For a given burn, a greater dose was required to raise the temperature to the same level when the spectral distribution of the source included both the visible and the near infrared. Temperature rises compatible with steam production have not been obtained even for very intense burns. In cases of retinal explosion the temperature rose above 40°C, which when added to the body temperature gave a total of about 78°C, sufficient to produce albumin coagulation. Temperature rises 1 or 2 mm. away from the center of the burn remained below 2°C, regardless of the intensity of the burn.

The application of light coagulation to ocular therapeutics, as well as the potential danger to the eye from flashes due to detonation of atomic weapons, in the past ten years have stimulated a detailed and careful evaluation of the physical and biological nature of retinal burns.

Several aspects of the problem have been studied and reported upon. Many important factors, however, remain undetermined. One of the prime difficulties in establishing absolute values is the inherent variation in the concentration of pigment in the pigment epithelium of the individual animal eye. The variation of the optical system of the animal also constitutes a handicap. The minute and delicate anatomical configuration of the choroid and the retina also hinders the progress of intraocular determination, necessitating elaborate instrumentation. Choroidal hemorrhage or retinal tear frequently complicate the experiments. Consequently, temperature rise and heat conduction have not yet been measured accurately in vivo.

We have placed very small thermocouples within the coat of the eye in an attempt to measure the temperature rise at the site of the burn and heat conduction at varying distances from the burn center.

**Method**

Gray chinchilla rabbits weighing from 4.5 to 6 pounds were used in this study. Animals were selected with retinas whose pigmentation appeared homogeneous and of moderate density.

To determine the temperature rise and the heat conduction during production of a retinal burn, thermocouples were placed within the rabbits' eyes. These consisted of 38 Brown and Sharp gauge (0.01 cm. in diameter) copper-constantan wire, made by copperplating constantan wire along half its length and using the terminal point as the junction. One or more thermocouples were placed for each experiment.

Thermocouples were chosen in preference to thermistors because their small size facilitated their placement in the subretinal space without
causing damage to the tissues. They also give an absolute measurement, while thermistors are generally nonlinear. The cool junction was maintained at room temperature by surrounding it with insulated material. The thermocouples were used primarily to measure the temperature rise rather than to determine the energy delivered by the source, at the site of the burn. The thermocouples were connected to a Honeywell Type 906 Visicorder. This is a direct-recording oscillograph which utilizes high-sensitivity miniature plug-in galvanometers having a sensitivity of 0.20 mv. per inch. These Heiland galvanometers are specially designed to prevent drifts of the galvanometer light spot as a result of changes in temperature, vibrations, or other disturbing conditions.

The Heiland recording chart is a treated photosensitive paper which develops its image when exposed to a fluorescent lamp, requiring no darkroom developing. Timing marks were placed on the chart by feeding a 60 cycle signal to one of the galvanometers.

The exposure time was recorded by means of a silicon cell which intercepted reflected light from the cornea of the rabbit. A modified Meyer Schwickerath light coagulator was employed as the source of energy for the burn. The energy bands used were either 380-750 μm or 380-1,350 μm; these were obtained by means of appropriate infrared water and ultraviolet filters.

General anesthesia was obtained with pentobarbital sodium 25 mg. per kilogram of body weight injected into the marginal ear vein. Pupils were maximally dilated with atropine 1 per cent, homatropine 2 per cent, Neo-Synephrine 10 per cent instilled in the conjunctival sac. Tetracaine 0.5 per cent was used to produce topical anesthesia.

A retrobulbar injection of 1 per cent Novocain completed the anesthesia and produced an exophthalmos desirable for the circumstances. It also prevented the nystagmoid motion frequently observed with barbiturates. The barbiturates were used in preference to Flaxedil because of the negligible drop in body temperature observed during anesthesia.

Peritonitis was followed by resection of the recti muscles. A suture ligature was placed on the proximal and distal ends of each severed muscle, the former for hemostasis, the latter for traction. The globe could thus be rotated upward, exposing a large portion of the posterior pole. The remaining conjunctiva, with Tenon's capsule, was dissected free. Special care was taken to avoid the vortex veins.

Under direct visualization of the fundus with a binocular indirect ophthalmoscope the site of implantation of the thermocouple was chosen. The globe was then fixed in a specially designed plastic holder. Two scratch incisions 2 mm. apart and about 1 mm. long were made in the sclera down to lamina fusca. A 32-34 gauge cannula was inserted through the thickness of the choroid, emerging through the second incision. This procedure was carried out under direct ophthalmoscopic control. It was particularly significant to observe the position of the needle in relation to the pigment epithelium. In moderately pigmented animals it was relatively easy to determine whether the needle was anterior or posterior to the pigment epithelium. Only those eyes with needle anterior to the pigment epithelium were used.

After the needle was properly placed, the thermocouple was threaded into the lumen of the needle and pulled out the other end, bringing the junction into approximately the desired position. The needle was then withdrawn, the thermocouple junction visualized with the ophthalmoscope and adjusted to its final position. The wire was then anchored to the sclera with two 7-0 black silk sutures. After the desired number of thermocouples were successfully placed, the plastic holder was removed. The position of the junction was again checked and the animal was ready to be exposed.

Results

Thermocouples were placed in 30 eyes; significant data were obtained from 21 of them. Technical difficulties or complications during recording account for this discrepancy. One or two thermocouples were used in each experiment. One hundred and twenty-two thermal lesions were made.

In a previous publication, we had established certain ophthalmoscopic criteria for the evaluation of the burns. More than 3,000 burns were evaluated by the same observer and histopathologic examination was carried out in a great number of them.

The following classification was adopted:

0 Burn—No lesion seen after five minutes.

1 Burn (E burn)—Same as an E burn but a small amount of coagulation in the center of the lesion.

2 Burn—Silent coagulation of the retina with choroidal vessels seen underneath. Burn not well delineated.

+1 Burn—Moderate coagulation of the retina;
no choroidal vessels seen. Burn well delineated with halo of edema.

+2 Burn—Dense white coagulation of the retina and choroid; presence of hemorrhage or vitreous burn.

+3 Burn—Explosion of the retina and choroid.

In this study the intensity of the lesion created varied from minimal to explosion of the retina. Significant data were obtained for 1, ±, and T burns. The average burn size was 1.2 mm.

Measurements were made directly at the site of the burn and at various distances from the center.

For T burn, the temperature rise varied from 12.5° to 20.6° C.

For ± burn, the temperature rise varied from 20.1° to 26.3° C.

For burns above +1, the temperature rise was greater than 37° C.

The average body temperature of the animal was 38.3° C, and the room temperature was 28° C.

Thermocouples placed at 1 mm. away from the center of the burn recorded about 1.4° C, and at 2 mm. 0.2° C, depending upon the intensity of the burn.

Only data for the T burn were considered in the analysis of the thermal conduction. The E burn was not considered because the energy was not enough to produce a measurable temperature rise at 2 mm. The +1 burn was too extensive and created impairment of the choroidal circulation.

It was found that the temperature rise decreased very rapidly when the distance between the burn and the reference point increased from 1 mm. to 2 mm. The decrease continued steadily but less sharply between 2 mm. and 3.5 mm.

No measurements were made at distance less than 1 mm. and only one was taken at 6 mm.

Fig. 1 shows the curve of the temperature rise for a 1.2 mm. T burn made with the same spectral characteristics. The dose varied slightly because of individual variations of the rabbit's eyes.

The time lag between the burn and the reference point was measured in all cases where two thermocouples were used.

This lag was found to increase with the intensity of the burn. It varied from 1.25 msec. to 8.75 msec. for the T burn and from 8.75 msec. to 37.5 msec. for more intense burns. No explanation can be offered, for the moment; however, this seems to indicate a dual mechanism in the conduction of the heat which reaches the retina. When the energy is not enough to produce choroidal damage, as in the case of the T burn, conduction is achieved primarily by the choroidal vessels, but for more intense burns with choroidal destruction the conduction takes place by a less efficient mechanism.

This is evidenced by the small temperature rise obtained at 2 mm. away from the initial burn produced by a temperature rise of greater magnitude than the T burn. For instance a +1 burn shows a temperature rise of 26° C in the center, for a temperature rise of 0.1° C at 2 mm. away after an 8.75 msec. delay.

Discussion

Dissection of the eye was carried out after each experiment in an effort to ascertain that the thermocouple junction was placed anterior to the pigment epithelium and that the burn was placed at the junction. In the majority of cases, the retina could be separated from the underlying tissue, leaving the uncovered thermo-
Thermocouple measurements of burns in rabbit retina

Thermocouple measurements of burns in rabbit retina

by the same distance as exists between the two thermocouples. Control dissection was done to verify distances. The temperature rise in the posterior thermocouple was the same in both cases.

Although direct measurement of energy delivered at the site of the burn could have been obtained from the thermocouple reading, this experiment was undertaken to measure temperature rise and heat conduction during production of retinal burn. In this manner, the thermocouple reading could represent an absolute value of the temperature rise in the retina independent of body temperature or of room temperature.

These thermocouple measurements do not agree with the theories of Vos, which are based on the presence of steam production in the burn mechanism. The temperature rise in ± burns of about 1.2 mm. in size was found to be about 25° C. This, added to the average body temperature of the rabbit during the experiments, 38° C., results in a total of about 66° C., which clearly is not in the region of steam production but is in the temperature range required to produce albumin coagulation.

It would seem that in intense burns with explosion of the retina, as observed with very high doses, steam production could account for the results. A couple of rabbits studied in that range demonstrated a temperature rise above 40° C.

The data relative to heat conduction seem to indicate that conduction does not take place in the retinal plane. For example, the temperature rise 2 mm. away from the center of a 1 mm. burn does not exceed 2° C.

The question of heat transport by the choroidal blood supply has been considered by Vos and others, and the general opinion is that it could not account for appreciable cooling, the blood transport being too small to be effective in the short exposure time. Work is now in progress to demonstrate the participation of the choroidal circulation in the thermodynamics of retinal burn.

couple on the pigment epithelium. The exudate produced by the burn was helpful in detaching the retina and rendering the procedure very simple. In a few cases, retinal layers seemed to have been caught by the wire. This was easily observed at dissection. Since the thickness of the rabbit retina, 0.13 to 0.15 mm., approximates that of the thermocouple (0.1 mm.), no attempt was made to place the thermocouple intraretinally. The pigment epithelium, being the site of heat absorption, offered a better approach for the measurement than the retina per se.

The theoretical difference between the temperature as measured by the thermocouple and the actual temperature of the burn was considered.

It has been found by some authors that a 3 per cent error exists for temperature of 1,100° C. The heat loss is due to the conduction through the wire.

In our experiments, the correction factor was found to be negligible because of the small size of the thermocouples and the low range of temperature involved.

In order to control the effects of the possible changes induced by the presence of the thermocouple wire in the thermodynamics of burn production, several burns were placed in the same area using the same dose. No marked difference in ophthalmoscopic appearance was observed between the burn placed on an intact area and the burns placed on the thermocouple.

The effect of the presence of the thermocouple itself upon heat distribution within the retina was studied by the insertion of two thermocouples within the same eye, separated by a known distance. One was placed anterior to the other along the same meridian. The posterior one was chosen as the point of reference. A burn was placed upon the more anterior thermocouple and the temperature rise at the posterior thermocouple was recorded. Immediately thereafter a burn of identical parameters was placed posterior to the posterior thermocouple, separated from it by the same distance as exists between the two thermocouples. Control dissection was done to verify distances. The temperature rise in the posterior thermocouple was the same in both cases.

Although direct measurement of energy delivered at the site of the burn could have been obtained from the thermocouple reading, this experiment was undertaken to measure temperature rise and heat conduction during production of retinal burn. In this manner, the thermocouple reading could represent an absolute value of the temperature rise in the retina independent of body temperature or of room temperature.

These thermocouple measurements do not agree with the theories of Vos, which are based on the presence of steam production in the burn mechanism. The temperature rise in ± burns of about 1.2 mm. in size was found to be about 25° C. This, added to the average body temperature of the rabbit during the experiments, 38° C., results in a total of about 66° C., which clearly is not in the region of steam production but is in the temperature range required to produce albumin coagulation.

It would seem that in intense burns with explosion of the retina, as observed with very high doses, steam production could account for the results. A couple of rabbits studied in that range demonstrated a temperature rise above 40° C.

The data relative to heat conduction seem to indicate that conduction does not take place in the retinal plane. For example, the temperature rise 2 mm. away from the center of a 1 mm. burn does not exceed 2° C.

The question of heat transport by the choroidal blood supply has been considered by Vos and others, and the general opinion is that it could not account for appreciable cooling, the blood transport being too small to be effective in the short exposure time. Work is now in progress to demonstrate the participation of the choroidal circulation in the thermodynamics of retinal burn.
We wish to thank Mr. N. Kremenic for his cooperation in the calibration and Mr. W. Derksen for his technical assistance.

REFERENCES