THE EXPERIMENTAL STUDY OF FLASH-BURNS*

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THE WEAPONS OF MODERN WARFARE have produced a thermal lesion from a very brief exposure to radiant heat of high intensity that has been called a "flash burn." This was first encountered in a mass form during the bombing of Pearl Harbor in December 1941.[22] Eckert and Mader,[6] writing of the casualties from this say "only exposed surfaces were burned, even an undershirt or shorts appeared sufficient to prevent areas covered from being burned." No third degree burns were seen. The armed forces continued to encounter the flash burn throughout the war, but it was not until the Japanese casualties of the atomic bomb explosions at Hiroshima and Nagasaki were studied that the tremendous implications of the problem became apparent. Burns of all degrees of severity were observed there.

LeRoy[15] estimated that of the atomic bomb casualties in Japan 65 to 85 per cent were burned, 70 per cent sustained wounds, and over 30 per cent had irradiation injury. Others have estimated that over three-fourths of the casualties were from mechanical or thermal injuries. Those near the center of the explosion were, to use the words of Parsons,[21] "killed three times" by blast, heat, and irradiation. But the injurious effects of the blast and heat extended beyond that of the irradiation, hence the larger number of casualties which they created. The heat producing these burns was tremendous, and some individuals 2.5 miles (3 Km.) from the center of the explosion were sufficiently burned to require treatment. The sequelae were many and prolonged[15] and the incidence of keloids was high.[2]

The physical mechanism producing these high intensity burns is quite unlike that causing the ordinary burn seen in civil life. It is reasonable to suppose that its effect upon the organism will also differ, and that the local lesion, clinical course, and prognosis will not be the same. A thorough search of past literature, a survey of work done under OSRD contracts, a review of current work on burns, and personal inquiry, indicate that this problem has not received adequate attention, either from a basic or clinical standpoint. The clinical problem of the management of thousands of severely burned casualties is enormous. We have recently seen how a few hundred burn cases strained the medical facilities of Hartford or Boston. Imagine this situation multiplied 200 times! Obviously, the methods used in present practice are too

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elaborate, for they would have required at Hiroshima trained medical personnel in excess of the population of New Haven; materials and supplies greater than the gross tonnage of a Liberty Ship; and tank cars of blood. In the solution of this baffling clinical problem it appears obligatory first to know the characteristics and effects of "flash burns." What do they do to the skin? How do they affect the organism, and how can this effect be modified? What is their clinical course and how can it be altered by treatment? How lethal are they and what factors influence their mortality? To try to answer these and other questions one must produce and study the lesion experimentally. This report deals with laboratory methods of creating "flash burns" and the lesions produced.

REVIEW

Experimental burns have been produced by many individuals in as many different ways. Leach, Peters and Rossiter[14] caused a very satisfactory experimental, moderate temperature burn, using a vessel through which water of a known temperature circulated. They found that an application of 70 to 80° C of only 10 to 20 seconds duration produced severe "scabbing." Intervening temperature and exposure times produced roughly proportional injury. Microscopic examination of the tissues showed degrees of cellular disintegration, with mild burns and heat coagulation with the more intense ones. Among other conclusions they found that severity of the burn was dependent on the *duration* and the *intensity* of the stimulus.

In amplification of this work, Mendelsohn and Rossiter[17] made subcutaneous temperature determinations, using a copper-constantan thermocouple. They found that a rather prolonged exposure of 45 to 60° C was required to elevate the subcutaneous temperature. The temperature rose rapidly in the first two minutes, then levelled off gradually at four minutes, dropping slowly after the discontinuance of the burning iron application to nearly a normal range in the next six minutes. They made an excellent histopathologic study of cutaneous thermal injury in the guinea pig.

Working along the same lines, but with more adaptable equipment, Henriques and Moritz[12] sought to define the physical factors determining the transfer of heat energy through the skin. It was found that the caloric up-take rate of the skin, as measured by thermocouples at the dermis-fat interface, during the first 0.2 minute was about six-fold greater than the average caloric up-take during the ensuing 7 to 10 minutes. Maintenance of the skin surface for five minutes at 45° C resulted in heat saturation of the dermis. However, with skin surface temperatures of 50 to 70° C, edema fluid accumulated at the dermis-fat interface, thus cooling the dermis within and decreasing the effective thermal conductivity by some 15 per cent. The epidermis, it was calculated, became heat saturated within 0.5 to 1.0 minutes heat exposure, when brought immediately to the desired temperature at the surface.

The further establishment of the importance of *time-temperature* relationship was developed in the comparative study of burns on human and pig skin. Using transepidermal necrosis as an end point, it was found that 44° C for six hours would produce an effect similar to 51° C for two to six minutes. When the surface temperature was lower than 44° C, there was a rapid decrease in the rate at which burning occurred, and the time-temperature curve was found to be asymptotic in the direction of the time axis. However, when the surface temperature was greater than 51° C, the exposure time was so short that during most or all of it the deeper layers were in the process of being brought to, rather than being maintained at, a state of thermal equilibrium with the surface. Thus the time-temperature curve above 51° C was found to be asymptotic in the direction of the temperature axis.

Moritz[18] in studying the pathogenesis of cutaneous burns, concluded that the quantitative results of a short exposure of high intensity might be similar to those of a long exposure of low intensity. However there were likely to be qualitative differences. Hyperthermia of high intensity resulted in a coagulative type of necrosis, in which the dead tissue was not autolyzed but rather disposed of by sequestration, while that of low intensity resulted in a noncoagulative type of necrosis, the dead tissue being autolyzed and readily susceptible to organization. It was possible, by using intense exposures of around 0.5 second duration, to carbonize the superficial shreds of stratum corneum without causing sufficient subsurface rise in temperature to damage the basal layers of epithelial cells, or to cause perceptible vascular reaction. Again, protracted vascular reactions were noted, without noticeable harm to the epidermis.

The findings of Henriques, Moritz *et al* are fundamental for any study of thermal injury. The demonstration of the time-temperature relationship and its importance in the production of different types of burns, forms a foundation for the further study of these types of burns. The observation was made that so brief an exposure to flame temperature is required to raise the epidermal-dermal junction to "cell-killing" level, that anything capable of impeding heat transfer to the skin, "would be sufficient to make the difference between burning and absence thereof." Even a thin film of moisture on the surface of the skin would be sufficient to prevent a burn at near threshold levels.[18] The continuation of this investigation will in effect be the extension of the curve (Fig. 1) towards the time axis, and away from the temperature axis.

METHODS

A flash source must have the characteristics to produce burns, and yet be controllable, and accurately measurable. It seemed that at least the following criteria should be met to produce an ideal flash:

1. Transient duration on the order of 0.1 second.
2. Extremely high intensity, of a known and possibly variable nature.
3. A known or obtainable spectral distribution.
4. Safety and convenience of handling.

The complicated nature of heat transmission makes it more practical to produce the burn by radiant heat. This also simulates field conditions. So attempts have been made to eliminate flame, or direct contact sources, *per se*. By confining the heat transmission to radiation alone, an accurate knowledge of the spectral distribution of the source is required, as well as its emissivity in its flashing state. Since the skin can be considered as behaving in the same manner as a perfect black body at 300°K,[10] absorption of radiations from such a source can be considered to be complete.

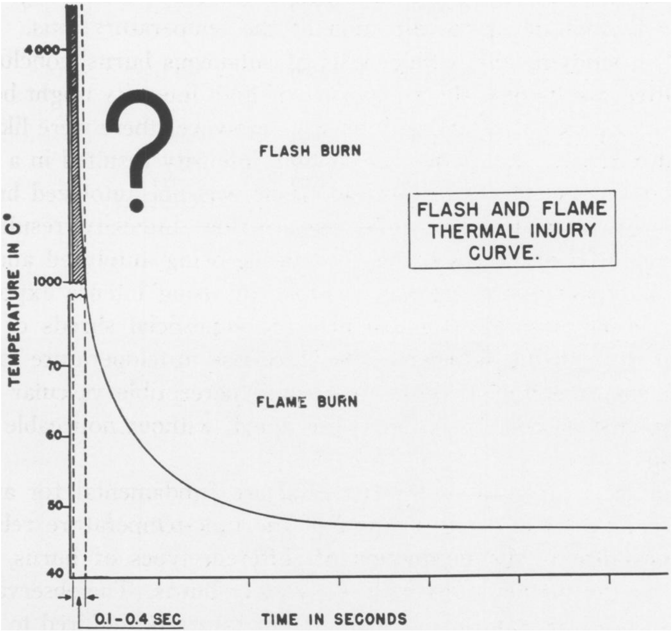

FIG. 1.—The curve of time-temperature thresholds of epidermal injury has been drawn from Henriques' results to include the "flash burn" range which is under investigation. Physical measurements in this area are difficult, but in general the experimental data obtained confirms that derived from computation.

Accordingly, a search for possible sources was begun. The agents tried are listed in Table I. Measurements of the duration, intensity and spectra of the various agents were gathered largely from the literature. Measurements under the experimental conditions are being made. Three general principles were tried: (a) the release of electrical energy from a bank of condensers to create a flash, (b) the creation of a constant high intensity source which is directed upon the target for known intervals by means of a shutter or trip mechanism, and (c) the use of substances that burn rapidly with an intense flame. (See Table I).

Anderson in 1919[1] described a method of exploding or burning a copper wire placed between two electrodes which were connected to a bank of condensers. Edgerton[7] used a similar arrangement for testing xenon photo-

TABLE I.—*A Summary of Various Sources, Their Physical Characteristics, Effectiveness, and Complications*

Source	Duration Seconds	Approximate Temperature C.	Burn Produced	Complication
(FT14) Electric discharge........ (xenon filled) Flash tube[7]	0.002	6300	None	Unable to focus energy
Exploding wire[1]................	0.00001	20,000	None	Unable to focus energy Too brief Blast wave
Thermite[5]......................	Variable	3500	Not tried	Spatter Low intensity Handling difficulty
Gun powder[9]....................	To 1.0	3000	Failed	Low intensity radiation
Magnesium[23]...................	0.36	3500	Severe	Smoke
Carbon arc[16]....................	Constant	4000	Severe (Constant)	Small area burn

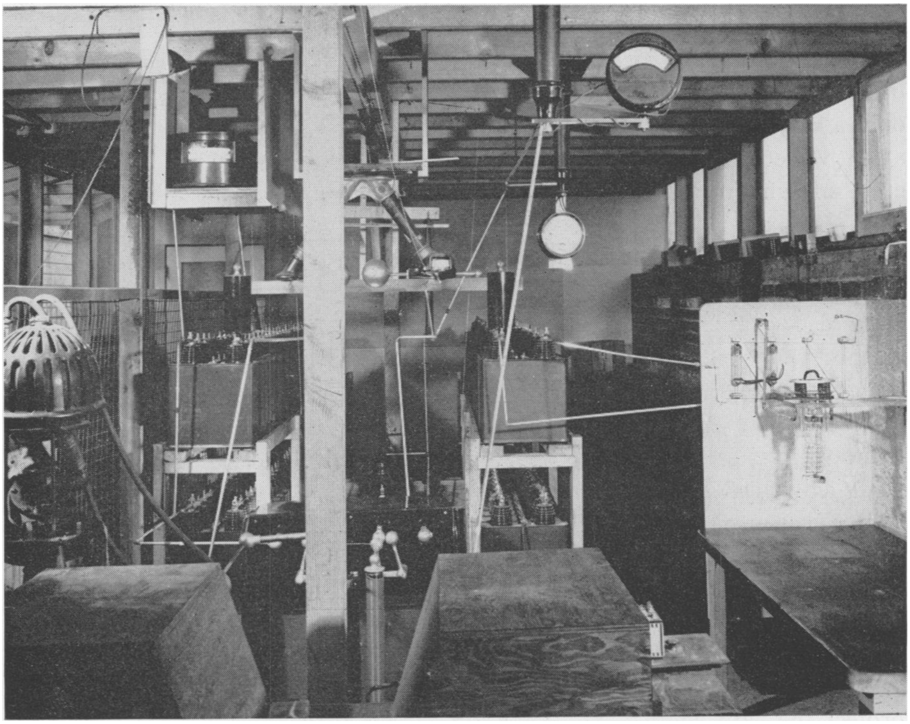

FIG. 2.—The bank of condensers is connected to the xenon filled flash tube (F. T. 14) of Edgerton. This method did not cause burning.

graphic flash tubes. Our condensers had a capacity of 64 microfarads and were charged to 25,000 volts (Fig. 2). Neither of these methods caused burning. The exploding wire generates temperatures in the range of 15,000 to 20,000° C, but this is so transient, in the order of 0.00001 sec., that injury does not occur. The inability to focus this energy and the blast wave produced are additional disadvantages. The Edgerton xenon filled flash tube produces approximately 6300° C in 0.002 sec. with 10,000 volts at about 16 microfarads. Efforts to magnify this by using 20,000 volts with 32 microfarads resulted in blowing out the flash tube. Burning by an electrical arc jumping across a gap was not tried. Flash burns are occasionally caused by means of an arc in the electric power industry but the intensities are greater than those produced in the laboratory.

Archimedes, by burning the fleet of Marcellus,[4] demonstrated the possibility of focusing heat with a concave reflector. Using this principle, the energy from a carbon arc source could be brought to a focal point and the intensity, here 4000° C, largely reproduced.* A timing device must then be added to the apparatus to limit the exposure. We have used a rotary type shutter as shown in Figure 6, or a car carrying the animal across the focal point at a known rate. The former method gives a "spot" burn whereas the latter results in a strip of burned skin across the side of the animal. This is a relatively precise method, capable of being controlled, which is very useful in observing the local changes produced but has the disadvantage of injuring only a relatively small area of the total body surface.

A variety of substances that burn quickly with a hot flame were considered, of which gun powder, thermite, 100 octane gasoline and magnesium were studied. The assistance of the Ordnance branch of the Department of the Army was sought, and several arsenals were visited. Plants of the photographic industry, and the electrical industry dealing with illumination were also visited. To date, magnesium has been found to be the best source of this type. It is much more easily controlled and handled than others, gives a high intensity in a short time and has as its only disadvantage the production of smoke. We have detonated as much as three pounds of magnesium powder without disaster. A contrasting example is thermite, which causes extreme spatter of hot particles (Fig. 3), giving contact burns that confuse the experiment. It is also dangerous and difficult to handle.

Fauley and Ivy[8] devised a small brass cannon, which would spark fire aliquots of 0.5 Gm. of magnesium at "targets," such as filter paper, rabbit skin, and the forearms of human subjects. At a distance of 24 cm. from the maw of the cannon the temperature was estimated at 1,000 to 1,500° C, while at the mouth of the device it was about 2,600° C. An undershirt served to protect the skin against the burn, and an ointment of 50 per cent titanium dioxide prevented the flash burn.

We used a standard photographic flash powder, practically pure mag-

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* We are indebted to Dr. Rudolph Langer for assistance with this apparatus.

FIG. 3

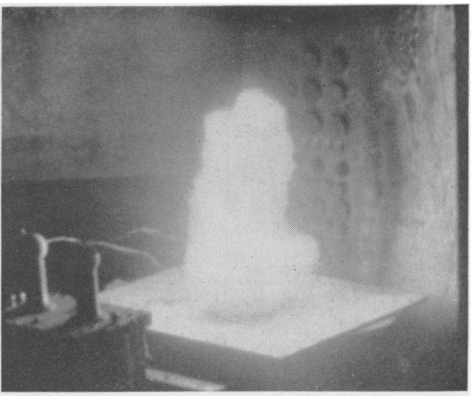

FIG. 4

FIG. 3.—Burning thermite, with or without magnesium added, results in widespread dissemination of molten iron particles which complicate the experiment by contact burns. Thermite is also difficult and dangerous to handle, has a relatively slow rate of combustion and is not a suitable source for producing flash burns.

FIG. 4.—The early stage (about 1/30 sec.) of burning magnesium showing the shape of the flame. The transformer igniter and shielded box containing the anesthetized experimental animal are also shown.

nesium. Various methods of firing were tried, the most dependable being a high tension electric spark resulting from 110 v, 60 cycle A.C. current being passed through a GE type K 916 x-ray transformer, connected in series with a resistance coil used as a ballast. It was necessary to do most of the firing in the open, because of the large amount of smoke generated by the combustion of the agent.

High speed motion pictures were taken of the flash, from which the duration was computed. For 124 Gm. the flash duration was about 0.338 second (Figs. 4 and 5). From these same films it was found that when the magnesium was burned on a flat surface of fire-resistant material, the flame and flash seemed to spread diffusely in a hemisphere about the source. However, when it was placed in a saucepan, with upward sloping walls, the flame was seen to go up at an angle corresponding to the angle of the pan edge.

Preliminary studies of the flash duration made with a phototube pick-up device recorded on a cathode-ray oscilloscope, paralleled the motion picture findings. Radiation

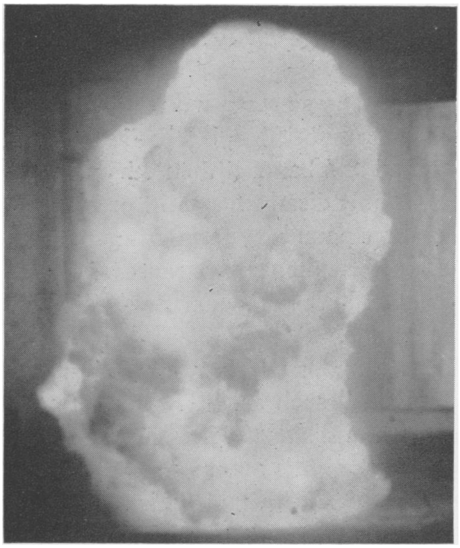

FIG. 5.—A later stage of burning magnesium which demonstrates the size of the flame and the smoke produced. Magnesium is a satisfactory source to produce flash burns.

calorimetric studies, using various black-body receptors as well as indicators, are in the phase of development.

From the work of Moritz, *et al*[20] the swine was shown to have a skin very similar in structure and physiologic reaction to that of the human being. Therefore, the pig was chosen as the standard experimental animal, though some experiments have been done on dogs, rats and rabbits. Young Chester white pigs were chosen, about two months old, with weights of 8 to 15 Kg. These were well anesthetized with veterinary nembutal given intraperitoneally, or intravenously into the superior vena cava.[3] One side of the animal was closely clipped. The clipped animals were placed in a box, one side of which contained perforations. Through these perforations a variable area of the lateral surface of the pig was exposed. This surface contained skin of approximately the same thickness, and was fairly smooth. The distance and the amount of magnesium were varied at first but later a standard experiment was set up in which 124 Gm. of magnesium was used with the box at 30 cm. from the source.

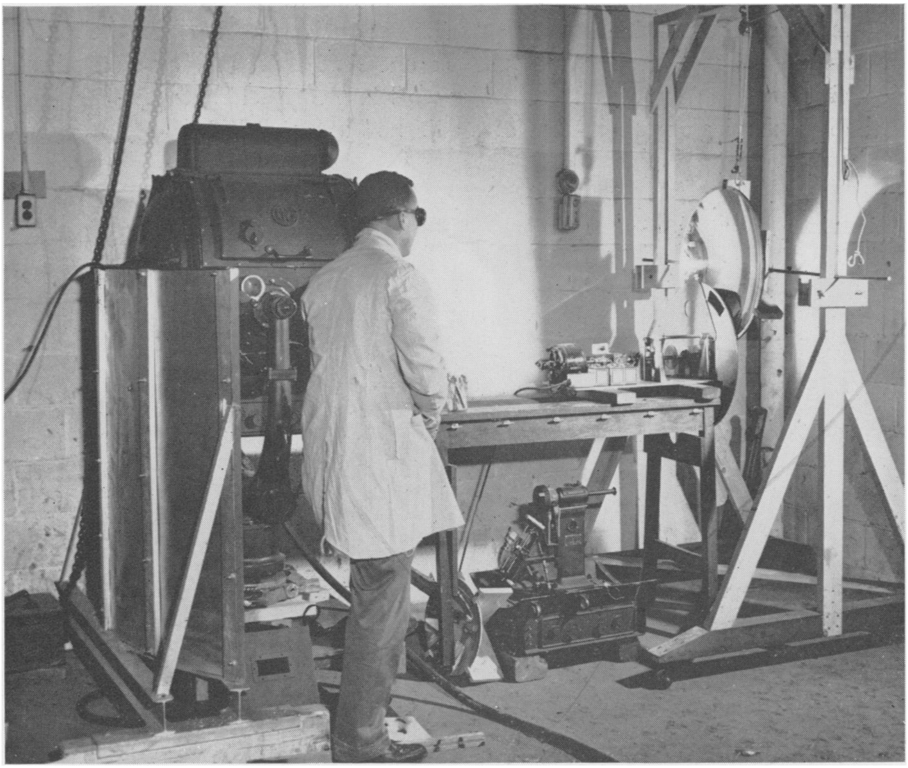

FIG. 6.—A 24-inch Army carbon arc searchlight is directed at a concave reflector which brings the focal point into the range of a high speed, electrically controlled, flash producing shutter. A car can also be used to traverse the focal point at a known rate.

Immediately after the flash the burns were observed, measured and photographed with 35 mm. Kodachrome, panchromatic, or infra-red film. The areas were biopsied at various periods of time, ranging from one hour to two weeks; special emphasis being placed on the 1, 6, 12, 24, 48, and 72 hour periods. Usually no more than one biopsy was taken from each burn and it was so taken as to include a generous portion of normal skin on either side. The sections were fixed in Bouins solution and stained with hematoxylin and eosin. Ninety burns have been studied in this way.

The burns received no treatment. The animals were kept on their diets of commercial pig feed throughout. If one died as a result of anesthesia (which was often the case early in the work), a complete autopsy was done, including histologic examination of all burned areas.

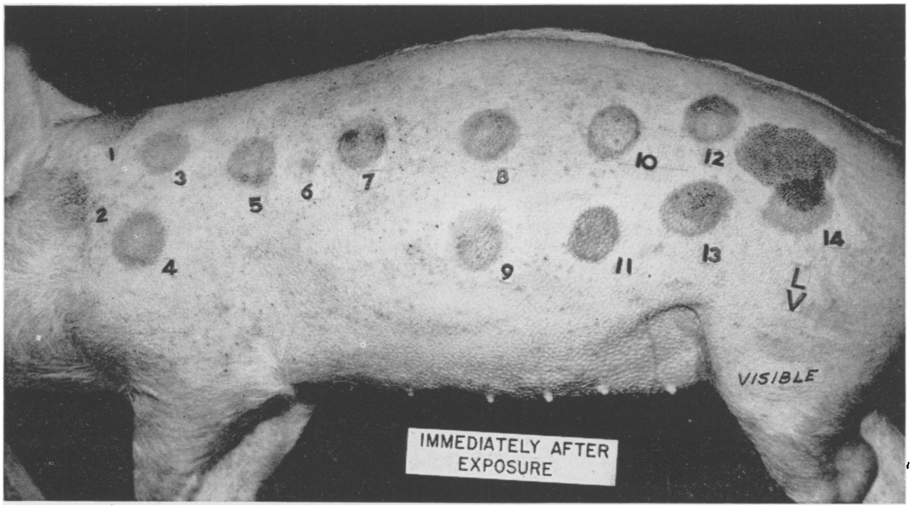

Fig. 7.—Small circular burns produced immediately after exposure to 124 Gm. of burning magnesium at 30 cm. These occur through 3.5 cm. holes bored in the side of the animal box.

RESULTS

Theoretically, the rapid exposure to intense radiant heat should change the histologic picture, for there is not time for reflex vasodilitation from warming nor from the axone reflex. This prevents the cooling effect of blood in dilated capillaries. The rapidity of the injury should not allow lateral diffusion of heat, so making the margins abrupt. This same speed might also prevent the cooling at the dermis-fat interface, thus allowing deeper penetration. In general these theoretical considerations were confirmed by observation.

The severity of the burns produced varied with the distance of the skin from the source, the amount of energy used, and the anatomical location of the burn area. In the pig the mild lesions were characterized by an erythema which developed within the first few hours, deepening in color, and becoming tan or brown over the next few days, and finally disappearing within a week with perhaps a fine scaling of the surface.

The moderately severe lesions demonstrate a peripheral flare. This flare subsides within one hour, leaving a ring of erythema about a central gray-white area of dry, cutaneous necrosis. The erythema again deepens in color, subsiding within a week. The central area also deepens in color and becomes thickened and raised by 24 hours. The edema reaches its peak by 48 hours, then subsides, giving way to induration and later to a flat, brown crust covering the burn (Figs. 7 and 8). The crust remains adherent to hairs which have grown out, but it finally drops off in seven to ten days. Occasionally, vesicles are present in the central necrotic area immediately after the burn, or the epidermis may be separated entirely, leaving a raw dermal surface exposed.

FIG. 8.—A burn 10.5 x 15.0 cm. in size produced through a larger port in the animal box by burning 124 Gm. of magnesium at 30 cm. distance.

Histologically, the flash burn presents several interesting features not noted in the moderate temperature burn. The common type (moderately severe, produced by 124 Gm. of magnesium burned at 30 cm. from the skin) presents a shredded stratum corneum. The epidermal transition from burned to normal epithelium is abrupt (Fig. 9) and often accompanied by epidermal-dermal separation at the line of juncture. The unburned epidermis is basophilic, the cells of normal architecture (Fig. 10), and immediately adjacent, the burned cells are eosinophilic, present nuclear pyknosis and cytoplasmic vacuolation. The burned cells run the gamut of types described by Leach, Peters and Rossiter. Various degrees of dermal-epidermal separation are present throughout, with attachment by elongated tono-fibrils in some areas. A similar abrupt demarcation of burned from normal epithelium is seen in the skin crypts and the hair follicles with deeper injury. The dermis reflects the depth of the penetration by a coagulation of the fibrils, with some fragmentation appearing later. These changes are less striking, and so are harder to detect.

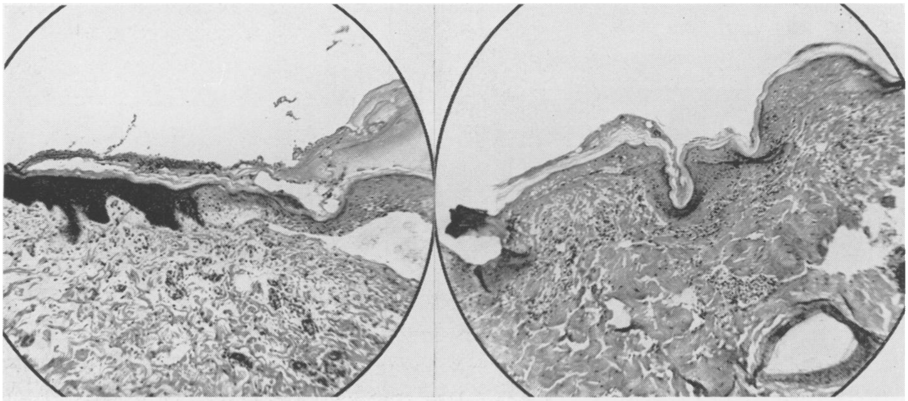

FIG. 9 FIG. 10

FIG. 9.—Biopsy immediately after burning which shows the abrupt lateral delineation of the injured epidermis and epidermal-dermal detachment x 65.

FIG. 10.—Biopsy 12 hours after exposure showing sharp horizontal demarcation through a hair follicle and mild upper dermal coagulation x 65.

In the sections, the edema is manifested by a loosening of the dermal collagen fibrils, this appearing about six hours after burning. Polymorphonuclear leukocytic infiltration appears simultaneously. By 24 to 48 hours, both phenomena are at a maximum, fading off thereafter, to disappear entirely in the milder lesion by the fifth day.

Healing is fairly rapid in the pig in the mild and moderately severe burns. Re-epithelialization begins at 48 hours and generates from surviving epithelium of hair follicles, crypts and lateral margins. It is completed by ten days. The thermally damaged epithelium is undercut by the growing epithelium and the former shed as a dense sequestrum. This eschar remains, covering the lesion, several days after complete re-epithelialization has occurred. Only rarely was granulation seen in the experiments.

In the more severe, transcutaneous burns, demarcation is not as marked laterally or in depth. The epidermis, dermis and underlying fat have a fixed, coagulated appearance. The characteristic leukocytic boundary and healing by granulation seen in lower temperature burns are present in this degree of flash burn. It is our impression that if the injury penetrates deeply, its horizontal nature may destroy all epithelium in crypts and hair follicles, leaving no epithelial islands for regeneration.

DISCUSSION

The severity of the flash burn is a rough index of the intensity of the burning stimulus, and as such, is governed by the laws of energy transfer. Severity varies inversely as the square of the distance of the skin surface from the source. It varies also with the intensity of the source, the thickness of the skin and with the curvature of the cutaneous target exposed to the source.

The most striking characteristics of experimental flash burns are found in the histologic picture. Most remarkable is the abrupt and diagrammatic demarcation between burned and normal skin. The normal, basophilic epidermal cells change, on a straight line, to the acidophilic burned cells which have all the characteristics of thermal injury. In the deeper skin this demarcation is at the burn border, in the crypts and hair follicles. It is present in the dermis but is less easily demonstrated. There is no gradual transition zone from normal cells to burn cells as described by Leach, Peters and Rossiter, and Moritz in the moderate temperature, long duration burns. Moritz[19] noted the phenomenon of demarcation on a few occasions when his animals were subjected to high temperatures for brief exposures.

Another characteristic of the flash burn is the method of healing. The burned epithelium and dermis represents a coagulative "fixed" type of necrosis, with eschar formation and subsequent sequestration, rather than the organization in the non-coagulative necrotic tissue of the moderate temperature burn. With a flash burn of average severity the epithelium grows out freely (and indeed beautifully) from normal borders and hair follicles, beneath the unorganized eschar, so that healing is rapid. Yet if the area is large and the injury deep enough to destroy the epithelium in the crypts and hair follicles, then this characteristic of demarcation will result in delayed repair from lack of epithelial islands.

The demarcation seen is probably a function of the rapid transcutaneous heat transfer. This process is most difficult to measure. It is relatively easy to compute the energy of the source, but much harder to record that delivered on the target. Physicists have told us it is practically impossible to measure the penetration of that energy into the skin. The transfer is so brief that the lag in ordinary instruments prevents recording. Yet it is felt that efforts should be continued to measure the heat penetration at various levels, for it is desirable in an understanding of the physiologic and pathologic changes created. Some of the work done on burns in the past is difficult to evaluate because of the lack of such precise physical measurements.

The studies on the effect of flash burns are being continued. This report is limited to the lesion produced in pig skin. The observations on the histopathology and healing of severe trans-dermal burns are incomplete and are being extended.[13] The influence on the healing process of anemia, infection, hypoprotenemia and ionizing irradiation will be studied. There is much that remains to be done. Yet at present we feel that the short exposure of high intensity heat causes differences, both histologic and reparative, from those seen in moderate temperature burns. Whether or not this will alter the systemic effect of the burn on the organisms remains to be seen.

SUMMARY

1. Methods are described which produce a short exposure of high intensity radiant heat capable of creating a flash burn.

2. Observations on the gross and histologic changes in the skin of pigs injured by flash burns indicate that the lesion is dissimilar from the ordinary moderate intensity burn.

3. The healing process in flash burns is not the same as that in moderate temperature burns.

4. It is felt that the differences noted are intimately related to the physical transfer of heat through the cutaneous layers.

5. It is planned to extend these observations to study of the many variables which may alter not only the local changes but also the systemic effects.

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DISCUSSION.—DR. EVERETT IDRIS EVANS, Richmond, Va.: The paper by Dr. Pearse and his associates is timely and important. The importance lies in the fact that he has developed a method which produces a flash burn which in many ways simulates the burn caused by explosion of an atomic bomb, that is, a burn caused by a vast burst of energy of very short duration but enormous intensity.

The local pathologic effects on the skin appear to be different than heat of lower degree, but it remains for future study to determine how much and in what sense are altered the metabolic effects by this particular type of thermal injury.

(Slide) You can see from this slide that radiation injury accounted for not much more than 15 per cent of the casualties at Hiroshima.

The chief importance of Dr. Pearse's presentation to this surgical group may be that he has placed in a proper light, I think, the true nature of the atomic bomb effects on civilian and military personnel.

As far as recent publications and public discussions show, the chief interest, medically speaking, in the new bomb has been the radiation hazard. This may be true because to most of us this hazard is bizarre and mysterious. We fear most what we understand the least. I would be the last to deprecate the radiation hazard imposed by this new bomb, but even superficial analysis of the lethal effects of its use at Hiroshima and Nagasaki will show that a greater number of persons died from thermal injury than from radiation injury.

The surgical significance of this fact has not been stressed properly. It is important because it is in the group of persons suffering from major thermal but minor radiation injury (that is, outside the two kilometer zone) that most of the salvageable will be found, if proper research and proper preparation is made for the care of these casualties.

What does this proper research and proper preparation entail? This is mentioned here because, as Dr. Rankin stated in his presidential address, it is mainly on the membership of this organization that the responsibility will fall for this research and development.

As a nation we need at once constructive efforts which will lead to the solution of some of these problems; I state here some of the more important as I observed them at Hiroshima and Nagasaki: