor of absorption. z in the exponent is the thickness of the irradiated object. α is a complex function which has in it the dielectric constant, conductivity, frequency, and other entiti

A simple set up was used to measure the power which passed through freshly excised cow's eye. The eye was suspended by thread in a square of lucite in which a hole had been cut large enough for the eye to pass through. On the front surface of the lucite square a good thickness of lossy material was affixed which also had a hole in it so that the incident energy could strike the eye. In back of the eye a small receiving horn was placed which was connected through a calibrated attenuation network to a Hewlett-Packard Field Intensity Meter. The power passing through the eye was measured. A number of such measurements showed that the quantity e^{2az} had a numerical value of 1.64 in the case of the cow's eye.

Elsewhere I have reported on the use of spheres having the dimension of a cow's eye made of 35 percent gelatin as a simulant.[7] In order to establish the equivalency Figure 9 is presented. In all my work where temperatures in cow eyes were compared with gelatin spheres the maximum temperature in the eye was 12 percent higher than that in the sphere. Measurements of the numerical value of e^{2az} in gelatin spheres showed that it too was about 1.64.

Figure 10 shows the temperature reached as a function of the duration of irradiation. It will be noted that this curve shows the data when the power density was increased to 1.0 W/cm^2. This was done to compensate for the difference between the temperatures measured in cow eyes and those reached in gelatin spheres, and was accomplished by reducing the effective area of the antenna horn.

In experiments using gelatin spheres their absorption was measured at diminishing levels of incident power. This was done by increasing the distance between the antenna horn and the sphere over a range from 2.0 cm to 30 cm. It was found that the percentage absorption was surprisingly constant at 39 percent. Furthermore the agreement with calculated absortions using Maskalenko's equation was good. These data are shown in Table II.

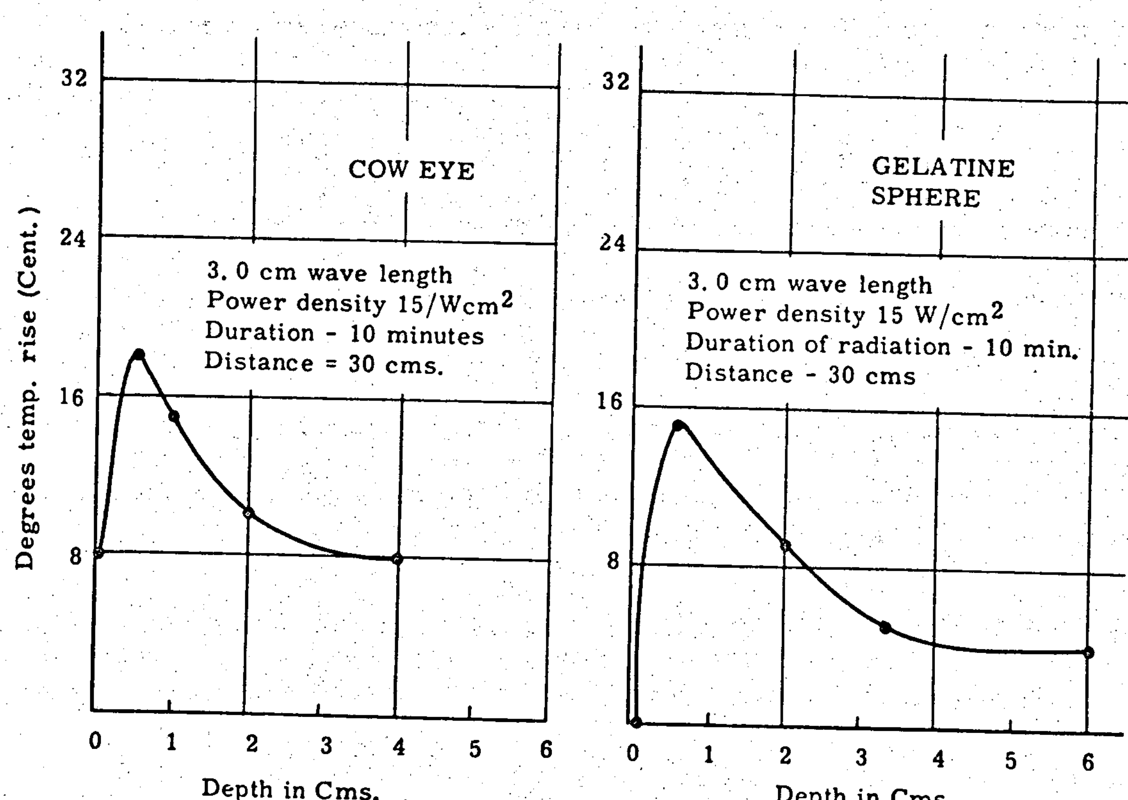

Figure 9. Comparative plots showing temperature rise versus depth in excised cow eyes and 35 percent gelatin spheres.

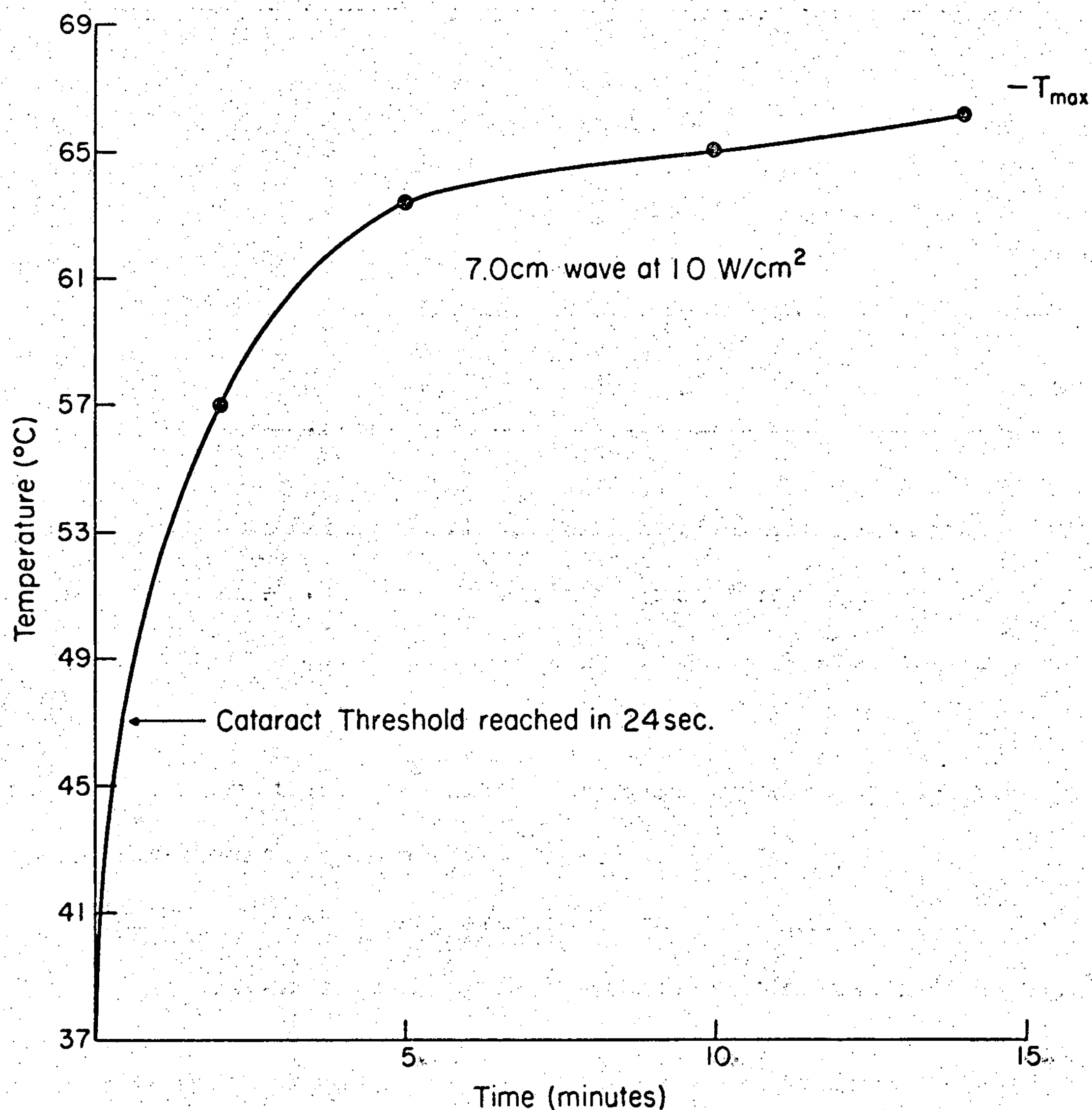

Figure 10. Temperature rise versus time in a 35 percent gelatin sphere of the same dimension as a cow eye.

TABLE II

POWER ABSORPTION BY 35% GELATIN SPHERES

Distance from Antenna (cm)	Incident Power (Watts)	Power Passed through (cm)	Percentage Absorbed
2	368	224	39
4	92	56	39
8	23	14	39
20	4	2	39
24	3	1.5	39
30	2	1	39

If one can accept the assumption that the human eye and the cow eye have essentially the same absorption characteristics, then one can say that the patient in this case absorbed about 39 percent of the incident energy on his eyes. During those times when his head was in the Fresnel Zone, and he was facing the horn, his eyes probably were receiving between 39 W/ft.^{2} (0.04 W/cm.^{2}) and 351 W/ft.^{2} (0.38 W/cm.^{2}) of RF energy. This does not take into consideration the parameter of time which is always of the essence in dosage calculations, and time per se is meaningless unless the rate of absorption is known.

In order to investigate the rate at which RF energy was absorbed, freshly enucleated cows' eyes were placed in a perfusion apparatus which caused a modified Ringer's solution to circulate through them at a temperature of 37° C. These preparations remained apparently viable for as long as twelve hours as evidenced by finding active mitosis in the corneal epithelium at the end of that period of time. A bead thermistor was placed at the back of the lens and temperature was measured versus time. A typical result is presented in Table III.

TABLE III

TEMPERATURE RISE IN LENS AS A FUNCTION OF TIME

Time	Temperature	Temperature Rise
Start	37°	0°
5 minutes	49°	12°
10 minutes	52°	3°
15 minutes	54°	2°

If one makes five assumptions then he can estimate the rate of absorption by a tissue mass. These assumptions are:

1. The rate at which the radiant energy is being delivered is constant.

2. The rate at which the lens temperature increases is directly proportional to the rate of radiant energy absorption.

3. The percentage of energy absorbed is constant.

4. The temperature reached in the lens is directly proportional to the amount of absorbed energy.

5. As tissue damage progresses, repair also commences, and that repair continues during hiatuses between exposures. The implication of this being that the amount of tissue damage is mitigated by repair processes to the end that the elapsed time of exposure probably does not truly reflect resultant effect. One should, therefore, use some function of time in dosage calculations. A common one in current use by radiobiologists is the square root of time.

Using these assumptions one can set up a relationship which states th the absorbed power is equal to the incident power times the percentage absorption multiplied by the square root of the duration of exposure. Such a relationship would have the form:

6. $$P_a = P_i \times A_{bs} \times \sqrt{t}$$

where:

P_a = Power absorbed. (W/cm^2, min).

P_i = Incident power. (W/cm^2).

A_{bs} = Percent of P_i absorbed. (%).

t = Time (minutes).

This data is presented graphically in Figure 11.

In the experiments previously described it was noted that opacificatior the lens began at 47° C, so additional experiments were performed using several other methods of determining the critical temperature for coagulati e.g. placing excised lenses in a water bath whose temperature was graduall increased. That 47° C was the threshold temperature for opacification of the bovine lens was confirmed.

In the Fresnel Zone of the antenna involved in the present case we hav seen that the power density varied from 900 Watts/ft^2 in the vicinity of its center axis to 300 Watts/ft^2 at the edges. This amounts to 1.16 W/cm^2 and 0.39 W/cm^2 respectively. Integrating the energies over a plane coinciding with the rim of the horn can be practically accomplished by dividing the peak power by the effective area of the antenna horn, i.e.:

7. $$\frac{P_o}{A_{eff}} = P_a$$

where:

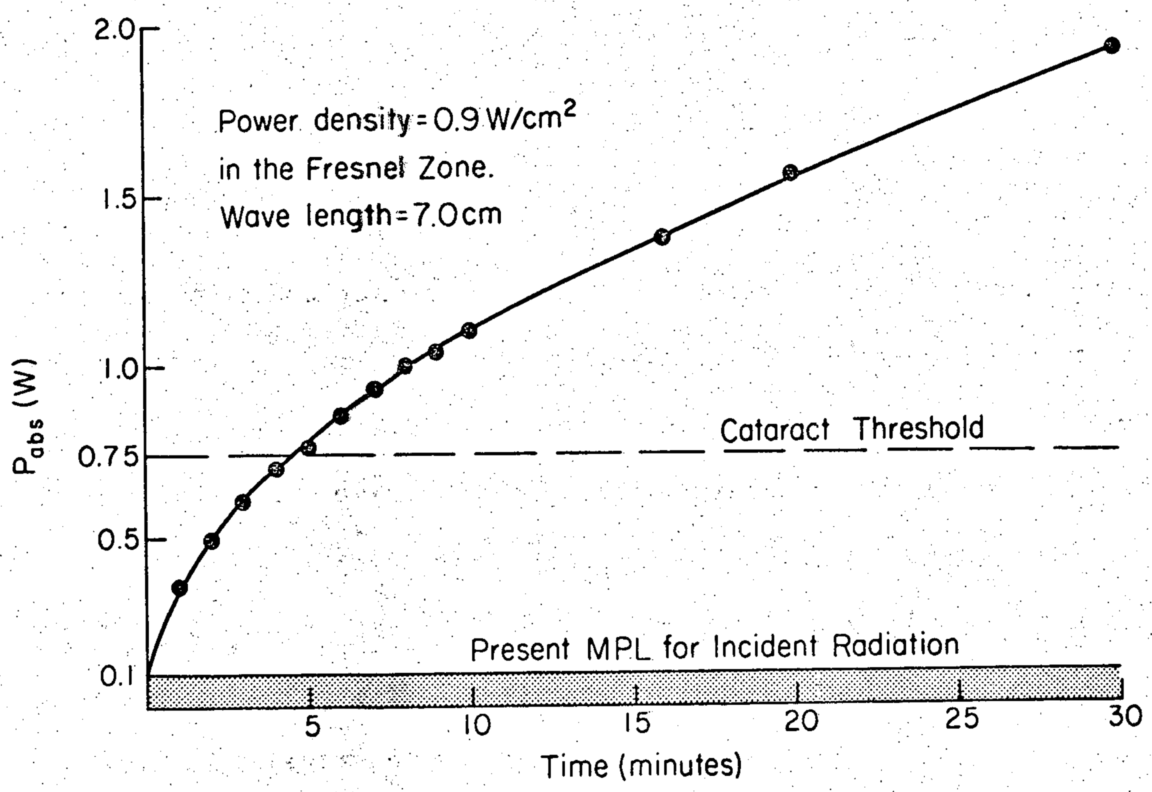

Figure 11. A plot showing the calculated probable absorbed dose as a function of time.

P_o = Peak power (Watts).

A_{eff} = Effective area of the antenna (cm^2).

P_a = Average power density (Watts/cm^2).

In this instance the peak power was 500 Watts and the effective area of the antenna was 550 cm^2, so:

$$\frac{500\ W}{500\ cm^2} = 0.9\ W/cm^2$$

It is now possible by using Equation 6 to calculate the probable absorbe dose when the patient's head was in the Fresnel Zone facing the horn for any given period of time. When this is done and plotted one obtains a curve whic is shown in Figure 11. If one also plots this data on log-log paper (Figure 1 one obtains a straight line from which an equation can be derived which relat absorbed power to time of exposure. This equation has the form:

8. $$P_{abs} = .35\ t^{.497}$$

where:

P_{abs} = Absorbed power (Watts).

t = Time of exposure (minutes).

In an earlier graph (Figure 10) the relationship between temperature a time was delineated. By combining these two sets of data one can now plot absorbed power versus lens temperature, since the parameter of time is common to each of them. When one does this on semi-log paper, one obtai a straight line. This plot is shown in Figure 12. It is now possible to deriv an expression which describes the slope of the line depicted which has the form:

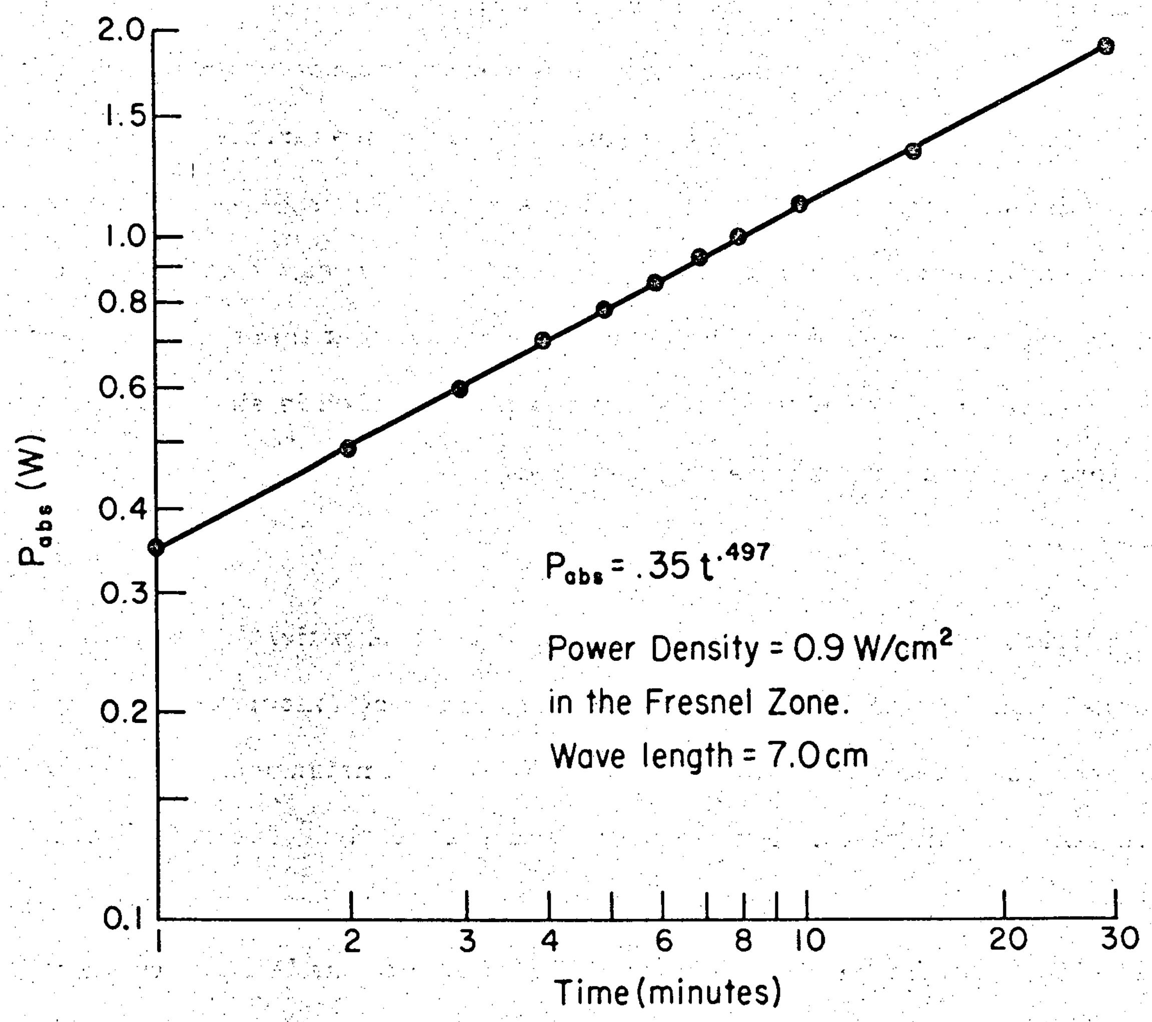

Figure 12. The same data as in figure 11 plotted as a log-log relationship; the slope of the line is described by the equation shown.

9. $T = 51 (P_{abs})^{\frac{1}{3}}$

where:

T = Lens temperature (Degrees C).

P_{abs} = Absorbed power (Watts).

Cogan[9] has stated that when an eye has absorbed about 0.75 W/cm^2 of power development of opacities begins. My own measurements indicate that when a lens reaches 47° C opacification starts. One sees from Figure 13 that when the lens temperature has reached 47 degrees, 0.66 W/cm^2 of radiant energy have been absorbed. To conclude that there is a range between 0.65 W/cm^2 and 0.75 W/cm^2 of absorbed power which is sufficient for the development of a cataract seems justified.

SUMMARY

Using the data at hand one sees that when the patient's head was in the Fresnel Zone for as little as five minutes damaging amounts of power were probably absorbed by his lens tissues. The circumstances of his exposure were such that this situation did occur and frequently. The fact that the left side of his head received a greater exposure to energy than did the right side, coupled with the fact that the damage to the left eye was greater seems to be very significant.

Although one is unable to derive a single number which describes his absorbed dose of radiant energy, there can remain but little doubt that his cataracts and chorio-retinal lesions resulted from absorption of the microwave energy to which he was exposed.

I want to be emphatically clear that the magnitude of the exposure to rad- iant energy in this instance is unique, and is not of a sort likely to be duplica

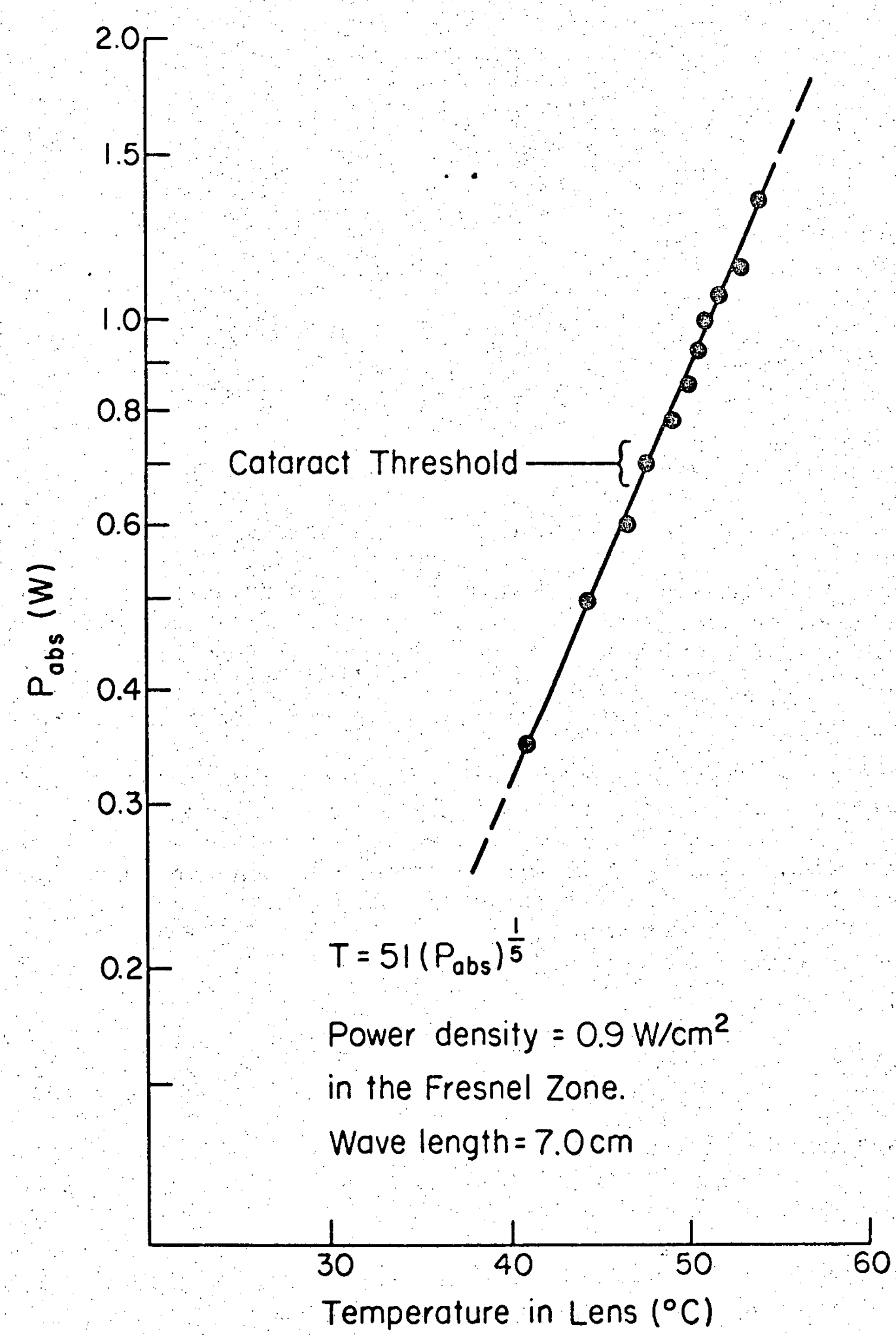

Figure 13. A log-log plot of power absorption versus temperature rise in the lens.

in the usual occupational or operational situation. This case does serve, however, to illustrate what can happen when an excessive amount of RF energy is absorbed by the human eye.

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