UR-394

STUDIES OF FLASH BURNS: THE RELATION OF THERMAL
ENERGY APPLIED AND EXPOSURE TIME TO BURN SEVERITY

by:

J. L. Lyon
T. P. Davis
H. E. Pearse

DO NOT PHOTOCOPY

This document is
PUBLICLY RELEASABLE

Hugh Kinsler

Authorizing Officer

Date

9/2/68

THE UNIVERSITY OF ROCHESTER
ATOMIC ENERGY PROJECT
ROCHESTER, NEW YORK

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

-1-

U N C L A S S I F I E D

UR-394

Health and Biology

THE UNIVERSITY OF ROCHESTER
Atomic Energy Project
P. O. Box 287, Station 3
Rochester 20, New York

* * *

Contract W-7401-eng-49 between the U. S. Atomic
Energy Commission and the University of Rochester,
administered by the Department of Radiation Biology
of the School of Medicine and Dentistry.

STUDIES OF FLASH BURNS: THE RELATION OF THERMAL
ENERGY APPLIED AND EXPOSURE TIME TO BURN SEVERITY

by:

J. L. Lyon
T. P. Davis
H. E. Pearse

This document is
PUBLICLY RELEASABLE
High Commissioner *Hugh Kissner*
Authorizing Official
Date 9/2/00

Division: Special Programs

Division Head: H. A. Blair

Section: Flash Burns

Section Head: H. D. Kingsley

Date Completed: 4/30/55

Date of Issue: 5/24/55

U N C L A S S I F I E D

STUDIES OF FLASH BURNS: THE RELATION OF THERMAL
ENERGY APPLIED AND EXPOSURE TIME TO BURN SEVERITY.

By

J. L. Lyon
T. P. Davis
H. E. Pearse

ABSTRACT

The principle objective of these experiments was to construct a dose-response pattern for the reaction of pig skin to radiant thermal energy over a wide range of exposure times, and radiant exposures. This was done by a carefully controlled study of the gross and histologic appearance of 1735 burns produced by the carbon arc. The data were subjected to probit transformation in order to obtain 50% median effective exposures.

Absolute reciprocity between total energy and time of application was not demonstrated for surface lesions graded 1+ severe or more. This was also true for burns judged from their microscopic appearance, except for mid and deep dermal injury where a reverse reciprocity relationship existed.

Each surface burn was compared with its respective microscopic appearance, and from this it was demonstrated that for the gross lesions graded 1+ and 2+, an increase in exposure time did not effect the depth of damage. But for 3+, 4+ and 5+ burns prolonging the exposure time beyond one second had a marked effect on the depth penetration.

A comparison was made of the results of this experiment with previously obtained information on humans. It was found that the energy requirements for 1+ mild burns on pigs are similar to those for minimal erythema in humans. In addition, the energy necessary to produce a 2+ mild pig lesion is comparable to that for major vesiculation of human skin.

INTRODUCTION

For several years workers in this laboratory have been interested in the thermal lesion produced by a pulse of high intensity radiant energy not only to gain more knowledge of flash burns from the atomic bomb, but also to clarify the basic factors governing cutaneous burns. A detailed study was presented by Perkins, Pearse and Kingsley in 1952 (1). Working in this laboratory and employing the carbon arc as a heat source, they carried out an analysis of the effects of high intensity, short duration thermal radiation upon bare porcine skin. An attempt was made to correlate the gross appearance of the burn with that of the microscopic depth of damage, and to relate the burn in human with that in the pig. The information obtained in this study has been of great value for subsequent experiments.

Consideration of their results has demonstrated some areas in which statistical analysis is not possible due to insufficient data. Since the completion of their study, experiments on other factors influencing the severity of flash burns have been done in this laboratory by methods designed to permit probit transformation of the data. As a result, this more recently obtained material could not be compared with the previous studies on bare skin.

In addition, improvements in physical equipment and refinements in technique have been made since their work was completed. The exposure port of the carbon arc source has been redesigned; so that its temperature is maintained constant by circulating water. Calorimetric measurements of the carbon arc source are now taken each week and plotted in the form of control charts; so high confidence can be placed in the stability of the source. The calibrated range of the carbon arc source has been extended downward;

so that the output can be reduced to $1/340$ of the maximum energy without introducing noticeable assymetry in the radiation distribution at the exposure plane. Finally, Berkley (2) has established that a variation of a few degrees in the surface temperature of the skin may alter the severity of the burn to a considerable degree. Hence, skin surface temperatures of the animals used in this experiment were kept at relatively constant levels.

With the employment of these modifications, a new experiment, similar in general outline to the work of Perkins, Pearse and Kingsley, was carried out. The range of exposure time extended from 0.25 to 10.0 seconds, which was considered adequate to demonstrate the relationship between radiant exposure and exposure time in the flash burn. The data so obtained was subjected to the probit method of analysis and a dose-response pattern formulated.

This information for bare skin, evolved with unmodified thermal radiation from the carbon arc source, can now form a basis of comparison for the data obtained on skin protected by fabric, (3, 4, 5) as well as for that from spectrally modified forms of thermal energy (6, 7, 8). Although the results obtained in this experiment may be compared with the data from field tests, the dissimilarity of the two pulse forms may render direct correlation inaccurate.

METHODS

Physical

The heat source was the modified 24 inch Army carbon arc searchlight previously described (9). The principle changes over the instrument used previously consisted of a newly designed, hollow, chrome-plated, brass exposure port, through which water with its temperature thermostatically

controlled at 37° C., was circulated. The circular opening of 1.5 cm diameter, placed in the exposure plane of the arc, defined the exposure area. The incident energy from the arc was controlled by the sliding transite diaphragms previously described, and, in addition, two polished aluminum, attenuating screens were used, one single and one double, with transmissions at about 17%, and 3% respectively. With the employment of these controlling devices the incident energy at the exposure area was made to range from 0.1 cal/cm²/sec to 34 cal/cm²/sec.

A high capacity air conditioning unit, with both heating and cooling coils thermostatically controlled, maintained a constant ambient temperature of 24° C. in the burning room. In all instances the animals were brought to the room at least 1/2 hour before the initiation of burning. The skin temperature of the animals was determined at various sites by a measuring thermistor and consistently fell between 35° and 38° C., being lowest in the flank and rump regions, and highest over the spleen and liver areas.

Experimental Design

A method of objective randomization was used in planning and executing this study. By employing uniform 20% increments of radiant exposure for each of the six exposure times, i.e., 0.25, 0.5, 1.0, 2.0, 5.0, and 10.0 seconds, it was determined through initial pilot work, that 115 exposure-time combinations represented the range to be covered in the experiment.

Fifteen replications for each combination were thought to give adequate data to allow statistical analysis and to moderate the variables which are inherent in any biological investigation. Two sides of two animals were needed for each replication. Thirty burns appeared on each of

three sides and 25 on the fourth, or a total of 115. Thirty animals were used; so that 1735 burns were studied for gross changes. All were biopsied and examined microscopically.

Biological

A. Animals

The skin of pigs has a close histological resemblance to that of humans (10). For this reason Chester White pigs weighing 10 to 15 kilograms were used. They were anesthetized with Dial in Urea-Urethane (Ciba) in doses of 70 mgm/Kg of body weight given intraperitoneally (11). The hair was then removed with close cutting electric clippers and the skin gently sponged with plain water. The animals were kept at a controlled ambient temperature for 1/2 hour before burning.

B. Evaluation

I. Gross Appearance

The burns were assessed from their surface appearance approximately 24 hours after burning. The system of judging gross burn severity was that which has been previously reported (1, 12):

<u>Grade</u>	<u>Description</u>
0	No burn visible
1+	Erythematous burn
2+	Patchy white burn
3+	Uniform white burn
4+	Blebbled white burn
5+	Carbonized burn

Each of the five major categories of burn severity was divided into mild, moderate, and severe, giving 16 degrees of damage. The entire range of gross burn severity was explored at each exposure time, except that burns of the more severe grades could not be obtained at the shorter exposure times due to the limitation of the heat source.

Assessment of degree was established by reading the severest portion of each burn. This usually was represented by the central square centimeter of burn surface, but occasionally even a smaller area represented the most severe portion of burn.

II Microscopic Appearance

Immediately following the gross evaluation, a biopsy was taken of each burn area using a circular knife 1.8 cm in diameter. The biopsy specimens were cut deep enough to include subdermal fat, thus insuring the entire thickness of the skin for microscopic evaluation. The specimens were placed in Bouins' fixative and were stained with hematoxylin and eosin.

The method of assessment of microscopic damage is that which has previously been described (1), and may be summarized as follows. The first change noted is acidophilism of epidermal cells, which may be partial or complete. As more energy is applied the basal layer of epidermis may be seen to separate from the underlying dermis; this, also may be partial or complete. Dermal injury is divided into superficial, mid, and deep, for the purpose of assessment. Superficial dermal damage has occurred if the depth of injury is less than 500 microns; mid, if between 500 and 1000 microns; and deep, if more than 1000 microns. A micrometer scale in the eyepiece of the microscope delineated the depth measurements. These categories may be tabulated as follows:

Symbol	Description
E.A. _p	Epidermal acidophilism, partial
E.A. _c	Epidermal, acidophilism, complete
D.E.S. _p	Dermal epidermal separation, partial
D.E.S. _c	Dermal epidermal separation, complete
D.D. _I	Dermal damage, superficial < 500 μ
D.D. _{II}	Dermal damage, mid 500 - 1000 μ
D.D. _{III}	Dermal damage, deep > 1000 μ

Statistical Analysis

The simplified method of Litchfield and Wilcoxon (13) for analysis of dose-response data was used for obtaining 50% median effective exposures (EE_{50} 's) and 95% confidence limits.

RESULTS

The data obtained from gross assessment of the burns is presented in Table I, in such a manner, that the number and percentage of burns produced with each exposure-time combination for any level of severity, can be read. From these data the median effective exposure (EE_{50}) has been calculated for every subdivision of each grade of severity at the exposure times used, by the method referred to. The results are given in Table II and shown graphically in Fig. 1, which is a logarithmic plot of the EE_{50} 's with the abscissa as exposure time and the ordinate as radiant exposure. The 95% confidence limits are indicated by I symbols.

It should be emphasized that this experiment was not constructed chiefly to obtain EE_{50} 's for each level of burn severity. If this were the aim, two principle alterations in the experimental design would have

TABLE I

DOSE, RESPONSE DATA FOR MACROSCOPIC ASSESSMENT OF BURN SEVERITY AT THE SIX EXPOSURE TIMES USED.

Time (sec)	Radiant Energy (cal/cm ²)	0	1+			2+			3+			4+			5+			Total No. of Exposures
			Mild	Mod	Sev	Mild	Mod	Sev	Mild	Mod	Sev	Mild	Mod	Sev	Mild	Mod	Sev	
.25	1.0	12	3 (20%)															15
	1.2	5	7 (47%)	3 (20%)														15
	1.5	3	8 (53%)	4 (26%)														15
	1.8		3 (20%)	7 (47%)	5 (33%)													15
	2.2		2 (13%)	6 (40%)	3 (20%)	4 (26%)												15
	2.6			1(6.6%)	6 (40%)	6 (40%)	2 (13%)											15
	3.2					8 (53%)	6 (40%)	1(6.6%)										15
	3.9				1(6.6%)	6 (40%)	5 (33%)	3 (20%)										15
	4.7					6 (40%)	6 (40%)	8 (53%)	1(6.6%)	4 (26%)								15
	5.8							4 (26%)	7 (47%)	6 (40%)	4 (26%)							15
	7.0											5 (33%)						15
8.5											3 (20%)	5 (33%)	5 (33%)	2 (13%)			15	
.50	.82	13	2 (13%)															15
	1.1	8	6 (40%)	1(6.6%)														15
	1.2	1	9 (60%)	4 (26%)	1(6.6%)													15
	1.5		7 (47%)	5 (33%)	3 (20%)													15
	1.7		6 (40%)	7 (47%)	2 (13%)													15
	2.0		3 (20%)	8 (53%)	4 (26%)													15
	2.5			3 (20%)	7 (47%)	4 (26%)	1(6.6%)											15
	2.9				3 (20%)	7 (47%)	4 (26%)	1(6.6%)										15
	3.6				1(6.6%)	5 (33%)	5 (33%)	4 (26%)										15
	4.4					1(6.6%)	5 (33%)	8 (53%)	1(6.6%)	3 (20%)								15
	5.3						2 (13%)	5 (33%)	5 (33%)	3 (20%)								15
	6.5								6 (40%)	1(6.6%)	4 (26%)							15
	7.8								2 (13%)	4 (26%)	7 (47%)	1(6.6%)						15
	9.5									4 (26%)	3 (20%)	5 (33%)	4 (26%)					15
	11.6										1(6.6%)	4 (26%)	5 (33%)	5 (33%)				15
	14.0										3 (20%)	3 (20%)	8 (53%)	1(6.6%)				15
	17.0										1(6.6%)	2 (13%)	9 (60%)	2 (13%)	1(6.6%)			15
1.0	.81	12	3 (20%)															15
	.95	7	5 (33%)	3 (20%)														15
	1.2	4	7 (47%)	4 (26%)														15
	1.5	1	9 (60%)	5 (33%)														15
	1.6	2	3 (20%)	6 (40%)	4 (26%)													15
	2.1		4 (26%)	7 (47%)	4 (26%)													15
	2.4				4 (26%)	2 (13%)												15
	2.9			5 (33%)	8 (53%)	2 (13%)												15
	3.4				8 (53%)	2 (13%)												15
	4.0				7 (47%)	3 (20%)												15
	4.9					2 (13%)												15
	5.9						1(6.6%)											15
	7.2						3 (20%)											15
	8.7						2 (13%)	7 (47%)	4 (26%)	3 (20%)	1(6.6%)	1(6.6%)						15
	10.6								6 (40%)	4 (26%)	9 (60%)	4 (26%)						15
	12.9												6 (40%)	3 (20%)	3 (20%)			15
	19.0												4 (26%)	5 (33%)	2 (13%)	7 (47%)	6 (40%)	15
	23.1												2 (13%)	6 (40%)	7 (47%)	8 (53%)	4 (26%)	15
	28.0													3 (20%)	7 (47%)	8 (53%)		15
34.0																	15	

[illegible]

||

TABLE II

MEDIAN EFFECTIVE EXPOSURES FOR ALL GRADES OF SURFACE
INJURY AT THE SIX EXPOSURE TIMES STUDIED.

Grade	0.25 (sec)	0.5 (sec)	1.0 (sec)	2.0 (sec)	5.0 (sec)	10.0 (sec)
1+ Mild	1.3 (1.2-1.4)	1.0 (.94-1.1)	1.0 (.95-1.1)	.90 (.83-1.0)	1.2 (1.1-1.3)	1.3 (1.2-1.4)
1+ Mod.	1.6 (1.5-1.7)	1.6 (1.3-1.7)	1.7 (1.6-1.8)	1.7 (1.5-1.9)	1.8 (1.6-2.0)	1.7 (1.6-1.9)
1+ Sev.	2.1 (2.0-2.2)	2.1 (1.9-2.2)	2.3 (2.1-2.5)	2.6 (2.3-2.8)	2.8 (2.4-3.3)	2.8 (2.6-3.1)
2+ Mild	2.5 (2.3-2.7)	2.6 (2.4-2.8)	3.6 (3.3-3.9)	4.2 (4.0-4.5)	5.1 (4.9-5.4)	5.5 (5.1-5.9)
2+ Mod.	3.6 (3.4-3.9)	3.3 (3.1-3.5)	4.1 (3.9-4.3)	5.0 (4.5-5.5)	5.8 (5.5-6.1)	6.6 (6.3-7.0)
2+ Sev.	4.6 (4.3-5.0)	4.2 (3.9-4.5)	4.5 (4.3-4.7)	6.1 (5.4-6.7)	7.5 (7.1-7.9)	8.0 (7.4-8.6)
3+ Mild	5.5 (5.3-5.7)	5.3 (5.1-5.7)	5.4 (5.1-5.7)	7.0 (6.5-7.5)	9.5 (9.0-10)	10 (9.5-11)
3+ Mod.	5.8 (5.6-6.0)	6.2 (5.9-6.6)	6.3 (6.0-6.6)	8.3 (7.6-9.1)	10.5 (10-11)	12 (11-14)
3+ Sev.	7.0 (6.8-7.2)	7.1 (6.7-7.5)	7.8 (7.2-8.4)	9.0 (8.6-9.4)	13 (12-14)	14 (13-15)
4+ Mild	7.2 (7.0-7.4)	7.6 (6.9-8.4)	9.2 (8.3-10)	11 (10-12)	16 (15-17)	18 (17-20)
4+ Mod.	-	9.3 (8.9-9.8)	11 (10-12)	13 (12-14)	18 (16-20)	23 (21-25)
4+ Sev.	-	11 (10-12)	12 (11-13)	15 (14-16)	19 (18-21)	28 (25-31)
5+ Mild	-	13 (12-14)	14 (12-16)	19 (18-21)	23 (22-24)	38 (35-41)
5+ Mod.	-	-	22 (20-25)	27 (25-30)	28 (25-31)	43 (40-46)
5+ Sev.	-	-	-	41 (37-46)	41 (38-45)	56 (52-60)

12

been observed. First, the intervals between each radiant exposure would have been made smaller, i.e., about 10%. Second, the exposure-time combinations would have been grouped only around the approximate EE_{50} levels for the severity degree under consideration as determined by initial pilot studies, and less attention would have been paid to intermediate exposure-time combinations. The EE_{50} 's have been calculated and tabulated, but these are more for the convenience of reference than for precise interpretation.

Several writers have pointed out that a reciprocal relationship exists between temperature and time of exposure for a given level of skin damage. Moritz and Henriques (10) demonstrated this relationship with hot water contact burns on pig skin using transepidermal necrosis as their criterion of injury. Waller (14) and others (15, 16) have shown that the product of time and intensity of applied ultraviolet radiation is constant for certain photochemical changes produced by this type of radiation. The failure of time-energy reciprocity in burns from high intensity thermal radiation was observed by Alpen (17) and by Perkins, Pearse and Kingsley (1). Consideration of Fig. 1 shows that, for 1+ mild burns, less total energy is required at exposure times of 0.5, 1.0, and 2.0 seconds. The reason for this is not apparent at this time. The curves for all other levels of surface damage indicate an increased total energy requirement as the exposure time becomes longer. As the degree of damage increases, this total energy requirement becomes greater; so that, for 2+ mild, the ratio is approximately 2:1 and, for 5+ mild, is 3:1.

The principle objective of this study was to establish a dose-response pattern, for the reaction of bare skin to thermal energy, over a wide range of time, and radiant exposures. This has been accomplished;

Figure 1. The median effective exposures for the 5 major grades of surface severity are plotted on a logarithmic scale.

14

Figure 2. Three dimensional dose-response surface for 2+ mild burns.

15

and is presented in three dimensional form in Fig. 2. This diagram was constructed by placing the lines obtained from probit transformation of the raw data for 2+ mild burn severity upon a linear percent scale; thus giving them a sigmoid configuration. The radiant exposure and exposure time scales have been arranged logarithmically. In an identical manner the dose-response surface could be constructed for each level of severity.

By reference to Fig. 2, the probability of a 2+ mild burn occurring can be stated in terms of percent for any of the exposure-time combinations studied. A specific example of this relationship is as follows: given a radiant exposure of 2.7 cal/cm^2 , delivered in 0.25 seconds, 60% of the burns will be 2+ mild or more severe. Similarly, if any two of the three parameters, i.e., exposure time, radiant exposure, and percent probability, are known, the third may be readily secured.

The microscopic assessment of burn injury is presented in Table III, which is identical in form to Table I. The microscopic grades employed, have been described. A tabulation of EE_{50} 's, obtained from probit transformation of the data from Table III, is shown in Table IV. These results of the EE_{50} 's for microscopic depth of damage are charted on logarithmic paper in Fig. 3. This figure is on an identical scale with that of Fig. 1, and may be superimposed to show the comparison of surface damage and depth of injury.

Fig. 3 demonstrates that the energy required to cause injury of only the epidermis, is not markedly altered by a change in the exposure time. Statistically the curves could be considered a straight line. When dermal-epidermal separation is used as the criterion, the curve of energy-time relation tends to slope upward; so that more energy is required to produce

TABLE III

DOSE, RESPONSE DATA FOR MICROSCOPIC ASSESSMENT OF BURN SEVERITY AT THE SIX EXPOSURE TIMES USED.

Time (sec)	Radiant Exposure (cal/cm ²)	No Burn	Epidermal Acidophilism		Dermal-Epidermal Separation		Dermal			Total No. of Exposures
			Partial	Complete	Partial	Complete	Superficial	Mid	Deep	
0.25	1.0	12	3 (20%)							15
	1.2	6	5 (33%)	2 (13%)	2 (13%)					15
	1.5	8	5 (33%)	2 (13%)						15
	1.8	2	6 (40%)		1 (6.6%)					15
	2.2	3		5 (33%)	7 (47%)					15
	2.6			2 (13%)	9 (60%)	4 (26%)				15
	3.2				6 (40%)	5 (33%)	4 (26%)			15
	3.9				3 (20%)	3 (20%)	9 (60%)			15
	4.7				1 (6.6%)	4 (26%)	10 (67%)			15
	5.8					3 (20%)	12 (80%)			15
	7.0						15 (100%)			15
	8.5						13 (87%)	2 (13%)		15
0.5	.82	12	3 (20%)							15
	1.1	9	5 (33%)	1 (6.6%)						15
	1.2	8	5 (33%)	2 (13%)						15
	1.5	3	8 (53%)	3 (20%)	1 (6.6%)					15
	1.7	4	5 (33%)	6 (40%)						15
	2.0	4	7 (47%)	4 (26%)						15
	2.5		2 (13%)	6 (40%)	7 (47%)					15
	2.9			1 (6.6%)	10 (67%)	4 (26%)				15
	3.6				5 (33%)	8 (53%)	2 (13%)			15
	4.4			1 (6.6%)	1 (6.6%)	5 (33%)	8 (53%)			15
	5.3						15 (100%)			15
	6.5						15 (100%)			15
	7.8						15 (100%)			15
	9.5						9 (60%)	5 (33%)	1 (6.6%)	15
	11.6						8 (53%)	5 (33%)	2 (13%)	15
	14.0						6 (40%)	8 (53%)	1 (6.6%)	15
	17.0						7 (47%)	7 (47%)	1 (6.6%)	15
1.0	.81	11	4 (26%)							15
	.95	10	4 (26%)	1 (6.6%)						15
	1.2	7	5 (33%)	3 (20%)						15
	1.5	7	5 (33%)	3 (20%)						15
	1.6	3	7 (47%)	5 (33%)						15
	2.0	1	5 (33%)	6 (40%)	3 (20%)					15
	2.4		3 (20%)	6 (40%)	5 (33%)	1 (6.6%)				15
	2.9		2 (13%)	3 (20%)	6 (40%)	3 (20%)	1 (6.6%)			15
	3.4			1 (6.6%)	8 (53%)		6 (40%)			15
	4.0				8 (53%)		3 (20%)			15
	4.9					4 (26%)	14 (93%)			15
	5.9					1 (6.6%)	13 (87%)			15
	7.2					2 (13%)	14 (93%)			15
	8.7				1 (6.6%)		12 (80%)	2 (13%)		15
	10.6						9 (60%)	6 (40%)		15
	12.9				1 (6.6%)		5 (33%)	7 (47%)	2 (13%)	15
	19.0						3 (20%)	4 (26%)	8 (53%)	15
	23.1							4 (26%)	11 (73%)	15
	28.0							3 (20%)	12 (80%)	15
	34.0							2 (13%)	13 (87%)	15

2.0	.68	12	3 (20%)							15
	.80	11	4 (26%)							15
	.98	10	3 (20%)	2 (13%)						15
	1.2	7	6 (40%)	2 (13%)						15
	1.6	6	6 (40%)	2 (13%)						15
	1.9	3	5 (33%)	5 (33%)	2 (13%)	1 (6.6%)				15
	2.4	2	5 (33%)	5 (33%)	3 (20%)					15
	3.0	1	1 (6.6%)	9 (60%)	4 (26%)					15
	3.6		1 (6.6%)	3 (20%)	9 (60%)	1 (6.6%)	1 (6.6%)			15
	4.2			1 (6.6%)	8 (53%)	1 (6.6%)	4 (26%)	1 (6.6%)		15
	5.0				1 (6.6%)	3 (20%)	11 (73%)		1 (6.6%)	15
	6.0			1 (6.6%)	2 (13%)	4 (26%)	8 (53%)			15
	7.1				1 (6.6%)	4 (26%)	10 (67%)			15
	8.2					2 (13%)	10 (67%)			15
	9.8						11 (73%)	3 (20%)		15
	11.8						9 (60%)	4 (26%)		15
	14.4				1 (6.6%)		4 (26%)	8 (53%)	2 (13%)	15
	17.4							7 (47%)	8 (53%)	15
	21.2						1 (6.6%)	4 (26%)	10 (67%)	15
	24.8						1 (6.6%)	14 (93%)		15
	31.4						1 (6.6%)	14 (93%)		15
	38.0						1 (6.6%)	14 (93%)		15
	46.2							15 (100%)		15
	56.0							15 (100%)		15
5.0	.95	11	2 (13%)	2 (13%)						15
	1.2	8	4 (26%)	3 (20%)						15
	1.4	7	6 (40%)	2 (13%)						15
	1.7	4	6 (40%)	4 (26%)	1 (6.6%)					15
	2.0	1	7 (47%)	6 (40%)	1 (6.6%)					15
	2.5		1 (6.6%)	8 (53%)	5 (33%)		1 (6.6%)			15
	2.9		3 (20%)	8 (53%)	3 (20%)		1 (6.6%)			15
	4.0			4 (26%)	4 (26%)	4 (26%)	3 (20%)			15
	4.8		1 (6.6%)		5 (33%)	1 (6.6%)	8 (53%)			15
	6.0				1 (6.6%)	2 (13%)	12 (80%)			15
	7.4						14 (93%)	1 (6.6%)		15
	8.7						14 (93%)	1 (6.6%)		15
	10.5						9 (60%)	5 (33%)	1 (6.6%)	15
	12.0						4 (26%)	8 (53%)	3 (20%)	15
	14.5						3 (20%)	8 (53%)	4 (26%)	15
	17.0						1 (6.6%)	8 (53%)	6 (40%)	15
	20.0						1 (6.6%)	4 (26%)	10 (67%)	15
	24.5							2 (13%)	13 (87%)	15
	29.5								15 (100%)	15
	36.0								15 (100%)	15
	43.5								15 (100%)	15
	53.0								15 (100%)	15
10.0	1.1	11	4 (26%)	2 (13%)						15
	1.3	11	2 (13%)	3 (20%)						15
	1.5	3	6 (40%)	4 (26%)	3 (20%)					15
	1.9	3	8 (53%)	7 (47%)						15
	2.3	1	1 (6.6%)	5 (33%)	6 (40%)					15
	2.8	1	2 (13%)	8 (53%)	7 (47%)					15
	3.4			5 (33%)	5 (33%)		2 (13%)			15
	4.0			5 (33%)	6 (40%)	1 (6.6%)	3 (20%)			15
	4.9			3 (20%)	9 (60%)	1 (6.6%)	2 (13%)			15
	5.9			2 (13%)	6 (40%)	1 (6.6%)	6 (40%)			15
	7.2				2 (13%)	1 (6.6%)	11 (73%)	1 (6.6%)		15
	8.7						9 (60%)	5 (33%)	1 (6.6%)	15
	11.0						6 (40%)	7 (47%)	2 (13%)	15
	13.0						3 (20%)	8 (53%)	4 (26%)	15
	15.0							8 (53%)	7 (47%)	15
	19.0							1 (6.6%)	14 (93%)	15
	23.0								15 (100%)	15
	28.0								15 (100%)	15
	34.0							1 (6.6%)	14 (93%)	15
	40.0								15 (100%)	15
	49.0								15 (100%)	15

18

TABLE IV

MEDIAN EFFECTIVE EXPOSURES FOR ALL GRADES OF MICROSCOPIC
INJURY AT THE SIX EXPOSURE TIMES STUDIED.

Grade	0.25 (sec)	0.5 (sec)	1.0 (sec)	2.0 (sec)	5.0 (sec)	10.0 (sec)
Epidermal Acidophilism Partial	1.4 (1.2-1.6)	1.2 (1.1-1.3)	1.1 (.88-1.3)	1.2 (1.0-1.4)	1.3 (1.2-1.4)	1.5 (1.4-1.6)
Epidermal Acidophilism Complete	1.8 (1.6-2.0)	1.9 (1.7-2.1)	1.8 (1.6-2.1)	2.2 (1.9-2.5)	2.1 (1.8-2.4)	1.9 (1.7-2.1)
Dermal Epider- mal Separation Partial	2.2 (2.1-2.3)	2.5 (2.4-2.6)	2.6 (2.5-2.8)	3.2 (2.9-3.5)	3.2 (2.9-3.5)	3.0 (2.6-3.5)
Dermal Epider- mal Separation Complete	3.1 (2.9-3.3)	3.3 (3.2-3.4)	4.0 (3.6-4.4)	4.7 (4.1-5.4)	4.6 (4.3-4.9)	5.6 (4.9-6.4)
Dermal I or < 500 μ	3.9 (3.5-4.3)	4.3 (4.1-4.5)	4.2 (4.0-4.4)	5.2 (4.7-5.7)	5.2 (4.7-5.7)	5.9 (5.4-6.5)
Dermal II or 500-100 μ	-	12 (9.6-15)	13 (12-14)	13 (12-15)	12 (11-13)	10 (9.2-11)
Dermal III or > 1000 μ	-	-	19 (17-21)	19 (17-21)	17 (16-19)	15 (14-16)

Figure 3. The median effective exposures for the 7 grades of depth damage are plotted on a logarithmic scale. EA_p = epidermal acidophilism partial, EA_c = epidermal acidophilism, complete, DES_p = dermal epidermal separation, partial, DES_c = dermal separation, complete, DD₁ = dermal damage, superficial, DD₂ = dermal damage, mid, DD₃ = dermal damage, deep.

20

this effect with longer exposure times. The same holds for the production of superficial dermal (DD_1) damage. It should be observed that, at the short exposure times of 0.25 and .5 sec., there is a significant difference in the energy required to produce complete dermal-epidermal separation in contrast to that for superficial dermal damage. But with exposure times of 1.0 sec. or more, the difference in energy required for these criteria is not significant. The percentage of burns which show complete dermal-epidermal separation decreases at longer exposure times. This may be seen by reference to the data in Table III. When this level of injury is reached with long exposures, the damage usually extends on into the superficial layers of the dermis.

Injury of the dermis for 500 to 1000 u (DD_2) was unobtainable at 0.25 sec. exposure, while that of 1000 u or greater (DD_3) could not be obtained at 0.25 and 0.5 sec. exposures due to the lack of sufficient energy from the arc. The curves of both DD_2 and DD_3 follow the same general pattern. As the time of exposure is increased, less total energy is required to cause penetration of the damage to these levels. The downward slope of these curves combined with the upward slope of those for more superficial injury indicates a trend to convergence of the curves. This is less pronounced than in the curves obtained by Perkins, Pearse, and Kingsley, but is in the same direction.

Berkley (18) studied the relationship between surface appearance and depth of damage for burns from 1+ moderate to 3+ mild, at times of 0.5 sec. to 4.0 sec. He expressed his results in the form of frequency polygons, and came to the conclusion that exposure time did not markedly effect the depth of damage for a given surface lesion, over the range used. Figure 4 shows this general relationship of depth of burn to surface injury over the range of exposure times employed in the present experiment. This

Figure 4. Diagrammatic relationship of exposure time vs. depth of burn for 5 grades of surface damage. ED = surface epidermis, DEJ = dermal-epidermal junction, 100, 500, 1000 and 1500 μ = depth into the dermis in microns.

22

diagram was constructed by comparing the surface damage of each burn in the five major degrees of gross severity with its corresponding microscopic appearance and noting the frequency with which various depth levels occurred for each grade of surface injury. The depth level occurring most often at the indicated surface appearance is represented on the diagram for each exposure time studied.

It will be seen from Fig. 4 that in surface lesions graded 1+ and 2+ the microscopic depth of damage does not change with alteration in the exposure time, even in the range from 0.25 to 10.0 sec. It should be observed that the 2+ level includes microscopic changes seen in the dermal-epidermal junction. If this had been used as the only criterion of injury, then it would have been assumed that variation in exposure time had no effect on the depth of burn. But when the levels of total energy sufficient to cause dermal damage are reached, it is immediately apparent that prolonging the exposure time causes a marked increase in the depth of the burn. In the 3+, 4+, and 5+ surface grades of injury, exposure times of 1 sec. or less have little effect upon the depth of dermal burns. But beyond this, the dermal injury grows progressively more severe with prolonged time. The curves slope downward sharply; so that in the 3+ grade, for example, the depth changes from 100 μ with 1 sec. to 1000 μ with 10 sec. exposures, respectively.

DISCUSSION

Emphasis has been placed on the bare skin, dose-response surface for the square top pulse because this was the major objective of the present study. The three dimensional presentation of these data allows the visualization of this dose-response surface over a considerable range of time and radiant exposure. The pattern obtained is obviously not a plain one, but

varies with each exposure time considered, and the undulating character is immediately apparent by examination of Fig. 2. In one respect the irregularity of the surface is unfortunate, for it makes difficult the construction of a single mathematical expression which could be used to predict the probability of a burn occurring for any given dose-time combination.

The dose-response surface, or the data from which it is obtained, can now be contrasted with information from modified energy source-recipient relationships. Work has been done in this (6, 7, 8) and other laboratories (19, 20) on the spectral content of the carbon arc source and the contribution of the various spectral components to burn production.

Another use of the dose-response surface for bare skin will be its comparison with the results of study on the protective effect of various fabrics. It is expected that in the future there will be several such comparisons of these data with other types of modification of the energy from the arc or the surface studied.

The microscopic changes described by Perkins, Pearse, and Kingsley were confirmed in this study. Together with other earlier workers (1, 12) in this laboratory, they employed the term partial coagulation to describe the change associated with burns of 2+ mild surface appearance. In the present study the histologic criterion of epidermal coagulation, i.e., epidermal acidophilism, was nearly always attained at significantly lower energy levels than those necessary to yield a 2+ mild surface lesion. If the values in Fig. 1 for 2+ mild burn are compared with those of histologic dermal-epidermal separation in Fig. 3, a close parallel for these two can be seen. Whether or not this parallelism is indicative of the same altered dermal-epidermal relationship is not proven, but, in any event, it seems

24

reasonable to assume that the white spots indicating the 2+ mild burn represent some change at the dermal-epidermal interface which alters its optical relationship, rather than coagulation of discrete areas.

If the curve for the macroscopic 1+ mild burn in Fig. 1 is compared with the curve for microscopic partial epidermal acidophilism in Fig. 3, it is seen that slightly more energy is required to produce the latter. This suggests that minimal erythema may be produced at a lower level of energy than that required to yield microscopically demonstrable epidermal alteration, and that the former is actually the reversible change of dermal capillary dilatation as seen through the relatively transparent epidermis. This phenomena has been attributed to the photochemical action of the ultraviolet portion of the carbon arc spectrum. When the ultraviolet is removed from the spectrum by filters (7), an erythema occurs which is different in appearance, and is associated with microscopic changes in the epidermis.

A third observation to be stressed, in comparing Fig. 1 and 3, is the appearance of a negative slope of the curves for mid and deep dermal damage with long exposure time. As pointed out by Davis, a number of inter-related factors may be contributing to yield this phenomenon (1). At these levels of depth damage the skin surface is often carbonized, and in order to obtain this level of severity the tissue must be first dessicated of its water content. This is probably accomplished by conversion of the water to steam, an endothermic reaction which abstracts the large heat of vaporization, and thus renders it ineffectual for depth penetration. In addition, the violent, eruptive nature of the surface reaction tends to cause further efflux of heat from the burn area. Finally, a variable amount of thick smoke is created by the carbonization reaction which may further protect the remaining viable tissue from the incoming radiant energy. Certainly the effective

25

summation of all these factors at shorter exposure times is one of protection of deeper structures from lethal elevation of their temperature. At longer exposures this protective mechanism, being predominantly of a surface nature and necessarily brief in duration, is, to a large extent overcome, hence less total energy is required.

Direct comparison of the information obtained in the experiment with that of Perkins, Pearse, and Kingsley is difficult. As pointed out before, there are many areas in their study where insufficient data are present to allow statistical analysis. This is particularly true for the microscopic values, where a randomly selected group of biopsies were obtained. In the present study each burn was examined for its microscopic appearance; thus 1735 specimens were available for analysis, and all points represented have statistical validity. General agreement between the two experiments does exist, however, where adequate data are available to permit comparison.

TABLE V

COMPARISON OF HUMAN AND PIG BURNS

Surface Grade Human	EE ₅₀ 's @ 0.3 Sec.		Surface Grade Pig	EE ₅₀ 's @ 0.25 Sec. (cal/cm ²)
	Slight Pigmentation (cal/cm ²)	Moderate Pigmentation (cal/cm ²)		
Erythema	1.2	1.1	1+ Mild	1.3
Minor Vesiculation	2.3	2.1	1+ Sev.	2.1
Major Vesiculation	2.6	2.3	2+ Mild	2.5

26

It has long been felt that the gross character of a burn is not a valid indication of the depth of injury. The experience of the present study shows that for milder lesions, i.e., 1+ and 2+, the surface appearance does reflect the depth of damage, but as the degree of injury increases it becomes more difficult to state with certainty what depth level has been reached.

Accurate data on the energy requirements to produce human burns are limited, and there are no large series available, hence it is difficult to compare these with animal studies. However, it may be of some interest to contrast the results of the present experiment with those obtained for humans by Perkins, Pearse, and Kingsley. In order to do this, their data has been subjected to probit analysis to obtain EE_{50} 's, and the energy levels scaled down by a factor of .86, a step made necessary by the subsequent recalibration of the carbon arc. The redetermined values are summarized in Table V, with comparable values for bare pig skin included. A constant exposure time of 0.3 sec. was employed for these human studies. It can be seen that the figures in Table V for erythema compare with those for 1+ mild burns in pigs; those for minor vesiculation with the 1+ severe lesion; and major vesiculation with the 2+ mild level of severity. More recently, Evans and his coworkers (20) have obtained data on human burns employing the carbon arc source, both for the shaped and the square top pulses. Their values for the square top pulse are for one exposure time of 0.6 sec., using two irradiances, i.e., 3.9 and 4.8 cal/cm², and were not arranged for a statistical study. Hence, these data cannot be precisely contrasted with the results of this experiment.

27

SUMMARY AND CONCLUSIONS

1. A controlled study is presented of the gross and histologic appearance of 1735 cutaneous flash burns produced by the carbon arc with a wide range of radiant exposure and exposure time.
2. A method of dose-response probit analysis for obtaining 50% median effective exposures was used to interpret these data.
3. The principle objective of the experiment was to obtain a dose-response pattern for bare skin burns over a range of exposure times from 0.25 seconds to 10.0 seconds. From this the probability of a burn occurring at any dose-time combination may be predicted.
4. Absolute time-energy reciprocity for the radiant thermal burn was not found. In general, the more severe the burn, the more marked was the departure from absolute reciprocity.
5. Observations on the microscopic appearance of surface lesions graded 1+ and 2+ indicated that prolonging the exposure time did not effect the depth of damage.
6. For lesions grades 3+, 4+, and 5+ prolonging the exposure time over 1 second causes a marked increase in the depth of damage.
7. Statistical evidence indicates that the 2+ mild burn represents dermal-epidermal separation rather than epidermal coagulation.
8. The proposition that minimal erythema can be produced at a lower energy level than that required to demonstrate microscopic epidermal damage was confirmed.
9. Less energy is required to produce deep dermal damage than is necessary to cause severe surface carbonization at longer times. Some reasons for this are discussed.
10. Comparison of results of the experiments on pig skin with the available information on human burns is presented.

28

BIBLIOGRAPHY

1. Perkins, J. B., Pearse, H. E., and Kingsley, H. D., Studies on Flash Burns, Univ. of Roch. Atomic Energy Project Report, UR-217, (1952).
2. Berkley, K. M., Pearse, H. E., and Davis, T. P., The Influence of Skin Temperature in the Production of Cutaneous Burns in Swine, Univ. of Roch. Atomic Energy Project Report, UR-338, (1954).
3. Morton, J. H., Kingsley, H. D., and Pearse, H. E., Studies on Flash Burns: The Protective Effects of Certain Fabrics, Surg., Gyn., and Obs., April, 1952, Vol. 94, 497-501.
4. Mixter, G., Jr., and Pearse, H. E., The Protection Afforded by 2, 4 and 6 Layer Fabric Combinations, Univ. of Roch. Atomic Energy Project Report, UR-261, (1953).
5. Mixter, George, Jr., and Pearse, H. E., The Influence of Exposure Time and Irradiance on the Thermal Protective Qualities of Two Fabric Assemblies, Univ. of Roch. Atomic Energy Project Report, UR-355, (1954).
6. Berkley, K. M., and Davis, T. P., The Influence of Wave Lengths on the Production of Cutaneous Burns, Univ. of Roch. Atomic Energy Project Report, UR-283, (1954).
7. Berkley, K. M., The Influence of Ultraviolet Radiation on the Production of Cutaneous Burns, Univ. of Roch. Atomic Energy Project Report, UR-335, (1954).
8. Berkley, K. M., Davis, T. P., and Pearse, H. E., The Effect of Spectral Distribution on the Production of Cutaneous Burns, Univ. of Roch. Atomic Energy Project Report, UR-336, (1954).
9. Davis, T. P., Krolak, L. J., Blakney, R. M., and Pearse, H. E., Modification of the Carbon-Arc Searchlight for Producing Experimental Flashburns, J.O.S.A., Vol. 44, No. 10, 766-769, (1954).

27BIBLIOGRAPHY (Continued)

10. Moritz, A. R., and Henriques, F. C., Jr., The Relative Importance of Time and Surface Temperature in the Causation of Cutaneous Burns, Am. Jr. of Path., Vol. 23, 695-720, (1947).
11. Kingsley, H. D., Hogg, L. Jr., Payne, J. T., and Morton, J. H., Studies in Prolonged Anesthesia in Swine and Dogs, Univ. of Roch. Atomic Energy Project Report, UR-152, (1951).
12. Morton, J. H., Kingsley, H. D., and Pearse, H. E., Studies on Flash Burns: Threshold Burns, Surg., Gyn., and Obs., (1952).
13. Litchfield, J. T., Jr., and Wilcoxon, F., A Simplified Method of Evaluating Dose Effect Experiments, Jr. of Phar. and Thera., 96-99, (1949).
14. Waller, M. D., The Relation Between Energy Doses of Ultraviolet Radiation and Active Erythema Produced, Proc. Roy. Soc. of London, Series B., Vol. 108, 264-270, (1931).
15. Luckiesh, M., and Taylor, A. H., Erythematous and Tanning Effectiveness of Ultraviolet Energy, G. E. Rev., 42, 274-278, (1939).
16. Blum, H. F., and Gilbert, H. W., Studies of Photodynamic Hemolysis with Monochromatic Light: The Reciprocity Law, J. Cell. and Comp. Physiol., Vol. 15, 75-84, (1940).
17. Alpen, E. L., Sheline, G. E., Kuhl, P. R., and Ahokas, A., Quantitative Dependence of Tissue Injury on Duration of Exposure, U.S.N.R.D.L. Report 347, (1952).
18. Berkley, K. M., Evaluation of Surface Appearance of Burns by Depth of Damage, Univ. of Roch. Atomic Energy Project Report, UR-337, (1954).
19. Evans, E. I., Brooks, J. W., Schmidt, F. H., Williams, R. C., and Ham, T., Jr., Flash Burn Studies on Human Volunteers, Surg. 37, 280-297, (1955).
20. U.S.N.R.D.L. (Personal Communication).