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Operation UPSHOT-KNOTHOLE

NEVADA PROVING GROUNDS

March - June 1953

Project 4.5

OCULAR EFFECTS OF THERMAL RADIATION FROM ATOMIC DETONATION – FLASHBLINDNESS AND CHORIORETINAL BURNS

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OPERATION UPSHOT-KNOTHOLE

Project 4.5

(OCULAR EFFECTS OF THERMAL RADIATION FROM ATOMIC DETONATION - FLASHBLINDNESS AND CHORIORETINAL BURNS)

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by

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30 November 1955

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Project of
School of Aviation Medicine
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ABSTRACT

PART I

This project was designed to further evaluate the effects of atomic detonations on the eyes. This was studied in two previous projects, one on the daytime problem which was found to be of minor importance insofar as the production of flash blindness is concerned, and one on the nighttime problem where flash blindness was of considerable importance, but which was curtailed because two subjects received retinal burns.

The present project, like the second one mentioned above, was designed to determine the effect of the flash of atomic detonations at night upon the ability of military personnel to carry out their assigned tasks when such tasks involve the use of vision. It is considered that in general three types of visual tasks are involved in military operations: (a) reading of instruments in ships, aircraft, tanks, and vehicles; (b) central acute vision at low levels of illumination; and (c) peripheral vision at very low levels. After an atomic flash each individual involved in such military visual tasks would attempt to return to seeing under the light level then available to him. The time required for him to see under each of these circumstances was determined.

Subjects were dark adapted in a light-tight trailer. Their eyes were exposed to the atomic flash by a shutter arrangement. Eyes were protected by a combined infrared absorbing and red transmitting filter. This filter was chosen because it selectively filters out a large portion of the visible and infrared spectra of the bomb, and because individuals wearing it can see red-lighted instruments in vehicles, ships, tanks, and aircraft. The period of exposure to the flash began at zero time and extended through the period of the blink reflex.

Twelve subjects in a light-tight trailer were exposed to five nuclear detonation flashes at distances of from 7 to 14 miles. The dark adapted subjects looked at the flash with the left eye through filter ports which screened out all wavelengths except those between 600 and 900 millimicrons. Following exposure through the protective filters, return of visual function was determined using Zeiss nyktometers, adaptometers and readings on red-lighted aircraft instruments. Results were as follows:

a. Red-lighted instruments could be read correctly in an average of 18.4 sec (range of 5 to 27 sec) if illuminated with regulation type small red floodlights, and in an average of 55.9 sec (range of 44 to 81 sec) if illuminated with standard red internal lighting only.

b. Reasonably good central vision (20/40) under reduced illumination (1.57 Nit)* returned in approximately 154 sec.

c. Peripheral vision returned in an average of 160 sec under 0.001 Nit luminance (approximately that of moonless night sky) and in an average of 249 sec under 0.00001 Nit of luminance (slightly less than moonless night sky with overcast).

It is concluded that filters of the type used protect almost all individuals from retinal burns under the conditions of the experiment and allow performance of typical visual tasks required of a pilot flying the aircraft within 20 to 60 sec following the flash of the atomic detonation.

PART II

When the eye observes an atomic fireball, the energy received in the retinal image per unit time and area depends on the relative opening of the eye (pupillary diameter divided by focal length) and the energy emitted by the fireball per unit area. Due to the concentration of energy in the image formed on the retina, skin burns and retinal burns follow different laws. As a result of this concentration retinal lesions are produced at distances many times greater than those for minimal skin burns.

In comparison with the skin the central part of the retinal image gets a higher percentage of its total radiation at an earlier time.

The energy (per unit area and time) emitted by an atomic fireball has an early peak before 1/1000 of a second. Human and animal eye protective reflexes come too late for this first peak.

In order to determine the burn injury processes to the dark adapted rabbit eye and their possible correlation with those which occur in humans, 700 pigmented rabbits were exposed to six predawn atomic blasts at distances varying from 2 to 42½ miles. Dark adapted rabbit eyes suffered retinal burns at distances up to 42½ miles; 350 of the 700 rabbits placed in the field received retinal injuries. It was found that retinal damage varied with the bomb kilotonnage and diminished with the distance of the animals from the flash.

Pathologic findings in the exposed pigmented rabbit eyes correlated well with clinical observations and showed characteristic coagulation necrosis with or without major tissue and cell destruction in the retina and choroid. Explosive generation of steam in some cases caused rupture of the retinal elements with hemorrhage into the vitreous.

Four cases of accidental atomic chorioretinal burns have occurred in humans. These individuals viewed the flash at distances varying from 2 to 10 miles from ground zero. Clinically the lesions resemble those occurring in rabbits at corresponding distances and are supporting evidence for predictions made in the laboratory. Permanent scotomata have resulted in these individuals.

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* See Definitions for meaning of Nit.

PREFACE

PART I

This is the third report in the series on flash blindness. The first was a study of the effects produced by atomic detonations during daylight operations. This was reported as Flash Blindness, WT-341, Project 4.3, Operation BUSTER. The second study was reported as Flash Blindness, WT-530, Project 4.5, Operation SNAPPER. This was a study of the nighttime problem; however, it was interrupted because two of the test subjects incurred retinal burns. This third study represents a continuation of the interrupted project. Its purpose is to give operational units an estimate of the length of time personnel will be unable to see well enough to carry out their assigned duties if they are unexpectedly exposed to an atomic flash.

It is emphasized that these experiments were devised to obtain an estimate of the usefulness of a specific filter combination in eye dazzle protection. They were not intended to obtain basic data on dazzle effects and cannot be so interpreted.

PART II

The study here reported was done in four parts and is not yet entirely completed. The first portion will consider the physical factors involved in the effect of these factors on the eye. This will include the determination of the threshold energy required to produce a lesion in the retina by the wavelengths involved. The second portion will give the results obtained in an experiment using 700 rabbits in six atomic detonations in Nevada during UPSHOT-KNOTHOLE tests in 1953. The third portion will be a report of four human cases of chorioretinal burns produced by atomic flash. The fourth portion will be a brief summation of the pathological findings in the retinal burns.

ACKNOWLEDGMENTS

The Project Officer desires to express appreciation to Crew Training Air Force for cooperation in furnishing test subjects from Nellis Air Force Base for these studies and for the assistance of Col Jack Bristow, Ophthalmologist at Nellis, who examined the subjects and assisted in the tests.

To Lt Col E. A. Pinson, the Director of Program 4, appreciation is expressed for administrative assistance, technical guidance, and for procurement of supplies and transportation.

The statistical evaluation of the experimental results and the performance of certain other computations were done by Mr. David Rubenstein, Department of Biometrics, School of Aviation Medicine.

All photographs were taken by Sergeants Kohnitz, Burnap and Seal, who also gave much of their time in many other varied tasks.

Finally, much credit is due to personnel of the School of Aviation Medicine who conducted the testing, acted as subjects in a few instances, and traveled back and forth to the Nevada Proving Grounds in order that this work could be accomplished without interfering with their heavy duties at the School. Special credit is due to Lt Col John R. Grunwell, Jr., and to Lt A. D. Ruedemann, Jr.

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PART I

OCULAR EFFECTS OF THERMAL RADIATION FROM ATOMIC DETONATION

FLASHBLINDNESS

CHAPTER 1

INTRODUCTION

1.1 OBJECTIVE

This research was conducted to determine to what degree the flash of an atomic detonation impairs the vision and reduces the efficiency of military personnel during night operations. Observations were made which were intended to reveal the evolution, degree, and duration of the reduced vision. An attempt was made to evaluate the efficacy of a filter designed to protect against retinal burns and flash blindness and also designed to permit performance of visual tasks such as are required of aircraft pilots.

1.2 BACKGROUND AND THEORY

1.2.1 Daytime Situation

In considering the effect of atomic flashes on vision, both the daytime and nighttime situation must be mentioned. The effect of flash on daytime vision was studied in Flash Blindness, WT-341, Project 4.3, Operation BUSTER. The effect is transient because of two important factors. First, the pupil is constricted by the bright light existing prior to detonation. Secondly, after detonation, the individual returns to his visual task in the high illumination present in daylight. The retinal burn hazard in this situation is discussed in another section of this report.

1.2.2 Nighttime Situation

The night task is somewhat different. In this instance the individual has pupils which are more or less widely dilated, depending on the amount of light to which the eye is being exposed prior to detonation and the amount of illumination involved in the visual task at hand. There are essentially two types of night vision tasks which are of interest to the services. One of these is the situation in which an individual is looking at illuminated dials (usually red lighted) aboard ship, as pilot of an aircraft or driver of a tank. He may be exposed to a bright flash of light such as that produced by an atomic detonation and then returns to his task of attempting to read illuminated instruments.

The other type of night vision task is that of the soldier or airman on the ground. His visual task is carried out with only the illumination provided by the moon or stars. If he is exposed to the flash of an atomic bomb he returns to his task of trying to see objects under this dim illumination. This task is further subdivided into two because vision at moonlight levels permits the use of central (photopic) vision. When there is only starlight available, all vision must be peripheral (scotopic) vision.

Tests were therefore designed to procure data on all three of these visual tasks; the reading of red-lighted instruments, the recognition of objects by moonlight intensities and the recognition of objects under starlight intensities.

CHAPTER 2

INSTRUMENTATION

2.1 THE TRAILER

Since all of the detonations took place within 30 min prior to official sunrise and a considerable amount of illumination from the sun was present, it was necessary to use some means of exposing the eyes while the subject was dark adapted and had the normal dilated pupils that go with the night-seeing situation. This is, of course, necessary in order to obtain useful information applicable to night operational conditions. A light-tight trailer was used to house the observers so that dark conditions could be simulated (Fig. 2.1).

2.2 SHUTTERS

Along the side of the trailer were 12 ports fitted with shutter devices for exposing the eyes of the observers. The shutters were constructed in such a manner that the left eye only was exposed to the flash, while the right eye was used to fix the position of the eyes by regarding a luminous fixation object. The shutter-opening mechanism was initiated by means of a minus 1 sec signal sent out by the Control Point (1 ms accuracy). A built-in delay opened the shutter at an average of 11±3 ms before time zero. The shutter remained open for 1 sec. Mechanisms were calibrated before, during, and after each test. Shutter mechanisms worked satisfactorily during all tests (Figs. 2.2 and 2.3).

2.3 TESTING

Three types of equipment were used to examine the subjects after exposure. One group of subjects was asked to report readings on red-lighted aircraft instruments (Fig. 2.4). Return of the ability to read these instruments was recorded in seconds.

Zeiss nyktometers were used to indicate the return of mesopic vision following which the observers reported their ability to see Landolt rings in adaptometers of known luminosity (Fig. 2.5).

During the exposures all of the observers in each group viewed the detonation through a combined filter. One portion of this filter was an infrared absorbing glass which prevented the passage of the larger part

Fig. 2.1 Interior of Light-tight Trailer. The shutter mechanisms are on the right. The subjects were seated on stools. After exposure they turned around and faced the test apparatus shown on the left. Stools were guided to the proper apparatus by tracks on the floor. The various sections were isolated from each other by the dark curtains on the sliding rods. The black stovepipe visible was a portion of the light-tight forced air ventilation system.

Fig. 2.2 Shutter Mechanism. These shutters have a small self-luminous fixation spot before the right (unexposed) eye. This is brought to infinity by the strong plus lens shown. This device insures that the subject will be looking near, but not directly at, the detonation point and that his accommodation will be properly controlled. The shutters had an average opening lag of 11 ± 3 milliseconds, remained open 1 second and closed again automatically.

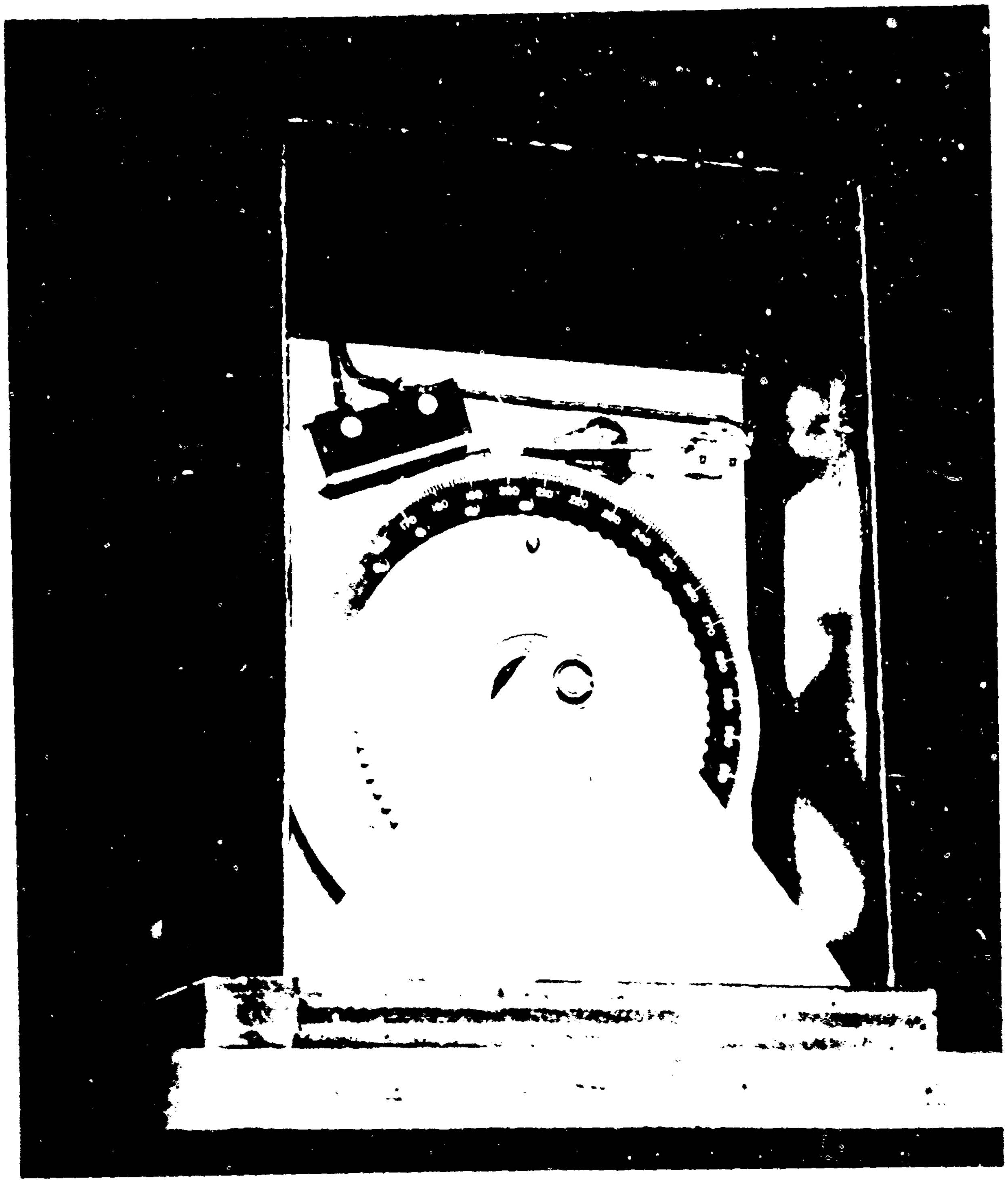

Fig. 2.3 Shutter timing mechanism capable of taking any input signal of one sec or less prior to detonation and activating the shutters. It has an accuracy of ± one millisecond.

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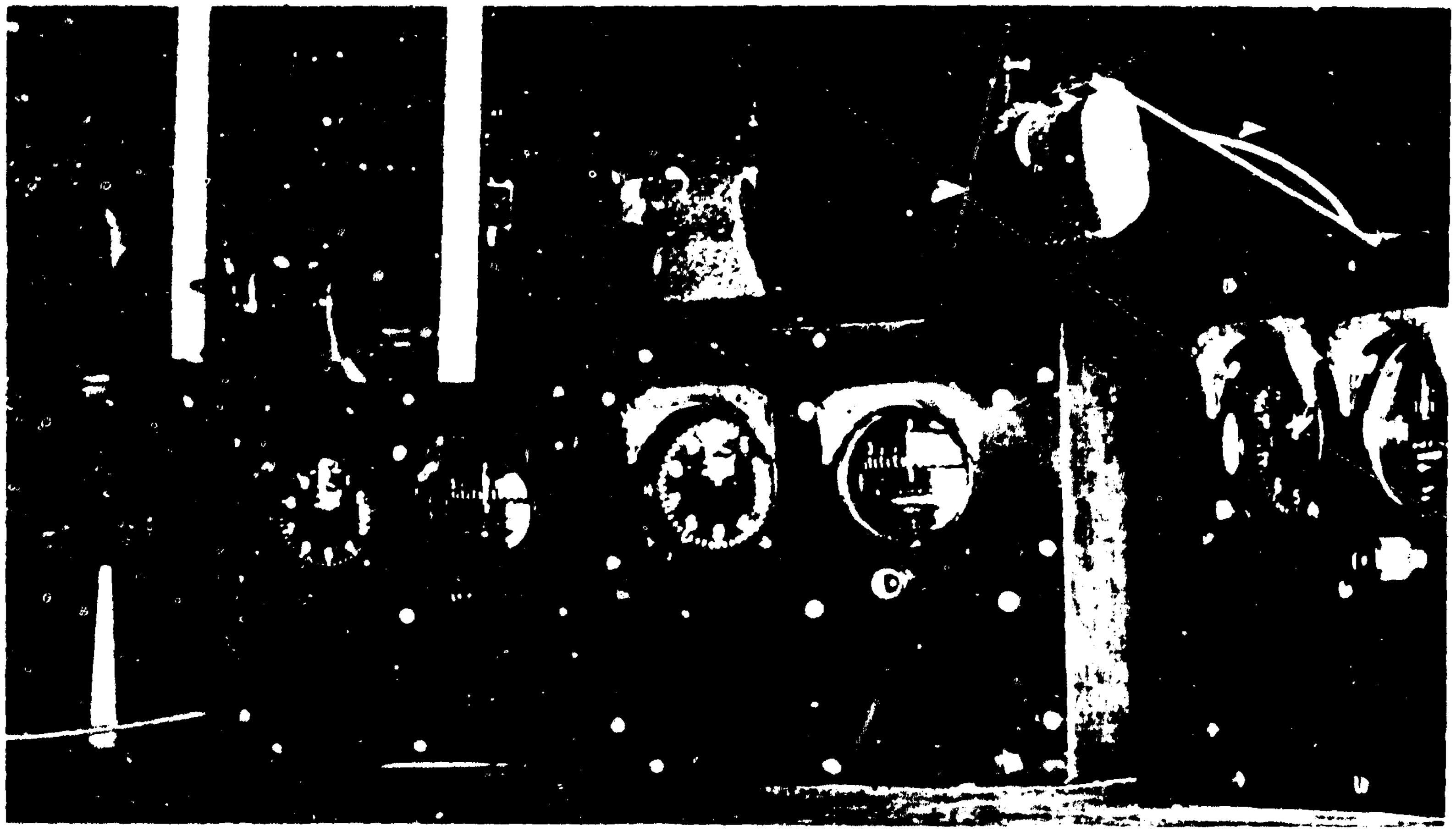

Fig. 2.4 Aircraft Instruments Used in the Instrument Reading Task - The red flood lighting and the individual instrument lighting sources are visible. Altimeter and gyro compass were selected because readings could be changed by the examiner and because they represent the typical instrument reading task of pilots

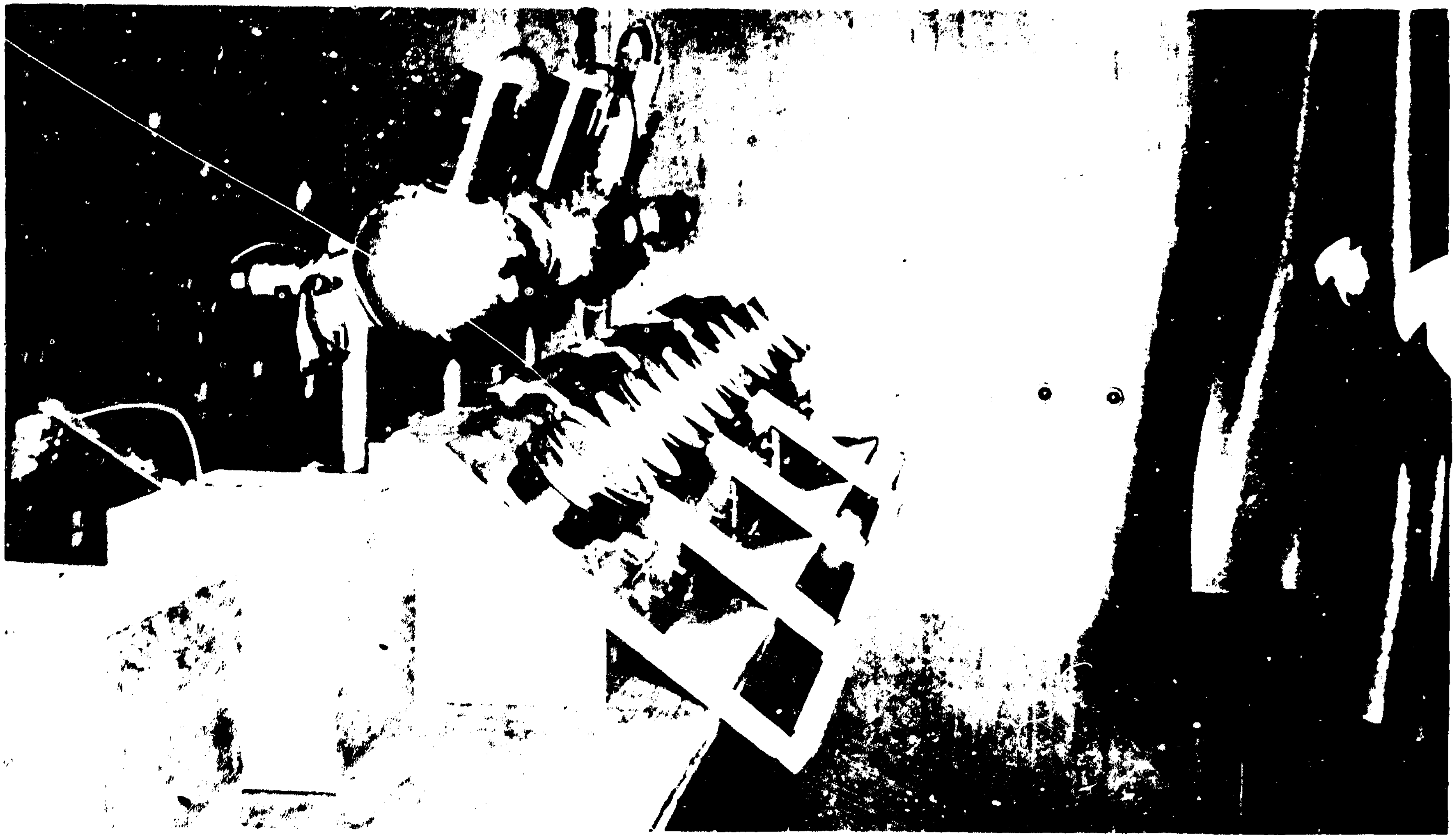

Fig. 2.5 Battery of Nyktometers and Adaptometers - These were used to plot the return of dark adaptation, both of the central and peripheral visual functions.

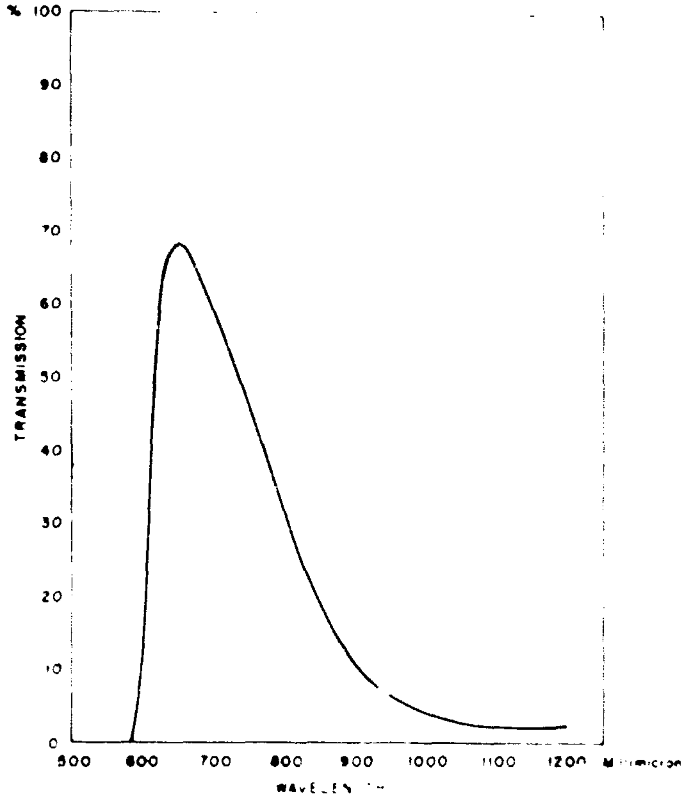

Fig. 2.6 Transmission Chart of Combined Red and Infrared Filters

of the radiation with wavelengths longer than 1 micron (Pittsburgh heat absorbing glass HA7). The other component of the filter, through which the flash was viewed, was the standard goggle, dark adaptation, Type E-1, Spec. No. 94-3142. This filter permits the passage of radiation with wavelengths longer than 590 μ, thus absorbing the short wavelengths, which have such high intensity early in the flash. By this combination of filters the light was reduced to a fairly narrow band between 600 and 900 μ, as indicated in Fig. 2.6. With the combined filters the retinal irradiation in the central image, formed at 10 miles distance from the fireball, during the first 1/10 of a second, was reduced to 20-25 per cent of the irradiation without the filters under otherwise equal circumstances.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 RESULTS

4.1.1 Statistical Data

Data for this project were obtained from five detonations. There were 19 subjects used with a total of 55 test observations. Of these, 39 were tests on red lighted instruments of the aircraft type and 16 were tests of mesopic and scotopic vision. The results of these tests are summarized in Table 7.1 to 7.4, and they indicate that the recovery of useful vision for reading red lighted instruments was very rapid. The average time to the first correct reading was 18.4 sec. This time varied but little for bombs of various sizes. It will be noted on the tables that these tests were conducted in very clear air conditions. Results might not be the same if haze or differing weather conditions prevailed.

Nyktometer tests showed that recovery of reasonably good mesopic vision (acuity 0.5 or 20/40) occurred on the average in 153 sec (range 47 to 420 sec).

The adaptometer tests indicated that recovery of scotopic vision to distinguish light at 0.001 Nit luminance occurred in an average of 152.8 sec (range of 45 to 250 sec). Visual acuity of 0.01 at this luminance returned on an average of 160.7 sec (range of 50 to 255 sec). At a luminance of 0.00001 Nit, the ability to distinguish form returned in an average of 226.3 sec (range 100 + to 300 sec), and visual acuity of 0.01 in an average of 248.9 sec (range of 105 to 330 sec).

4.1.2 Thermal Effects

One officer, used as a substitute on the last test, sustained a slight retinal burn in his paramacular area. He was the only subject of the 55 exposures who did. All other personnel were adequately protected by the combined filter used and careful objective and subjective examination showed no injury. This burn occurred on the final shot and was not detected until after the trailer had been dismantled, so the filters could not be rechecked to be sure they were intact. This officer does have an extremely darkly pigmented fundus and energy striking the pigment layer of his retina would be absorbed within a very thin layer of tissue. His injury occurred during the participation in the detonation of the largest of the bombs and the trailer was located nearer (7 miles) to ground zero than in any of the previous shots. The signifance of such a retinal burn is discussed in the other section of this report concerned with atomic chorioretinal burns.

4.2 DISCUSSION

There are two important eye problems relating to radiant energy released by the atomic detonation. One is the problem of physical tissue injury due to an increased temperature in the pigment layer of the choroid and the retina due to absorption of infrared and visible light. This problem is discussed in project report Chorioretinal Burns Produced by Atomic Flash, Project 4.5, Operation UPSHOT-KNOTHOLE.

The second problem is the temporary loss of visual function due to bleaching of the photochemical substances in the retina. This is the so-called flash blindness which is temporary. It was the aim of this study to determine the duration of this phase of the problem when a specific filter was used. Such filters are readily available and can be used by tactical organizations if the visual tasks of the individual can be carried out with the filter in place. Observation of red lighted aircraft instruments and navigational instruments are examples. In addition to reducing the period of visual disability, these filters in most instances will protect the eye against a chorioretinal burn.

The degree of protection afforded by these combined infrared absorbing and red transmitting filters cannot be determined with great accuracy since on each test there were many variables. In this latest bomb series not only were all individuals protected by filters, but different subjects were employed. Distances, total yields and atmospheric conditions varied on each shot. However, it may be inferred from our data and from the previous TUMBLER-SNAPPER study that an individual wearing such goggles in the vicinity of an atomic detonation at night would recover from the flash blindness in about 30 per cent less time than an unprotected person. While the percentage of time is not high, the length of time an aircraft can be flown at night without visual control is limited. Reduction in this temporary disability can be very significant from the standpoint of operation effectiveness and safety.

CHAPTER 5

CONCLUSIONS

5.1 CONCLUSIONS

It is concluded that a significant loss of central and peripheral vision occurs temporarily following exposure to an atomic detonation. It is also concluded that filters of the type tested serve to shorten by about 30 per cent the normally longer period of incapacitation in unprotected individuals as measured in the TUMBLER-SNAPPER operation. These filters will also protect almost all eyes against chorioretinal burns with bombs of the given yields, at the given distances, and under the stated atmospheric conditions. The atmosphere during the test was nearly ideally clear. Over industrial areas air attenuation would be higher.

PART II

OCULAR EFFECTS OF THERMAL RADIATION FROM ATOMIC DETONATION CHORIORETINAL BURNS

CHAPTER 6

INTRODUCTION

6.1 OBJECTIVE

To find the extent of damage caused by exposure of the dark adapted rabbit eye to the high intensity illumination of an atomic detonation with appropriate evaluation to determine whether human eyes might suffer similar injuries under the same exposure conditions. The injuries to the rabbit eyes were to be assessed by clinical photographic and histolgic means in an attempt to determine a threshold distance where retinal burns were no longer produced. An attempt was also to be made to correlate the size and frequency of retinal burns with weapon kilotonnage and distance of the animals from the fireball and insofar as possible with thermal flux intensity produced on the retinal image.

6.2 BACKGROUND AND THEORY

6.2.1 The Literature

The advent of the atomic bomb has produced new problems for the ophthalmologist and it has intensified some of the old ones. The neutron radiation problem is completely new. The gamma radiation problem is an expanded version of the roentgen ray and radium emanation problem. The radiant energy released at detonation of an atomic bomb in the form of infrared and visible light is again a physical agent with which opthalmologists are familiar because it produces the well-known eclipse burn of the retina. It is the same infrared and visible light which produces the atomic chorioretinal burns which are the subject of this presentation. Eclipse blindness with its typical macular burns has been reported by Birch-Hirschfeld (12), (13), (14), (15), Verhoeff, Bell and Walker (124), Alexander (1), Aubaret (3), Lundsgaard and Ronne (83), McCulloch (85), Rosen (105), Tower (121), Zade (138), (139), (140), Jess (67), (68), (69), and many others. Excellent reviews have been published by Lauber (76), Birch-Hirschfelt (14), Verhoeff, Bell and Walker (124) and Irvine (65).

6.2.2 Characteristics of Light

While the components of light from the sun and from the atomic bomb flash which produce the damage are the same (visible light and infrared), there are some rather marked differences between them. The eclipse burn is almost always macular; the atomic burn is usually not macular unless some fixation point has been provided giving the location of the bomb. The eclipse burn is incurred through a very small pupil, hence an appreciable period of time is required to heat tissue sufficiently to damage it. During this period the vascular system of the eye can dissipate some of this heat. In the atomic burn most of the energy is delivered so rapidly as to be almost instantaneous, thus giving no opportunity for vascular dissipation and very little for dissipation by conduction. In addition, it may well be delivered through the widely dilated pupil occurring at night. This wide open pupil will admit roughly 50 times the energy passed by the smallest pupil in the same period of time; so, while the mechanism is the same, there are differences which warrent careful consideration.

The extremely high intensity of radiation from the atomic flash has been recognized from the earliest tests. As a result, the eyes of practically all observers at atomic detonations have been carefully protected by very dense filters required by the test organization of the Atomic Energy Commission. These filters transmit less than 0.01 of 1 per cent of the visible light falling on them. A few individuals who have exposed their eyes in experiments and a few accidentally exposed eyes have sustained atomic chorioretinal burns. The literature reveals no report of such a burn except for a single case of bilateral central scotomata incurred in the Hiroshima atomic explosion, (Oyama and Sasaki (99)). The main reason for the paucity of burns in the Hiroshima incident is apparent - detonation in bright sunlight with pupils of the observers constricted to small size. There were other factors also, including size of the bomb.

Atomic chorioretinal burns are a real hazard from a national defense and civilian defense standpoint and the factors governing the production of these lesions should be known to ophthalmologists.

6.2.3 Physical Factors

Physical factors largely determine whether or not an atomic chorioretinal lesion will be produced. A theoretical consideration of the physical factors led to the prediction that such lesions could be produced considerably farther away from an atomic explosion than any other damage to living beings (Buettner and Rose (25), (26)). Heat damage to living tissue depends on the temperature and the length of time the temperature persists. The increase in temperature of matter depends on the energy absorbed per unit volume. If the energy is irradiated on a surface and absorbed by a layer of known thickness and absorption, the temperature during the heating period depends on the irradiance (that is, the energy arriving per unit area and unit time, e.g., cal/cm^2/sec). There is a difference between skin damage from thermal radiation and the production of chorioretinal lesion by thermal radiation. The irradiance from an atomic fireball on a surface, e.g., on skin, depends on radiant emittance, air attenuation, absorption and scattering, and on the inverse square of the distance. Due to the image formation in the eye the irradiance of the retina does not depend on the inverse square of the distance. It depends on the radiant emittance of the fireball, the square of the relative opening of the optics (pupillary radius divided by focal length) and on attenuation by the air and the ocular media. If air attenuation could be ignored, irradiance on the retina would not vary with distance. In the perception of brightness a similar phenomenon is well known. Due to the constancy of illumination of the retina a surface appears of equal brightness to us when we vary our distance from it. This is true as long as the distances are not large enough to introduce effects of attenuation by the air.

The radius of the image of an atomic fireball on the retina varies linearly with the radius of the fireball and inversely with the distance from the fireball. Thus with a pupil of given size at a given distance, a certain amount of energy is distributed over the image area. Now if the subject is twice as far away, the amount of energy passing through the same pupil will only be one-fourth as great, however, the image area into which the energy falls will only be one-fourth as large, therefore, the energy per unit area will be constant except for the attenuations produced by air and ocular media as mentioned above. Attenuation in the ocular media will change due to the change in spectral distribution of the fireball's radiation passing through the air. The significance of this change cannot be determined at present due to lack of spectral distribution data for short times.

When the angle subtended by the fireball is smaller than the resolving power of the optical system of the eye, an image of constant size results. The size of this image (often loosely called point-size or point-shaped image) depends on the diffraction at the entrance pupil, optical aberrations and scattering. The irradiation per unit area in such a "point-shaped" image on the retina is like irradiation of the slin dependent on the inverse square of the distance but it is higher than the skin irradiation due to the radiation gathering power of the optical system.

Most of the following discussion (but not all of the experiments later described) will be concerned with atomic bombs equivalent to 20,000 tons of TNT, (Effect of Atomic Weapons, 1950 (47)). Such a bomb produces a fireball of 1370 cm 0.1 ms after explosion. During the first second the fireball grows to about 10 times this radius, and it persists for about 3 sec after the explosion.

While expanding, the fireball cools rapidly. At 0.1 ms the surface temperature is 300,000°K. After 10 ms it is 2000°K; then it rises again, reaches a maximum of 7500°K after about 0.3 sec and finally drops to ambient temperature at 3 sec. (See also more recent data in The Thermal Data Handbook - AFSWP-700.) The radiant flux per unit area and the quality of radiation changes considerably with the surface temperature of the fireball. Spectral emission measurements have not been published. Figure 6.1 gives spectral emission computed on the assumption of black body radiation and Planck's formula.

The radiation at 0.1 ms is rich in ultraviolet and "blue" radiation. The radiation at 10 ms is "reddish;" the radiation during most of the time thereafter is fairly well represented by the third curve for 6100°K. The initial image on the retina subsequently receives the sum of this radiation energy for each unit area.

Ring-shaped zones around this initial image (corresponding to the enlarging fireball) receive less energy per unit area and radiation of different spectral quality (relatively more "reddish" than the initial radiation). If air absorption in the immediate vicinity of the fireball is considered, but air absorption on long paths of air is neglected, the irradiation of the ring-shaped zones of the image of the fireball can be given approximately in per cent of the irradiation which the central part of the image (corresponding to a fireball of 1370 cm at 0.1 ms = millisecond) would receive during 3 sec. The central image would have received at 100 ms 38 per cent, at 150 ms 40 per cent. A zone corresponding to a fireball of 2740 cm radius would have received at 100 ms 2.8 per cent, at 150 ms 5.5 per cent. The zones corresponding to fireballs of 4110 cm, 5500 cm, 6850 cm and 8250 cm would have received at 100 ms 1.7 per cent and at 150 ms 4.3 per cent. It is easily seen that at distances at which such zones can optically be resolved, the central zone will determine the threshold distance for damage.

The initial high radiant emittance and high temperature radiation is of special interest for several reasons. It can be assumed that an eye will react to the flash with closure of the lids. In man this reflex has a minimum latency of 55 ms (Brunn, Falk, Matthes, 1941 (24); Gerathewohl and Strughold, 1953 (54)), with an average nearer 100 ms. In rabbits the average lid closing time was found to be 284 ms.

About 35 per cent of the total energy emission of the central part of the fireball (radius 1370 cm) arrives at the eye during the first millisecond, (Fig. 6.2). For this part, the closure of the lids as well as the pupillary reflex have too much latency to be of any protective value.*

The transmission of the eye is assumed to be similar to the data in Fig. 6.3. This curve is a composite of data from Ludvigh and McCarthy, 1938 (84), from 400 μ to 640 μ and the data of Roggenbau and Wetthauer, 1927 (103) for wavelengths longer than 640 millimicrons. The latter data were recomputed for the thickness of the media of average human eye according to Listing, Helmholtz, and Gullstrand. It was extrapolated into the ultraviolet taking into consideration Kinsey's (70) data on rabbits. Data on the absorption of the pigment layer were not available for this study.

For the animal experiments as well as for those human eyes in which accidental damage occurred, refractive error must be considered. The enlargement of the image radius is approximately proportional to the pupillary radius and to the shift of the image from the retina. In human beings it can be assumed for the large majority that correct focusing occurs either by emmetropia, accommodation, or correction of refractive errors. The strain of rabbits used in the UPSHOT-KNOTHOLE experiments had about 2.5 diopters manifest hyperopia. For practical

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* The radius-time and temperature data quoted here was obtained from Effects of Atomic Weapons, 1950 (47). For reasons of expedience, in the publication of this report, more recent data (c.f. WT-710, Air Blast Measurements) was not utilized.

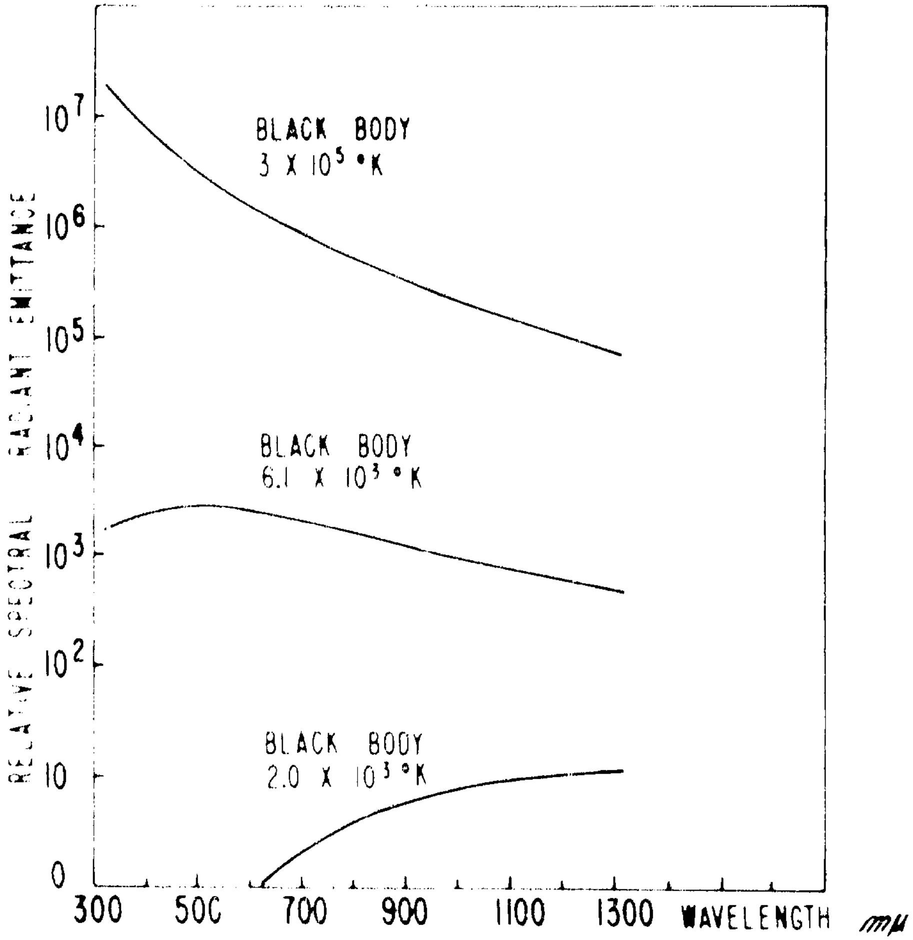

Fig. 6.1 Spectral Emission of Black Bodies of 300,000°K, 6100°K and 2000°K, Representing Three Phases of the Atomic Fireball.

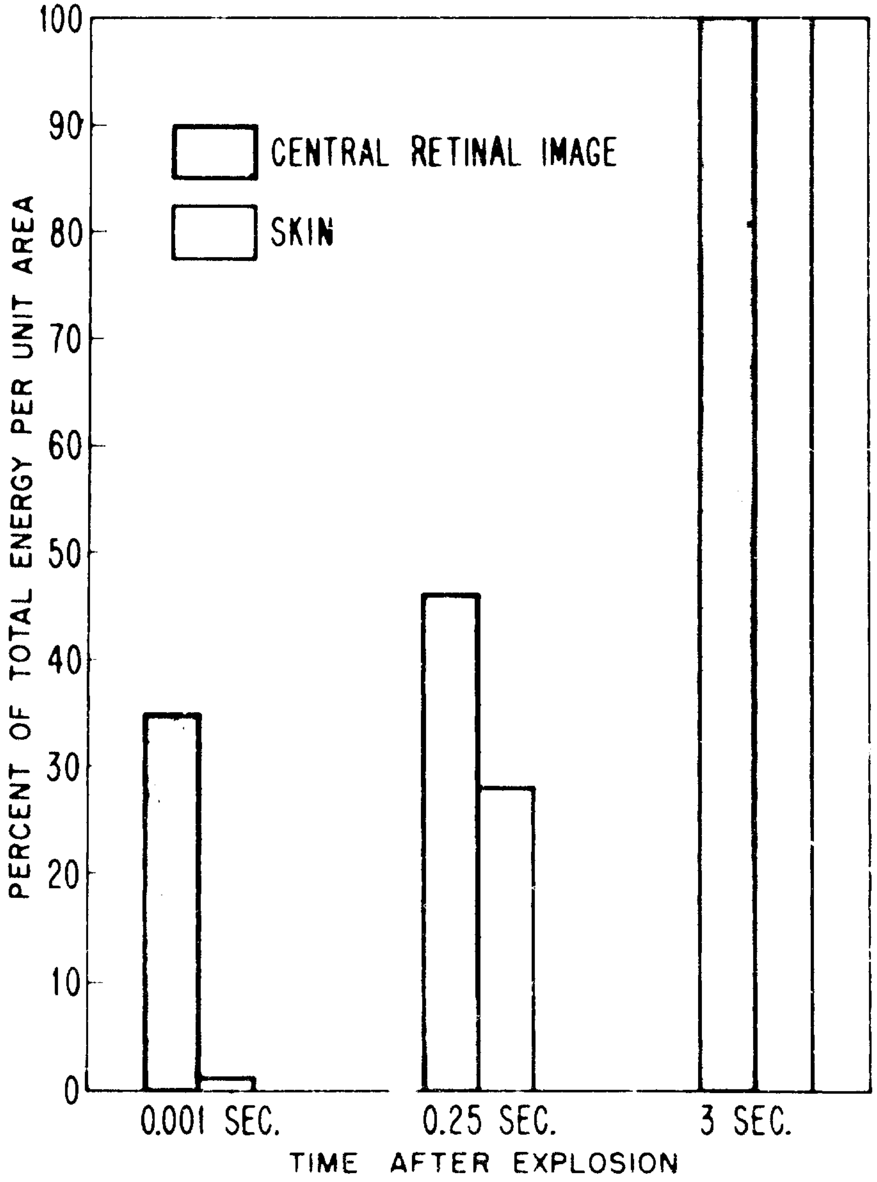

Fig. 6.2 Time of Incidence of Certain Percentagus of the Total Thermal Energy per Unit Area from a Nominal Atomic Bomb for the Central Part of a Retinal Image(dark column) and the Skin(white column)

purposes the resulting enlargement of the image radius is negligible (about 0.08 mm when pupil diameter 9 mm and focal length 10 mm). The increasing size of the actual fireball image, diffraction and scattering effects would overshadow the effect of small errors in refraction.

The relative opening of the eye differs in different species. A rabbit eye with wide night pupil, about 9 mm has about twice the relative opening of a human eye with wide pupil of 8 mm (the nodal point is closer to the retina in the rabbit). Since irradiance on the retina is proportional to the square of the relative opening of the eye, a human eye, if absorption were equal, would require at the cornea four times the irradiance necessary for a rabbit at the cornea for the production of a chorioretinal burn.

With equal irradiance on the retina differences in pigmentation exert a decisive influence on the production of lesions. Radiant energy can produce immediate effects only where it is absorbed. The dealing here is not with a specific effect of certain wavelengths, as in vision, but with non-specific heat effects from energy absorption. In an unpigmented albinotic eye, in spite of focusing by the optical system much radiation will pass through the eye and into the orbital fat. The little that is absorbed in the retina is absorbed in a relatively long path. Conversely, in a darkly pigmented eye much of the pigmentation is concentrated in the single cell layer of the pigment epithelium of about 5 micron thickness. It can be assumed that per unit length of path through the eye and per unit volume the pigment epithelium in a well pigmented eye has the highest energy absorption. It is the high energy absorption per unit volume and not so much the focusing effects which are responsible for the depth localization of the primary heat effect. This is obvious when one considers what happens in the case of an extended image where no "focal point" is formed. No data about absorption in the chorioretinal pigment are available. The absorption depends on individual pigmentation and should be very high in dark pigmented individuals.

Since from existing data the threshold for chorioretinal lesions could not be determined, an experiment with sun radiation was performed. A detailed report on this experiment will be given later. Only results pertinent to the present problem will be mentioned here. The experiment was performed on pigmented rabbits with pupils of 5 mm diameter.

The radiation from the sun was concentrated by means of a two mirror system. The irradiance at the cornea was measured by means of an irradiation meter devised by Dr. Oskar L. Ritter. The device was calibrated at the National Bureau of Standards by Mr. Ralph Stair. The irradiance at the cornea of the rabbits was 0.478 gm cal/sec cm^2. The exposure was 0.03 sec for the smallest chorioretinal lesion, which was of 1 mm radius. The assumption was made that this smallest lesion represented most closely the size of the "solar image," used for radiation, and that it showed the least secondary inflammation effects. Such effects tend in lesions obtained with more than threshold energy to make the lesion larger than the originally irradiated area.

During the 0.03 sec exposure 0.0143 gm cal/cm^2 was received at the cornea. The assumption was made that 40 per cent* of this energy was transmitted through the media of the eye and that all energy transmitted through the media and a 5 mm pupil was concentrated in the 1 mm diameter image. The relation of the area of the pupil to that of the image is 25/1. After applying the factors 0.4 and 25 the energy received per unit area of the retina is computed as 0.14 gm cal/cm^2. That is far less than the energy per unit area for the minimal skin lesion and less than reported formerly for eclipse blindness (Eccles and Flynn (46)).

Table 6.1 is an estimate of distances from atomic explosions for 0.1 gm cal/cm^2 in the central image on the retina which corresponds to the initial fireball of 1370 cm. No exact data about the spectral transmission of air during different weather conditions are available. The total air transmission data given in Effects of Atomic Weapons, 1950 (47) were used. For the human eye a daylight pupil of 4 mm diameter and a night pupil of 8 mm diameter were used for computation. The time interval was from explosion to 0.15 sec. For the rabbit at night twice the relative opening of the human eye and the time interval from explosion to 0.25 sec was taken.

TABLE 6.1 - Estimated Threshold Distances for Chorioretinal Lesions from a Nominal Atomic Bomb

Visibility (in miles)		Distance (in miles)		
		Human Eye		Rabbit Eye
		Day	Night	Night
Exceptionally Clear Air	25	31	40	50
	12	16	20	24
	7.5	10	13	17
Clear Air	6	8	10	12
Light Haze	1.9	3	4	5

The high initial irradiance of the retinal image has interesting consequences. If about 35 per cent of the total dosage of the central image arrives in 0.001 sec, there is scarcely time to dissipate this energy by conduction. The same number of calories arriving during a longer interval of time raises the temperature less because some energy is dissipated during the heating. If, due to short distance from the fireball, the temperature in the pigment layer reaches more than boiling temperature and there is insufficient time for heat dissipation (as during the first millisecond) an explosion of the boiling pigment epithelium is the necessary consequence. Tissue damage exceeding the original image in size is then to be expected. Furthermore, it is to

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* Estimated on the basis of eye transmission data from references 103 and 70.

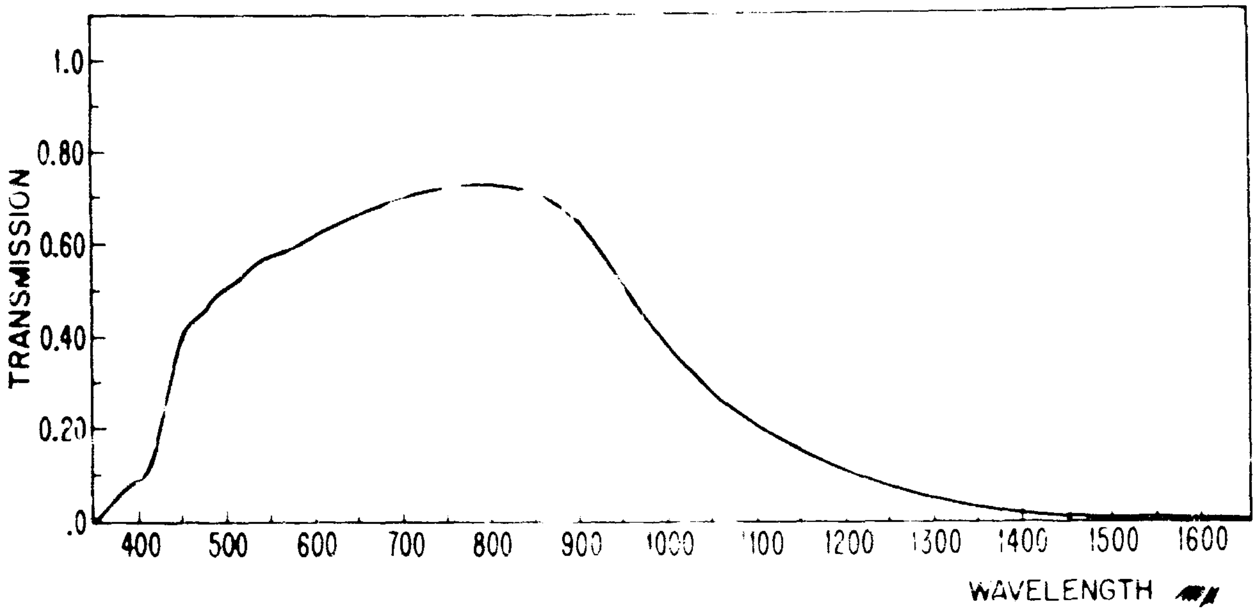

Fig. 6.3 Spectral transmission of the human eye, after Ludvigh and McCarthy, for 400 to 64 millimicrons and for the wavelengths longer than 660 millimicrons after Roggenbau and Wetthauer. The curve has been extrapolated in the ultraviolet using data from Kinsey. The Roggenbau-Wetthauer data were recomputed from the thicknesses of cow eyes from which they were measured, to thicknesses of human eyes.

be expected that a lesion due to explosion will differ from a lesion in which explosion does not occur, because destruction of individual cells and tissue structure occurs with the explosion.

It is not possible to give a useful estimate of the probability that the chorioretinal lesion destroys a definite part of the visual field or of the "normal" visual acuity. The size of the damaged area will in general be larger than the size of the image formed by the incident radiation. The effect of a certain size of a lesion depends on the location of the lesion. A lesion of the optic disc can cause considerable loss of the visual field or total blindness. A lesion in the macula will cause loss of visual acuity; secondary damage, like retinal detachment, can affect large parts of the visual field. If the appearance of a fireball were equally probable in all directions in space, and if the direction of gaze were completely randomized, then the probability that a certain structure of the retina were damaged by a lesion would be given by a fraction in which the product of the area of the lesion in square degrees and the area of the structure in square degrees forms the numerator, and where $41,253^2$ is the denominator. Obviously the direction of gaze is often toward the horizon and in pilots often in the direction of flight. Atomic fireballs are more probable near the horizon. For the direction of the fireball as well as for the direction of gaze weighting factors are necessary for the computation of a realistic probability of a certain lesion. Such weighting factors are presently not available. (The problem of weighting factors for the gaze was discussed at length by the Armed Forces - NRC Vision Committee in 1953 for reasons not connected with atomic fireballs. The discussion did not yield generally acceptable weighting factors.)

CHAPTER 7

INSTRUMENTATION

While computations and threshold determinations indicated that chorioretinal burns could be expected to a distance more than 45 miles as predicted by Rose (104), it was felt necessary to verify these predictions by actual experimentation. For this reason 700 pigmented rabbits were obtained. These were all male rabbits weighing between 4 and 6 lb. It was essential to utilize pigmented rabbits because the pigment in their fundi absorbs radiant energy in the same manner as does a human. These rabbits were exposed (one time each) during six different atomic detonations at the Nevada Proving Grounds. Shots participated in occurred on 7 March, 24 March, 18 April, 25 April, 19 May, and 4 June. They were all detonated 5 min before dawn under very clear atmospheric conditions.

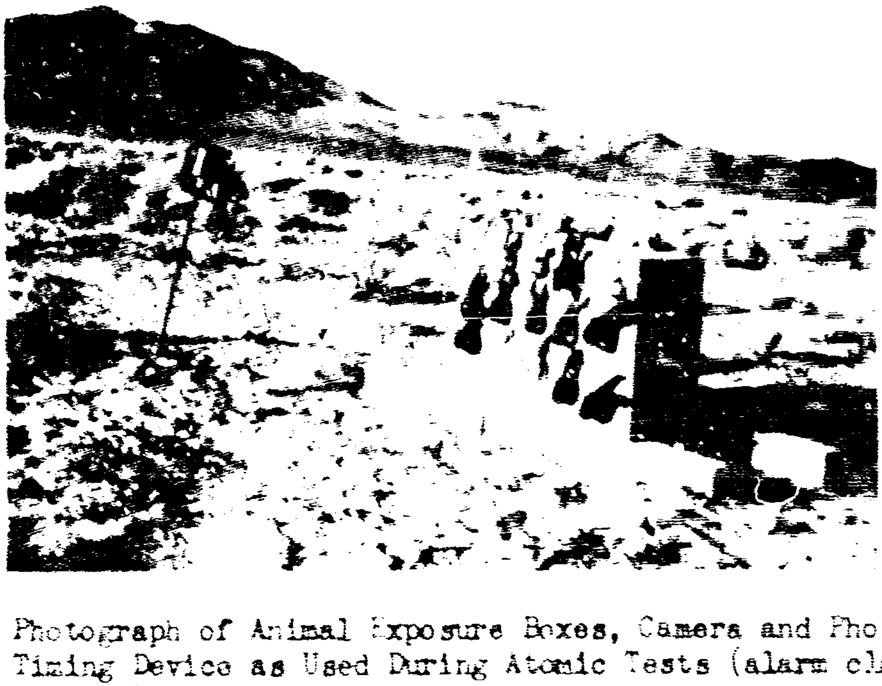

Fig. 7.1 Photograph of Animal Exposure Boxes, Camera and Photoelectric Timing Device as Used During Atomic Tests (alarm clock not visible)

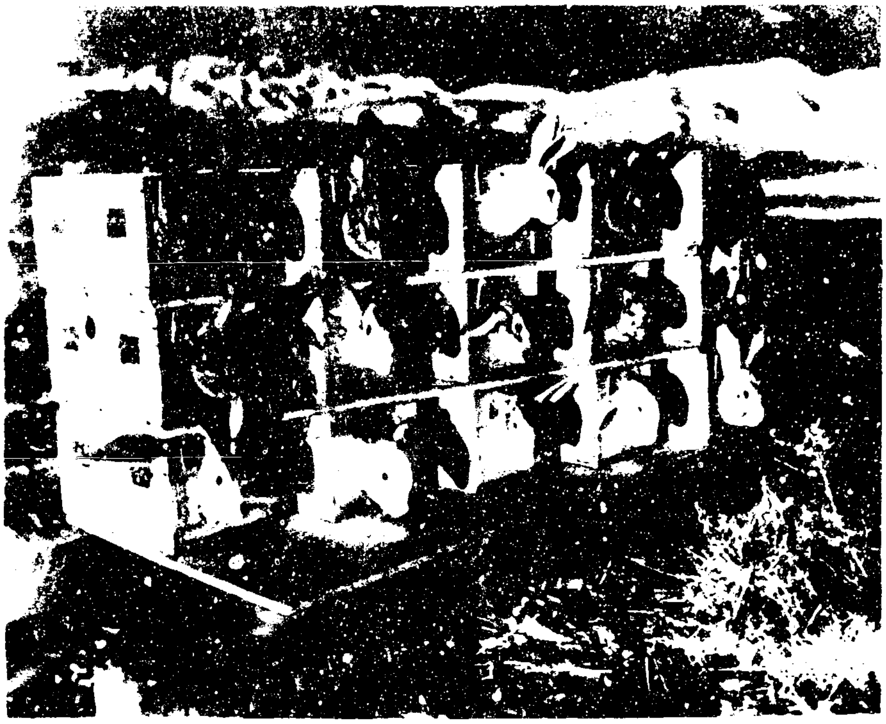

Fig. 7.2 Photograph taken by flash of atomic bomb. By this means animals with closed or shaded eyes could be eliminated from statistical consideration (alarm clock not visible). Note animal with head inside box.

The rabbits were placed in individual boxes which limited their head motion. They were aligned so that one visual axis was directed at the approximate location of the detonation. Since a rabbit moves his eyes very little, no method of eye fixation was required. They were placed in groups at various distances from the detonation point starting at 2 miles and going back in one instance to 42 miles. Alarm clocks were set to awaken the rabbits just prior to detonation. In addition, each group was photographed by the light of the bomb itself (see Fig. 7.1). This was done by a photoelectric timing device which snapped the picture during the first 21 ms, thus recording it before the rabbits could blink. In this manner the animals with closed or shaded eyes could be eliminated from statistical consideration (see Fig 7.2). The animals were examined ophthalmoscopically within the first few hours after the shot. Retinal burns were identified, described, and photographed with a fundus camera. Some animals were sacrificed at once in order to obtain the eyes for study; others were followed for longer periods to watch the subsequent course.

CHAPTER 8

RESULTS

8.1 RABBITS

The typical fresh lesion in the rabbit eye as seen with the ophthalmoscope is almost perfectly round, sharpely circumscribed and consists of a central and peripheral zone. In animals exposed near the detonation flash (within approximately 6 miles) one sees a deep central hole with glistening white base which appears to be sclera (see Fig. 8.1). Elevated volcano-like margins border this area. There may or may not be hemorrhage and/or coagulated debris exuding from the hole. Surrounding the central hole is a "halo" of dirty gray color, often twice the diameter of the hole. At greater distances from the flash the central area no longer appears to be a hole but is rather a yellowish-white plaque, (see Fig. 8.2) while the "halo" also diminishes in size with increasing distance until at the middle and extreme distances it disappears completely, whereas the plaque persists (see Fig. 8.3). The remainder of the retina appears entirely normal. Not all distances were utilized on all shots, and cameras and photoelectric equipment were not available for each station. In addition the photoelectric device failed to trip the shutters at some stations. From 5 to 50 rabbits were exposed at various stations. The rabbits shown photographically to have closed eyes at the time of detonation were eliminated from statistical consideration. On at least one of the shots chorio-retinal burns were produced in 100 per cent of the proven exposed animals at each of the following distances in miles: 4 5, 6, 7, 8, 9, 10, 12, 13, 14, and 27. Tables 9.1 through9.7 show statistical data pertaining to results of clinical examination of rabbits for each shot.

8.2 PATHOLOGICAL FINDINGS

8.2.1 Material

Sections of the eyes from a total of 173 pigmented rabbits have been prepared for the purpose of investigating the histopathological changes produced within the eye by atomic flash. In this report a few slides have been selected to correlate with the clinical picture and to

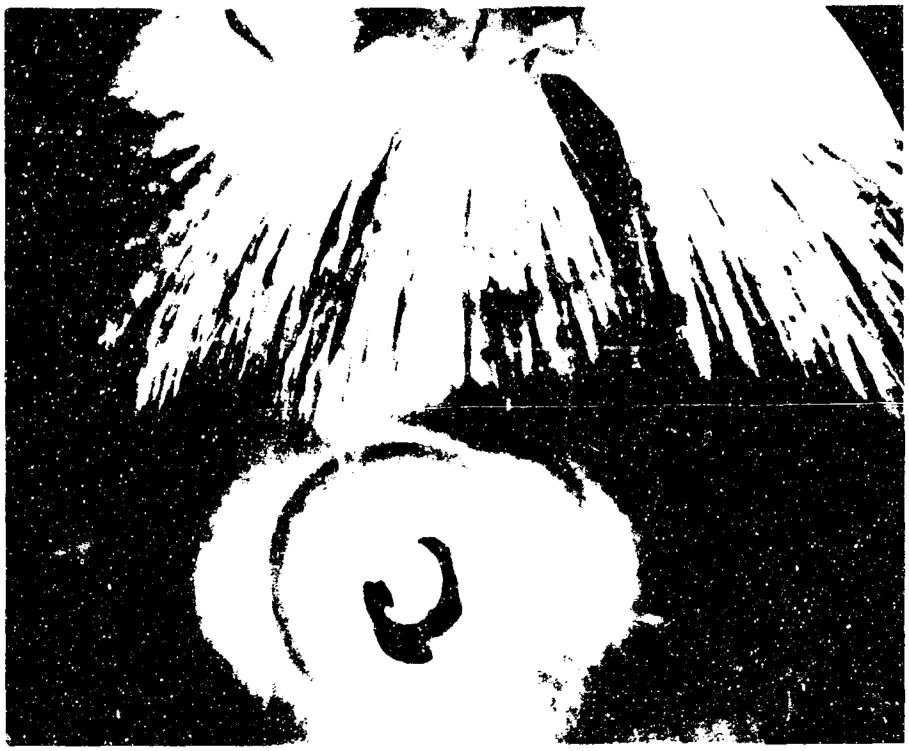

Fig. 8.1 Atomic Chorioretinal Lesion in Rabbit Incurred at 10.3 Miles During Shot 11. Note elevated margins, deep central hole with sclera at base, hemorrhage into the vitreous and surrounding coagulated area. (C-726)

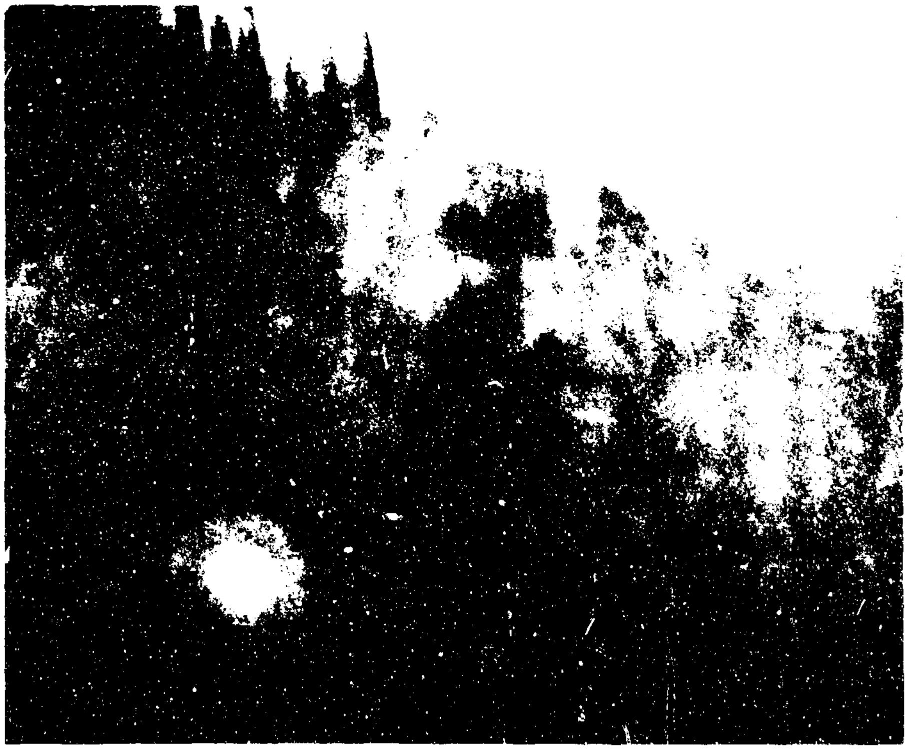

Fig. 8.2 Atomic Chorioretinal Lesion in Rabbit Incurred at 27 Miles During Shot 11. Typical of middle distances showing area of coagulation necrosis and small halo. (C-753)

elucidate the pathogenesis of both reversible and irreversible tissue changes accompanying atomic flash burns in retina, choroid, and sclera.

8.2.2 Technique

The rabbits were sacrificed by decapitation and the eyes enucleated immediately. The histological technique routinely employed was as follows: Buffered isotonic 10 per cent formalin solution was injected into the vitreous cavity of the freshly enucleated eyes which were then allowed to remain 3 weeks in the same fixative. This formalin-fixation was followed by alcohol dehydration. The eyes were finally embedded in celloidin under heat and increased pressure (Walls (129)). Microscopic sections were cut in a sagittal plane and were stained with hematoxylin eosin.

8.2.3 Morphology

The extent of the microscopic changes in the choroid and retina of pigmented rabbits exposed to atomic flash varied greatly, according to the amount of energy which had been absorbed by the tissues, primarily the retinal pigment epithelium and the choroidal chromatophores. These histologically visible changes in choroidal and retinal tissues can be divided into two characteristic types:

1. Lesions characterized by coagulation necrosis with additional major tissue and cell destruction in retina and choroid. This major tissue destruction is probably produced by explosive intracellular and extracellular generation of steam and gaseous expansion.
2. Lesions characterized by coagulation necrosis without major tissue and cell destruction in the retina.

Both types are best demonstrated by an unusual case in which a double retinal lesion occurred at 10.3 miles from the hypocenter (Shot 11). In this case, two disciform lesions of type 1 above were connected with each other by an opaque linear burn of type 2 (see Fig. 8.4). The diameter of the larger discoid lesion was 1.6 mm; that of the smaller discoid lesion was 0.5 mm. The length of the linear burn measured 6.5 mm; its width 0.2 mm. These measurements do not include the secondard choroidal reactive changes seen surrounding the lesions.

Ophthalmoscopically, both discoid lesions showed an immediate rupture of the retina and hemorrhage into the vitreous body. This vitreous hemorrhage disappeared within 2 days. The tissue around the necrotic center appeared as a gray milky ring which measured 1.6 mm in diameter on subsequent sectioning. After 2 days the animal was sacrificed for histopathological investigation of the eyes. The pertinent sections are shown in Figs. 8.5 and 8.6.

The microscopic picture of the larger lesion (Fig. 8.5) was that of circumscribed coagulation necrosis measuring 1.6 mm in diameter, with almost complete disintegration of nerve tissue and choroid within a central area of about 0.4 mm diameter. Hemorrhage from choroidal vessles had produced a circumscribed bulging elevation of retina into the vitreous with a horseshoe-shaped retinal tear. Although the retinal architecture is seen to be relatively well preserved over this

Fig. 8.3 Atomic Chorioretinal Lesion in Rabbit Incurred at 28.5 Miles During Shot 11. Typical of extreme distances showing sharply circumscribed area of coagulation necrosis and minimal halo. (C-717)

area, the underlying retinal pigment-epithelium and choroid have disintegrated. The choroid showed in addition dilatation of vessels, moderate edema, and minor hemorrhages.

The histological section cut vertically through the linear portion of the burn of Fig. 8.4 revealed (Fig. 8.6) marked choroiditis accompanied by structural changes in the adjacent retinal layer; whereas, only minimal alterations occurred in the remainder of the retina.

Retinal and choroidal lesions resulting from exposure to energy levels higher than those which produced the foregoing lesions (i.e., at closer stations during shots of highest thermal yield) are shown in Figs. 8.7 and 8.8 as follows: Figure 8.7 is a photomicrograph showing marked destruction of the retina over a central area of 1.1 mm, with choroidal alterations extending to a diameter of about 3 mm. This "perifocal" choroidal lesion seen histologically correlates closely in area with the ophthalmoscopically observed opacity of the retina which had been seen to surround the central area of retinal destruction. It is notable that there is no histologically demonstrable indication of retinal swelling or retinal edema within this perifocal area. One might be inclined to assume that the gray retinal opacity surrounding the central area of retinal disintegration, i.e., the perifocal retinal opacity, represents coagulation necrosis rather than edema.

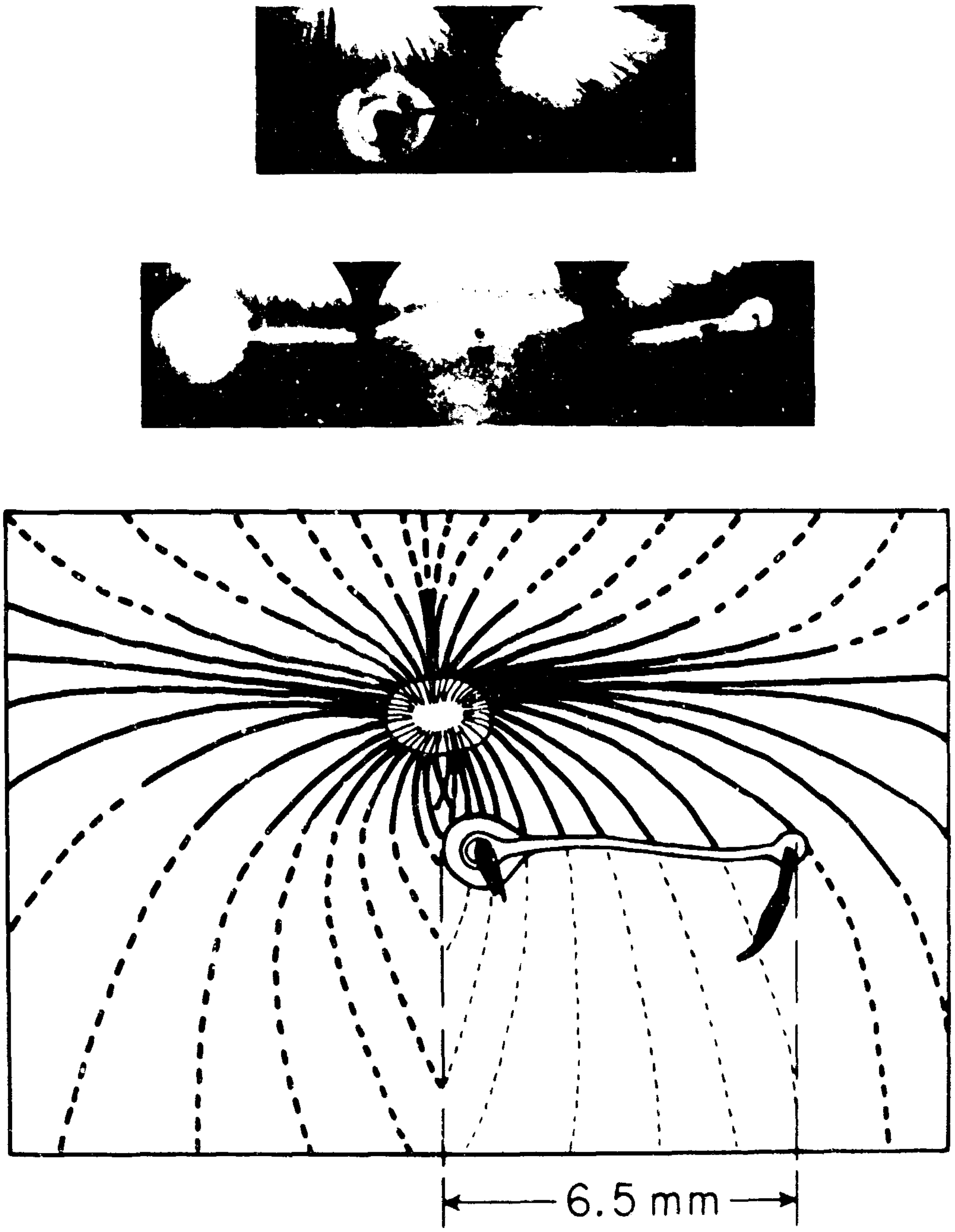

Fig. 8.4 Atomic Chorioretinal Lesion in Rabbit Eye Produced at 10.3 Miles During Shot 11. Unusual case of double disciform lesions connected by linear burn.
Top: 2 hr after exposure (high energy)
Center: 2 days after exposure
Bottom: Schematic diagram showing medullated nerve fibres in heavy lines, non-medullated nerve fibres in dotted lines. The latter have been obtained by extrapolation of the course of former. Magnification of lesion x 10 (USAF SAM R842)

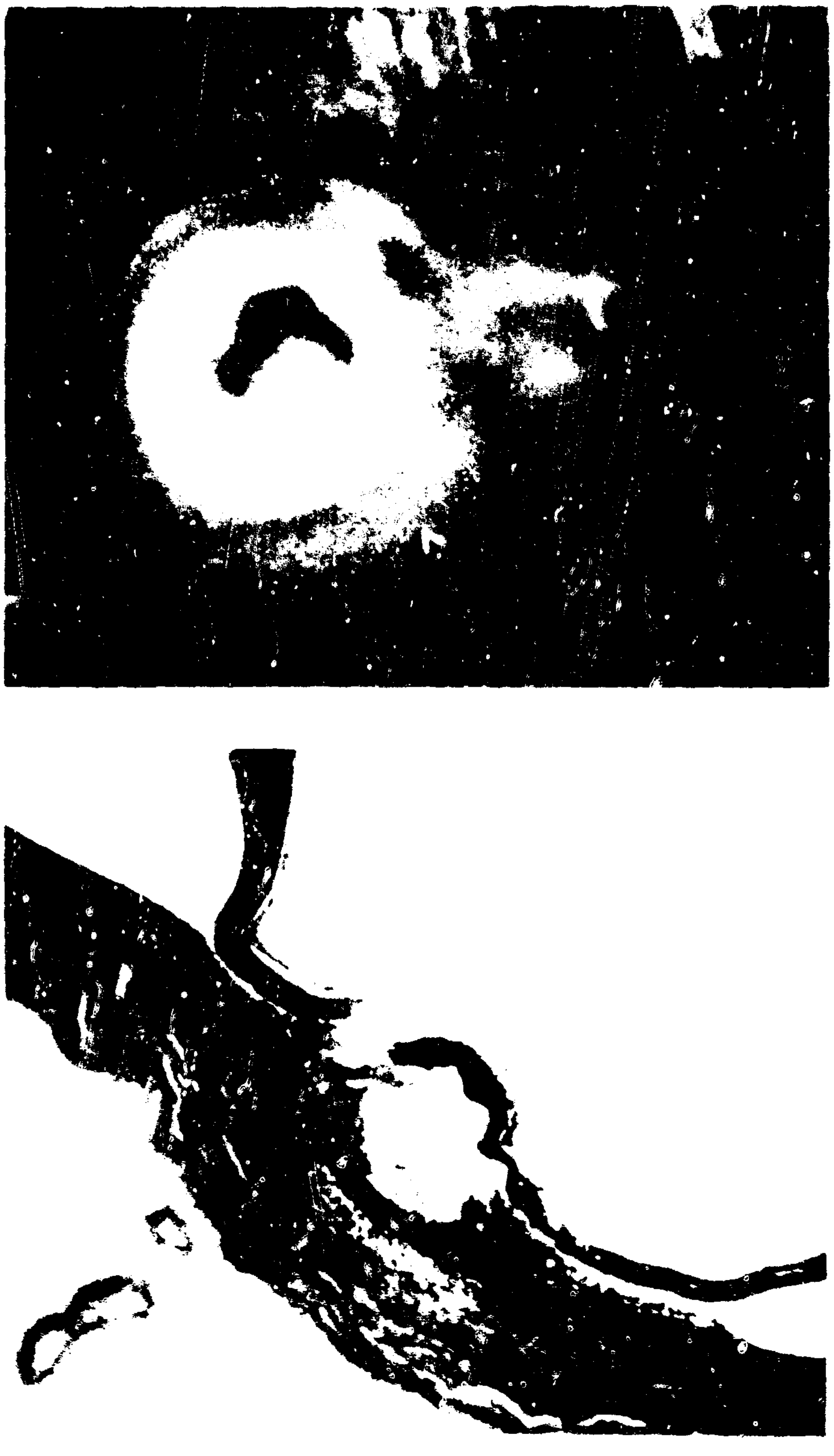

Fig. 8.5 Top: Early Stage of Atomic Chorioretinal Lesion (larger disciform lesion of Fig. 8.4)
Bottom: Microscopic section vertically cut through larger lesion coagulation necrosis with major tissue and cell destruction in choroid and retina. Exudation and hemorrhage in liquified center of lesion. Bulging and rupture of retina. Artificial detachment of retina. Magnification to scale of retinal picture. H&E, x 50 (USAF #842-C11).

Fig. 8.6 Early Stage of Atomic Chorioretinal Lesion. Vertical section through linear burn effect shown in Fig. 8.3. Notice the well preserved inner layers of the retina. Artificial detachment of the retina on both sides of lesion. H&E, x 150 (USAF SAM #842-C1)

Fig. 8.7 Early Stage of Atomic Chorioretinal Lesion in Pigmented Rabbit Eye Due to High Energy (6 mi, Shot 5). Sacrificed 2 days after exposure. H&E, x 60. Insert at left corner shows ophthalmoscopic picture of lesion. Magnification x 10 (SAM #309)

Fig. 8.8 Early Stage of Atomic Chorioretinal Lesion Due to High Energy (5 mi, Shot 2). Sacrificed 8 hr after exposure. Notice burn effect in sclera. H&E, x 50 (USAF SAM #113)

Fig. 8.9 Aseptic Inflammatory Reaction in Early Atomic Chorioretinal Lesion (10 mi, Shot 11). Accumulation of polymorphonuclear granulocytes, predominantly eosinophiles. H&E, x 200 (USAF SAM #844)

Figure 8.8 shows the tissue damage produced by extremely high levels of atomic flash energy. In such severe atomic burns almost complete destruction of the retina and choroid is found, often associated with a widespread coagulation necrosis which penetrates deeply into the sclera. However, even in these severe burns no case of perforation of the sclera was observed.

Figure 8.9, 8.10, and 8.11 illustrate the histologic changes associated with healing of these lesions. Figure 8.9 shows the appearance of aseptic inflammation which developed early in the repair phase. Polymorphonuclear granulocytes are present in the necrotic tissue of all the cases at this stage of repair. In many cases, such as the eye from which Fig. 8.9 was made, eosinophils predominated.

The final result of the repair process, after liquefaction, phagocytosis, and digestion of debris had taken place, and exudate had been absorbed, was a replacement of the disintegrated nervous tissue by glial tissue. In the choroid many of the dilated vessels were obliterated. Figures 8.10 and 8.11 illustrate the conversion of the granulation tissue to dense connective tissue which provides a relatively firm connection between retina and choroid.

8.3 ACCIDENTAL CHORIORETINAL BURNS IN HUMANS

Although not a specific result of the experiment as planned, the following information is pertinent to the study of retinal burns. Four human cases of chorioretinal burns severe enough to show on a fundus photograph have been observed during this and previous atomic tests. There are several more individuals who have looked at atomic detonations with unprotected eyes in the daytime and who have small otherwise unexplained scotomata.* These cases are not included. Of the four cases described here, only one has a serious disability. This man, S. H., was warned by his commanding officer that it would be dangerous to look at the flash, but he ignored the warning. He was an Army officer stationed with Army troops in trenches within 2 miles of the detonation point on Shot 8 (25 April). Fortunately, he did cover one eye which was therefore not damaged. Visual acuity in the exposed eye dropped immediately after exposure to 20/200. This patient was not seen in the Department of Opthalmology group until 6 weeks after his exposure. At that time he showed a central retinal lesion, about a disc diameter in size, the upper border of which bisected his macula. The area resembled a healed chorioretinitis with sharply defined borders. There were pigmentary changes surrounding the lesion. There was some neovascularization principally below. The central part of the clearly defined semicircular lesion was brownish in color. The entire lesion was depressed below the level of the surrounding retina and showed marked cicatrical contraction with a complete rosette of prominent retinal tension folds. Visual acuity was 20/70 with a sharply circumscribed absolute scotoma, measuring 4 degrees vertically and 5 degrees horizontally and located just above the fixation point (see Fig. 8.12).

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* Human Chorioretinal Burns from Atomic Fireballs, (Report in press, Archives of Ophthalmology.)

Fig. 8.10 Late Stage of Atomic Chorioretinal Lesion, Pigmented Rabbit, 18 Days after Exposure to Medium Energy (4 miles, Shot 8). Insert shows ophthalmoscopic picture to scale with microscopic photograph. Note obliteration and cicatrization of choroid in the center of the lesion, reactive hyperemia of choroidal vessels in surrounding tissue. Artificial detachment of choroid on both sides of lesion. H&E, x 10 (USAF # 600)

Three other human cases of retinal burns have been adequately documented in the series of bomb tests in this country, all of which occurred at approximately 10 miles. The first of these, B. V. C., occurred in 1952 tests during investigation of the changes in visual acuity, loss of dark adaptation and persistence of scotomata following atomic flash (see TUMBLER-SNAPPER report on Flash Blindness, WT-530). No protective filters were employed. Following the flash, subjective symptoms persisted for no more than 5 min, however, a nearly round absolute scotoma was later mapped out in the left eye, 3 mm from the fixation point, about 1/10 disc diameter in size. Ophthalmoscopically, a punched out fairly sharply demarcated area of blanching of the retina approximately 1/10 disc diameter was seen in a position corresponding to the scotoma just nasal to the macula. Visual acuity remained unaffected, OS: 20/15-1 (see Fig. 8.13).

Fig. 8.11 Late Stage of Atomic Chorioretinal Lesion, Pigmented Rabbit, 28 Days after Exposure to High Energy (3 mi, Shot 1) Advanced scarification of choroid causing large granulated "halo" in fundus picture. Obliteration of choroidal vessels and pigment atrophy. H&E, x 50 (USAF SAM #53)

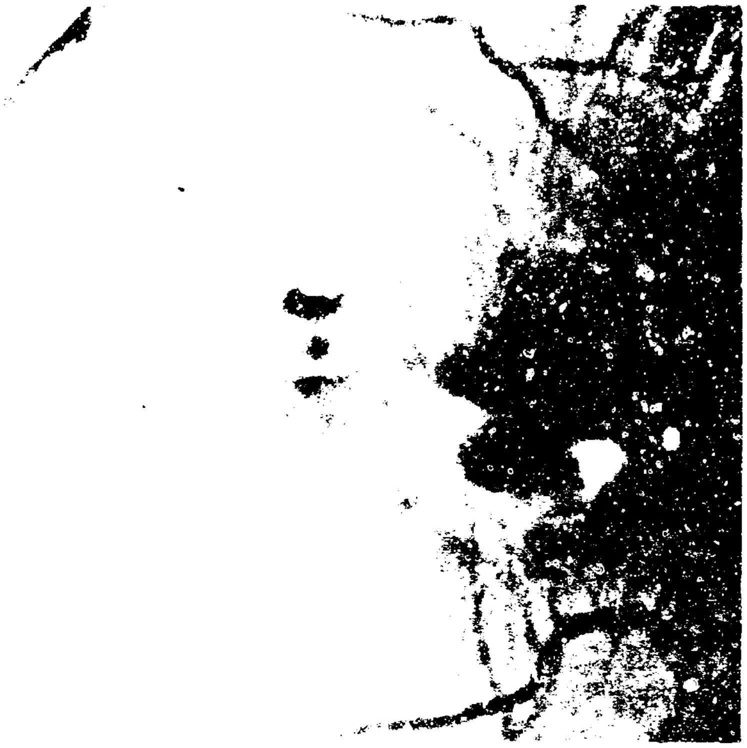

Fig. 8.12 Atomic Chorioretinal Lesion in Human (S.H.) 2 Miles from Explosion, Shot 8. Lesion in the lower right part of picture. Note radial tension folds. Two dark spots and white lines in the center are artifacts. Photograph taken 6 weeks after bomb exposure.

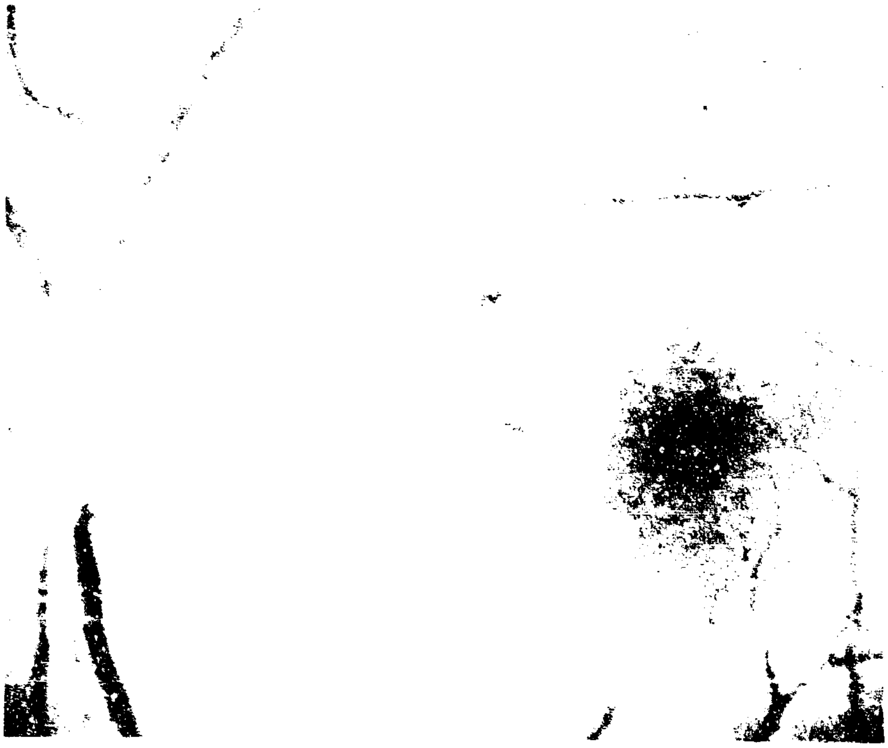

Fig. 8.13 Healed Atomic Chorioretinal Lesion in Human (B.V.G.) at 10 mi. from Explosion, TUMBLER-SNAPPER, 1 May 1952. Dark spots and white lines in center of picture are artifacts. Lesion isolated between macula and artifacts. Photo taken 1½ yr after exposure.

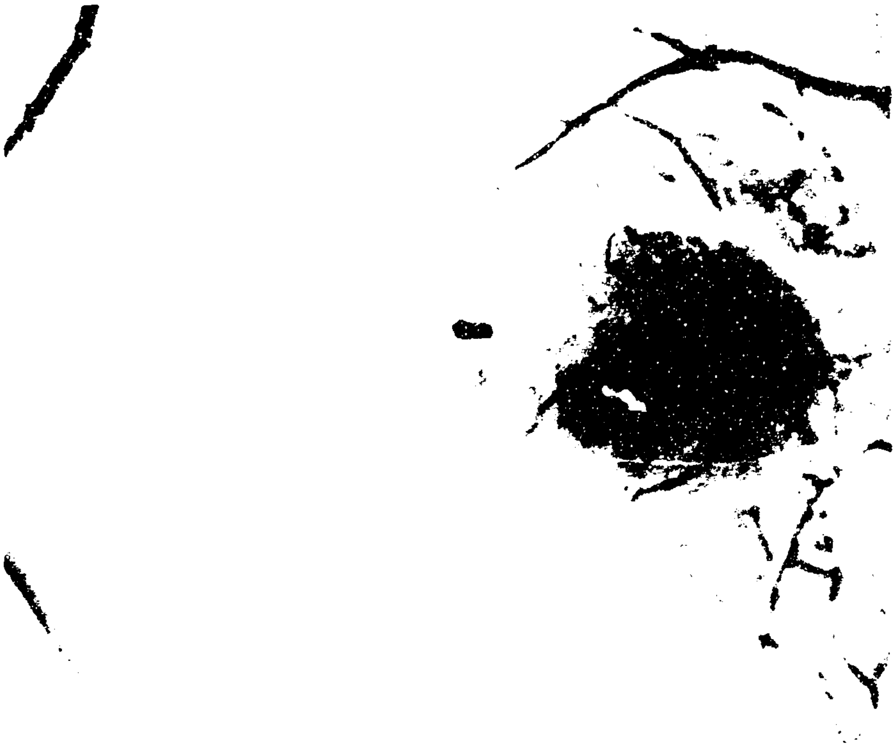

Fig. 8.14 Atomic Chorioretinal Lesion in a Human (M.C.B.) 7 Miles from Explosion (19 May 1953, Shot 8). Lesion: oval area below macula. Photograph 1 month after exposure.

Fig. 8.15 Atomic Chorioretinal Lesion (W.I.C.) in Human, Photograph 1 Month after Exposure. Incurred at 10 miles from explosion, Shot 7. Arrows point to lesion.

The last two cases occurred during UPSHOT-KNOTHOLE. C. B. was an officer who observed the flash (at 7 miles distance during Shot 7, 19 May) with his left eye through special ophthalmic filters designed to transmit much reduced intensity in a limited portion of the spectrum. A peripheral scotoma was noted immediately after the tests and has persisted to the present. Corrected visual acuity OD: 20/15; OS: 20/15. Examination showed a horizontally elliptical punched out lesion approximately 1/6 disc diameter in size just below and bordering on the left macula. Sclera is seen in the depths of the lesion. The center of the lesion is white in color and is in all respects quiescent. A 3-degree absolute scotoma persists (see Fig. 8.14).

The final case is that of an airman, W. L. C., who was preparing to photograph the atomic bomb (at 7 miles distance during Shot 7). He had just sighted the target when the flash occurred. He blinked immediately and turned away from the flash. The subject noted no symptoms whatever and was examined on a routine checkup one month later. Examination revealed identical bilateral symmetrically placed small lesions. The left is half way between disc and macula and slightly below a line joining them. The lesion of the right eye is lateral to and just below the macula. Lesions have a pale center with slightly pigmented margin. No edema or depression is seen. Corresponding scotomata were plotted. Visual acuity OD: 20/20; OS: 20/25 (see Fig. 8.15).

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CHAPTER 9

DISCUSSION AND CONCLUSIONS

9.1 DISCUSSION

The animal experiments have shown that danger to the retina from an atomic explosion actually exists far beyond all previously estimated distances. While the experiments were performed on rabbits, they show, within experimental error, agreement with the estimates made in Table 6.1. It is obvious from studying the burns in question that they do not represent the maximum distance but the threshold is being approached. There is therefore considerable support for the Department of Ophthalmology's estimates of threshold distances for human eye lesions as given in Table 6.1. The three human cases in which lesions occurred at 7 to 10 miles away from the detonation are further proof of the potential danger to the retina. Ophthalmoscopically these lesions were reasonably similar to those observed in animals at comparable distances. Subsequent observation showed that the healing phase in humans also corresponds to that in experimental animals. It is apparent that the diameter and severity of the lesion decreases with increasing distance. Close to the fireball the predicted explosions within the retina were observed. Near the estimated threshold distances no retinal explosions were observed. One must also consider the possibility of an atomic flash burn occurring directly on the optic nerve head. This would, if of sufficient size, result in complete blindness of the affected eye. The formation of radial tension folds suggests the possibility of future retinal detachment. In this manner even a small extrafoveal lesion which in itself would not essentially impair vision, will result in a potentially disastrous loss of vision.

From the series of microscopic sections studied thus far, it can be inferred that the pigment of the retinal epithelium and choroid is the principal site of absorption of the energy from atomic flash which produces intraocular lesions. The lesions are characterized by a coagulation necrosis accompanied by central major tissue destruction involving these same pigmented layers. In lesions caused by low radiation energy, the inner layers of the retina are usually well preserved. This does not necessarily imply functional integrity in vivo since moderate heat with temperatures below the boiling point may cause coagulation necrosis without destruction of the architecture. Similar cases had been described by Birch-Hirschfelt (13), (14), and by Verhoeff and associates (124). These investigators produced retinal burns with a carbon light for the purpose of correlating histopathological changes with the clinical picture of solar retinitis. Birch-Hirschfelt (12), (13), (14), (15) also observed that thermal damage produced in the choroid and retina of pigmented rabbits is greater than that produced in the eyes of albinotic rabbits. He interpreted his findings as evidence that the anatomic lesions of eclipse blindness are a transudation from the choroid, a necrosis of the outer retinal layers, and disintegration of the pigment epithelium, a conclusion already made by Czerny (14), Deutschmann (34) and Witmark (14). According to Birch-Hirschfelt (12), (13), (14), (16) the inner retinal layers were only secondarily involved - a conclusion which remains to be proved. There is strong evidence that coagulation necrosis, whenever caused by heat below the boiling point of tissue, is the cause of the milky gray discoloration of the retina seen with the ophthalmoscope.

Histologically, this gray retinal tissue was distinguished by a well preserved architecture. This discoloration could be interpreted not only as the result of a direct heat coagulation of the tissue, but also as the result of a delayed autolysis. Such a delay in autolysis could be explained by assuming that the applied heat destroys the ferments which normally initiate rapid autolysis.

The histological evolution of the tissue repair following these atomic bomb flash burns does not differ essentially from a repair following burns produced by other sources of energy. Remarkable, however, is the extensive accumulation of eosinophils in some cases. This finding suggests the occurrence of a hypersensitivity reaction to the denatured protein or its derivatives. Also surprising is the extent of the reactive hyperemia in the choroid surrounding the lesion. In some cases it exceeded the area of primary damage by more than six diameters. This observation suggested a study of the heat effect on the activity of certain enzymes in the retina and choroid which is presently being undertaken. In the final stage of repair, the prominent features of the microscopic picture were the obliteration of initially dilated vessels, the scarification in the area of the burn, and the solid fusion of retina, choroid, and sclera at the margin of the lesion. These atomic chorioretinal burns are important to the practicing ophthalmologist who should be aware of the danger of their production for military and civil defense reasons and who should be able to recognize them if they occur. Certain facts must be emphasized. A large part of the energy is delivered so rapidly that blinking and pupillary contraction have only limited protection value. Relative pupillary aperture is a most important factor, thus atomic chorioretinal lesions will occur much more frequently and at larger distances at night. The darker the pigmentation of the retina, the more susceptible it is to being burned. Defects produced in the visual fields will be peripheral unless the burn involves the macula or the nerve head, in which case very severe visual defects may result.

TABLE 9.1 - Estimated Threshold Distances for Chorioretinal Lesions from Nominal Atomic Bombs

Visibility Distance	Exposure Period after Time Zero (sec)	Threshold Distances for Various Diameters of Pupil Opening					
		2 mm		4 mm		8 mm	
		km	mi	km	mi	km	mi
k = 0.1; V = 40 km = 25 mi	0.15	36	23	50	31	64	40
	3	45	28	59	37	73	47
k = 0.2; V = 20 km = 12 mi	0.15	18	11	25	16	32	20
	3	23	14	30	18	37	23
k = 0.3; V = 12 km = 7.2 mi	0.15	12	8	17	10	21	13
	3	15	9	20	12	24	15
k = 0.4; V = 10 km = 6 mi	0.15	9	6	13	8	16	10
	3	11	7	15	9	18	12
k = 1.1; V = 3 km = 2 mi	0.15	3	2	5	3	6	4
	3	4	2.5	5	3	7	4

Estimated maximum distances at which a 20 KT equivalent (nominal) atomic bomb would cause a chorioretinal burn. The distances given with 0.15 sec are to be applied when the lid reflex is prompt. The distances given with 3 sec are to be applied when the fireball is viewed during its existence.

The size of the lesion is not given because this depends not only on distance but on biological variables such as chorioretinal pigmentation. The lesions contain areas of different types and degrees of damage and their relations to yield, being dependent on several variables, cannot be established from our present information.

k is the attenuation coefficient per kilometer; V is visibility. The table is computed for average human eyes using Gullstrand's data of the eye and under the assumption that 0.1 cal/cm^2 applied during times on the order of magnitude of a sec or tenths of a sec produce a minimal burn.

TABLE 9.2 - Recovery Time, Shot 1, 17 Mar 1953

Subjects viewed the bomb flash through the filter system described in the text.

A. Recovery of ability to read red floodlighted and internally red lighted instruments in protected individuals:

Subject	Recovery Time in Sec
W. K.	20
C. M.	20
R. S.	17
D. C.	20
L. W.	25
R. B.	25
E. H.	12
C. G.	20
	Average 19.9 sec

B. Recovery time in seconds of mesopic vision measured on the nyktometer:

Subject	Visual Acuity 0.1	Visual Acuity 0.5 (20/40)
J. K.	53	176
G. P.	55	*175
C. C.	28	158
W. F.	92	420
Average	58 sec	** 248 sec

C. Recovery time in min of scotopic vision measured on the adaptometer:

	Luminance 0.001 Nit		Luminance 0.00001 Nit	
Subject	Distinguish Light	Visual Acuity 0.01	Distinguish Light	Visual Acuity 0.01
J. K.	3:00	3:05	4:20	5:25
G. P.	4:02	4:12	4:50	5:30
C. C.	2:45	3:00	4:00	4:52
W. F.	4:10	4:15	5:00	5:20

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* 175 seconds is the time required to read 0.4 acuity, 0.5 reading not possible even at 8 minutes.

** 175 reading not included in this average.

TABLE 9.3 - Recovery Time, Shot 2, 24 Mar 1953

Subjects viewed the bomb flash through the filter system described in the text.

A. Recovery of ability to read red floodlighted and internally red lighted instruments in protected individuals:

Subject	Recovery Time in Sec
W. K.	40
C. M.	22
R. S.	21
D. C.	21
L. W.	20
R. B.	15
E. H.	25
C. G.	8
Average	21.5 sec

B. Recovery time in seconds of mesopic vision measured on the nyktometer:

Subject	Visual Acuity 0.1	Visual Acuity 0.5 (20/40)
J. K.	77	260
G. P.	20	56
C. C.	15	100
W. F.	35	* 125
Average	36.5 sec	** 138 sec

C. Recovery time in min of scotopic vision measured on the adaptometer:

	Luminance 0.001 Nit		Luminance 0.00001 Nit	
Subject	Distinguish Light	Visual Acuity 0.01	Distinguish Light	Visual Acuity 0.01
J. K.	4:21	4:22	4:56	5:10
G. P.	1:05	1:10	1:40	1:45
C. C.	2:40	3:00	3:30	5:15
W. F.	3:05	-	-	4:00

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* The 125 is 0.4 reading; no reading of 0.5.

** This does not include the 125 reading.

TABLE 9.4 - Recovery Time, Shot 5, 18 Apr 1953

Subjects viewed the bomb flash through the filter system described in the text.

A. Recovery of ability to read red floodlighted and internally red lighted instruments in protected individuals:

Subject	Recovery Time in Sec
W. K.	15
C. M.	12
R. S.	16
D. S.	9
L. W.	25
R. B.	19
J. F.	20
F. H.	5
Average	15.1 sec

B. Recovery time in seconds of mesopic vision measured on the nyktometer:

Subject	Visual Acuity 0.1	Visual Acuity 0.5 (20/40)
J. K.	-	89
G. P.	10	65
C. C.	11	85
W. F.	15	* 60
Average	12	** 79.6

C. Recovery time in min of scotopic vision measured on the adaptometer:

Subject	Luminance 0.001 Nit		Luminance 0.00001 Nit	
	Distinguish Light	Visual Acuity 0.01	Distinguish Light	Visual Acuity 0.01
J. K.	-	3:00	-	-
G. P.	0:45	0:50	3:00	
C. C.	1:40	1:45	2:25	3:10
W. F.	1:50	-	-	2:30

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* The 60 is 0.3 reading; instrument failed on 0.5.
** This does not include the 60 reading.

TABLE 9.5 - Recovery Time, Shot 7, 25 Apr 1953

Subjects viewed the bomb flash through the filter system described in the text.

A. Recovery of ability to read red floodlighted and internally red lighted instruments in protected individuals:

Subject	Recovery Time in Sec
W. K.	10
C. M.	14
R. S.	27
L. W.	25
R. B.	12
E. H.	6
H. W.	23
Average	16.7 sec

B. Recovery time in seconds of mesopic vision measured on the nyktometer:

Subject	Visual Acuity 0.1	Visual Acuity 0.5 (20/40)
J. K.	55	- (No 0.5 reading possible)
G. P.	14	47
[illegible]. C.	58	225
W. F.	17	170
Average	36	147

C. Recovery time in min of scotopic vision measured on the adaptometer:

	Luminance 0.001 Nit		Luminance 0.00001 Nit	
Subject	Distinguish Light	Visual Acuity 0.01	Distinguish Light	Visual Acuity 0.01
J. K.	1:50	2:00	3:50	4:00
G. P.	1:04	1:30	4:50	-
C. C.	3:50	3:50	4:25	4:40
W. F.	1:20	1:31	2:16	2:19

TABLE 9.6 - Recovery Time, Shot 8, 19 May 1953

Subjects viewed the bomb flash through the filter system described in the text.

A. Recovery of ability to read non-floodlighted red internally illuminated instruments in protected individuals:

Subject	Recovery Time in Sec
W. K.	8
R. S.	23
R. B.	14
W. F.	18
G. P.	23
J. Kell	20
J. Kav	30
M. B.	5.3
Average	16.4 sec

TABLE 9.7 - Summary of Previous Tables

A. Averages of recovery time of ability to read red floodlighted instruments in protected individuals for each shot:

Shots	Distance in Miles	Radiochemical Yield(KT)	Visibility in Miles	Recovery Time in Seconds
1 (17 Mar 53)	7.5	16.2	50	19.9
2 (24 Mar 53)	11.0	24.5	50	21.5
5 (18 Apr 53)	14.0	23.0	50	15.1
7 (25 Apr 53)	8.0	43.4	50	16.7
			Average	18.4
8. (19 May 53)	7.0	27.0	50	* 16.4

B. Average recovery time of mesopic vision measured on the nyktometer:

Shot	Visual Acuity 0.1	Visual Acuity 0.5 (20/40)
1	58 sec	248 sec
2	36 sec	138 sec
5	12 sec**	80 sec
7	36 sec	147 sec
Average	35.5 sec	Average *** 153 sec

C. Average recovery time of scotopic vision measured on the adaptometer:

Shot	Luminance 0.001 Nit		Luminance 0.00001 Nit	
	Distinguish Light	Visual Acuity 0.01	Distinguish Light	Visual Acuity 0.01
1	209.2	218.0	272.5	316.8
2	179.0	170.7*	202.0*	242.5
5	85.0*	111.7*	162.5*	170.0*
7	127.0	132.8	230.2	219.7*

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* Only the time required to read non-floodlighted internally illuminated instruments was measured.

** Indicates average based on less than 4 subjects.

*** This figure is undoubtedly considerably below the true average, since on each shot some individual failed to read the 0.5 test. Subjects viewed the bomb flash through the filter system described in the text.

TABLE 9.8 - Results of Clinical Examination and Placement Information on Rabbits for Shot 1 (17 March 1953)

Station (miles from GZ)	No. of Animals Placed	Camera Coverage	Proven* Exposures (No. of Animals)	No. of Animals with Retinal Burns	Per cent of Animals with Retinal Burns**
2	5	None		1	20 - ?
3	5	None		3	60 - ?
4	5	Still	4	4	80 - 100
5	5	Movie	5	5	100 - 100
6	5	Still	4	3	60 - 75
7	10	Still		5	50 - ?
8	10	Still	6	6	60 - 100
9	10	Movie		5	50 - ?
10	15	Movie	12	7	47 - 58
11	15	Movie	9	8	53 - 89
12	15	Movie	7	6	40 - 86

TABLE 9.9 - Results of Clinical Examination and Placement Information on Rabbits for Shot 2 (24 March 1953)

Station (miles from GZ)	No. of Animals Placed	Camera Coverage	Proven* Exposures (No. of Animals)	No. of Animals with Retinal Burns	Per cent of Animals with Retinal Burns**
3	5	None		4	80 - ?
4	5	None	5	5	100 - 100
5	5	None	5	5	100 - 100
6	5	Movie	5	5	100 - 100
7	5	Movie	4	3	60 - 75
8	10	None		6	60 - ?
9	10	Still	8	7	70 - 87
10	10	None		8	80 - ?
11	15	Still	9	8	53 - 89
12	20	Still	12	10	50 - 83
13	20	Still	15	13	65 - 87
14	20	Still	14	9	45 - 64

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* "Proven Exposure" includes animals with lesions plus those whose eyes were open at zero time as shown by photographs of the rabbits in situ.

** Per cent of animals placed showing retinal burns is followed by per cent of proven exposed animals showing retinal burns.

TABLE 9.10 - Results of Clinical Examination and Placement Information on Rabbits for Shot 5 (18 April 1953)

Station (miles from GZ)	No. of Animals Placed	Camera Coverage	Proven* Exposures (No. of Animals)	No. of Animals with Retinal Burns	Per cent of Animals with Retinal Burns**
3	5	None		4	80 - ?
4	5	None	5	5	100 - 100
5	5	None		3	60 - ?
6	5	None		3	60 - ?
7	5	Still	4	3	60 - 75
8	5	None		2	40 - ?
9	5	Still	4	3	60 - 75
10	5	None		3	60 - ?
11	5	None		3	60 - ?
12	10	Still	8	8	80 - 100
13	10	Still	8	8	80 - 100
14	15	Still	12	12	80 - 100
15	15	Still	13	5	33 - 38
16	15	None		7	47 - ?
17	20	None		9	45 - ?

TABLE 9.11 - Results of Clinical Examination and Placement Information on Rabbits for Shot 7 (25 April 1953)

Station (miles from GZ)	No. of Animals Placed	Camera Coverage	Proven* Exposures (No. of Animals)	No. of Animals with Retinal Burns	Per cent of Animals with Retinal Burns**
3	10	None		3	30 - ?
4	10	None		8	80 - ?
5	10	None		7	70 - ?
6	10	None		8	80 - ?
7	10	Still	6	6	60 - 100
8	15	Still	8	8	53 - 100
9	15	Still	10	10	67 - 100
10	20	Still	15	14	70 - 93
11	20	Still	12	11	55 - 91
25	10	Still	8	1	10 - 12

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* "Proven Exposures" includes animals with lesions plus those whose eyes were open at zero time as shown by photographs of the rabbits in situ.

** Per cent of animals placed showing retinal burns is followed by per cent of proven exposed animals showing retinal burns.

TABLE 9.12 - Results of Clinical Examination and Placement Information on Rabbits for Shot 8 (19 May 1953)

Station (miles from GZ)	No. of Animals Placed	Camera Coverage	Proven* Exposures (No. of Animals)	No. of Animals with Retinal Burns	Per cent of Animals with Retinal Burns**
9	10	None		7	70 - ?
23	30	None		1?	3?
25a	20	None		1?	5?
25b	20	Still	20	1	5
39	50	None		1?	2?

TABLE 9.13 - Results of Clinical Examination and Placement Information on Rabbits for Shot 11 (4 June 1953)

Station (miles from Extended GZ)	No. of Animals Placed	Camera Coverage	Proven* Exposures (No. of Animals)	No. of Animals with Retinal Burns	Per cent of Animals with Retinal Burns**
10.3	10	Still	8	8	80 - 100
18.5	15	None		8	53 - ?
25	15	Still	10	7	46 - 70
27.4	15	Still	11	11	73 - 100
28.5	15	Still		8	53 - ?
42.5	10	None		3	30 - ?

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* "Proven Exposures" includes animals with lesions plus those whose eyes were open at zero time as shown by photographs of the rabbits in Situ.

** Per cent of animals placed showing retinal burns is followed by per cent of proven exposed animals showing retinal burns.

TABLE 9.14 - Composite Results of Clinical Examination for Entire Series of Six Shots

Miles	No. of Animals Placed	No. of Animals with Retinal Burns	*Percentage of Animals with Lesions for Various Shots						Average per cent of all Animals with Retinal Burns	Average of consider only Sta. with Camera Coverage
			1	2	5	7	8	11		
2	5	1	20						20	
3	25	14	60	80	80	30			62	
4	25	22	80/100	100/100	100/100	80			90	100
5	25	20	100/100	100/100	60	70			82	100
6	25	21	60/75	100/100	60	80			75	87
7	30	17	50	60/75	60/75	60/100			57	83
8	40	26	60/100	60	40	53/100			53	100
9	50	32	50	70/87	60/75	67/100	70		63	87
10	60	40	47/58	80	60	70/93		30/100	67	84
11	55	30	53/89	53/89	60	55/91			55	89
12	45	22	40/86	50/83	80/100				57	90
13	30	21		65/87	80/100				72	93
14	35	21		45/64	80/100				62	82
15	15	5			33/38				33	38
16	15	7			47				47	
17	20	9			45				45	
18.5	15	8						53	53	
23	30	1					3		3	
25	10	1				10/12			10	12
25a	20	1					5		5	
25b	20	1					5		5	
25c	15	7						46/70	46	70
27.4	15	11						73/100	73	100
28.5	15	8						53	53	
39	50	1					2		2	
42	10	3						30	30	

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* Numbers preceding "slashes" represent per cent of burns before camera analysis of station. Numbers following slashes indicate per cent of burns after camera analysis.

9.2 CONCLUSIONS

Potential danger to the retina far beyond previously estimated distances has been described. In exceptionally clear air the nominal atomic bombs (20 KT) can be expected to produce atomic chorioretinal lesions in humans up to 36 miles in the daytime and up to 40 miles at night. The results obtained in the experimental exposure of 700 pigmented rabbits to the atomic flash along with four humans accidentally exposed are given. The pathology of the lesions has been briefly described. The physics of the generation of the pathologic process is discussed.

DEFINITIONS

1. Adaptometer - An instrument used to measure the state of dark adaptation of the human eye.

2. Fovea - The anatomical area of the eye which is the site of the highest concentration of visual end organs capable of giving the individual most acute vision.

3. Scotopic Vision - Vision which an individual employs (using rods alone) when luminance is lower than a moonlit night sky. The central portion of the retina cannot function at this luminance, so there is a scotoma in the visual field.

4. Mesopic Vision - Vision using both rods and cones.

5. Infrared Filter - A lens which permits the passage of almost all visible light, but absorbs infrared radiations.

6. Nyktometer - An instrument designed to determine the rate of recovery of mesopic visual acuity following glare.

7. Paracentral Vision - Vision outside, but close to the central area of very acute vision.

8. Red Filter - A filter transmitting mainly radiation of wavelengths longer than 600 millimicrons.

9. Red Internal Lighting - Illumination of instrument dials by lights inside the instruments rather than by external flood lighting.

10. Luminance - Formerly called brightness, the characteristic property of an area that makes it appear brighter or darker to the eye. It is measured in luminous intensity per unit.

11. Nit - A unit of luminance equivalent to 1 candle per square meter, or 0.00314 lambert (3×10^{-4}) or, 0.292 foot-lambert or 0.0929 candle per square foot.

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