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FURTHER STUDIES ON THE RELATIONSHIP BETWEEN EXPOSURE TIME
AND DEPTH OF DAMAGE OF MODERATE AND SEVERE CUTANEOUS BURNS

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ABSTRACT

To extend our earlier studies on the relationship between exposure time and depth of damage of moderate and severe burns, injuries were produced by each of six radiant exposures delivered during varying exposure times. The exposures investigated were: 5, 8, 10, 13, 16, and 20 calories per square centimeter. Within this range, as the radiant exposure increased, the exposure time for the production of maximum damage also increased. Injury from a given radiant exposure was less with exposure times either longer or shorter than some intermediate time which led to the most severe injury.

The relationship between steam bleb formation and decreased depth of injury from short exposure times is pointed out. When the superficial layers of the skin become so hot that vaporization of tissue fluid occurs, energy which might otherwise damage the deep layers is diverted by the conversion of water to steam.

For radiant exposures between 8 cal/cm² and 20 cal/cm² delivered with a square pulse, it is possible to predict with fair accuracy the exposure time which will result in the deepest burn.

INTRODUCTION

In two recent studies it was found that certain radiant exposures led to a less severe burn when the exposure time is extremely short than when it is longer (1, 2). This finding was contradictory both to some theoretical predictions of the relationship between severity of damage and exposure time and to experimental results obtained by assessing burn severity by surface appearance alone (3, 4). It was proposed that this phenomenon is due to reactions in superficial layers of skin, and that these occur when the "steam blebs" and the char of the 4+ and 5+ surface alterations occur (1, 2, 4). Some correlation between the appearance of the 4+ and 5+ surface reactions and the absence of damage to predicted depths in the dermis has been noted previously (1, 2, 4). Two of these studies (1, 2) have given an indication of the exposure times at which the maximal dermal collagen damage occurs in burns produced by radiant exposures of 16 cal/cm^2 and 10 cal/cm^2 . The experiment reported here was so designed that the exposure time at which greatest damage occurs might be defined more accurately for these two radiant exposures, and that this information for additional radiant exposures might be obtained. It has also enabled us to observe the effect of exposure time on the depth of damage in the hair follicles and to correlate the degree of damage to the superficial tissues of the skin with the total depth of tissue destruction.

METHODS

Young Chester White pigs were used as the experimental animals. They were anesthetized by intraperitoneal injection of 60 - 65 mgm/Kg. of Dial with urethane (Ciba). The hair was clipped from their sides, and the skin

was gently washed and dried. The ambient temperature in the room was maintained at approximately 78° F.

The radiant energy source was a modified 24 inch Army carbon arc searchlight (4, 5).

Radiant exposures of 5 cal/cm², 8 cal/cm², 10 cal/cm², 13 cal/cm², 16 cal/cm², and 20 cal/cm² were chosen arbitrarily. The following ranges of exposure times were selected to include the expected "critical exposure time" at which the greatest depth of damage would probably occur with each of the radiant exposures:

1. 5 cal/cm² - .15, .25, 0.5, 1.0, and 3.0 seconds.
2. 8 cal/cm² - .25, 0.5, 1.0, 2.0, 3.0, 5.0, and 9.0 seconds.
3. 10 cal/cm² - 0.5, 1.0, 2.0, 3.0, 4.0, 7.0, and 12.0 seconds.
4. 13 cal/cm² - 1.0, 3.0, 5.0, 7.0, 9.0, 12.0, and 15.0 seconds.
5. 16 cal/cm² - 1.0, 5.0, 7.0, 9.0, 12.0, 15.0, and 20.0 seconds.
6. 20 cal/cm² - 1.0, 5.0, 7.0, 9.0, 12.0, 15.0, 20.0, and 30.0 seconds.

These combinations were randomly assigned exposure sites on the sides of the animals. Each group of combinations was replicated 12 times for a total of 492 burns on six pigs.

Approximately 24 hours after burning, the central square centimeter of each site was evaluated for surface severity according to the method used in this laboratory:

- 1+ - Erythema
- 2+ - Spotty Whiteness
- 3+ - Complete Whiteness
- 4+ - Steam Bleb
- 5+ - Carbonization

In addition, each was biopsied, placed in 10% formalin, and stained by Hinshaw's Method (6) for differentiating burned tissue. The biopsies were taken across the entire diameter of the circular burn and included unburned tissue on each side.

With the aid of a micrometer scale the greatest depth of damaged collagen in each section was measured microscopically. This depth was then expressed both as the number of millimeters of damaged tissue and as a fractional part of the total dermal thickness. The latter method of expressing the results tends to compensate both for shrinkage of the severely burned, dehydrated zone, and for edematous tissue. The depth of altered hair follicle epithelium and the presence or absence of damage to glandular epithelium were also recorded. All measurements were made perpendicular to the skin surface. The total dermal thickness was defined as the distance between the epidermis and the tips of the collagen fingers which interdigitate between the glandular nests about the base of the hair follicle (Figure 1).

RESULTS

The results of surface assessment are presented in Appendix I. Maximum severity of the burns, judged by appearance alone, always occurs with the shortest exposure time.

In Appendix II the average depths of dermal collagen damage, measured in millimeters, are presented. Figure 2 gives this same information in graphic form. The greatest depth of damage occurs at the shortest exposure time (0.15 sec.) in burns produced by 5 cal/cm², but in the 8 cal/cm², 10 cal/cm², 13 cal/cm², 16 cal/cm², and 20 cal/cm² groups of burns, maximal damage occurs at an intermediate exposure time (Table 1).

TOTAL
DERMAL
DEPTH

Normal Pig Skin. Measurements of depth of damage are taken perpendicular to the skin surface. Notice that the depth of the base of the hair follicles, cut in cross section, closely corresponds to the total depth of the dermis (average total dermal depth 2.3 mm).

X-20

Table 1

EXPOSURE TIMES AT WHICH MAXIMAL DAMAGE OCCURS IN DERMAL COLLAGEN
AND HAIR FOLLICLE EPITHELIUM.

Radiant Exposure (cal/cm ²)	"Critical Exposure Time" (sec)		
	Assessment by Depth of Dermal Damage	Assessment by Pro- portion of Dermis Damaged	Assessment by Depth of Damage in Hair Follicles
5	0.25	0.15	1.0
8	2 (1 - 3)*	1 (5 - 3)*	2 (1 - 3)*
10	3 (2 - 4)	3 (2 - 4)	4 (2 - 7)
13	5 (3 - 9)	5 (4 - 7)	5 (3 - 7)
16	9 (7 - 12)	9 (7 - 12)	9 (5 - 15)
20	12 (7 - 15)	12 (7 - 15)	15 (9 - 20)

* The range represents the extremes of exposure time which will
result in damage very nearly as severe as that from the "critical
exposure time."

Figure 2.

During the microscopic examination of each burn, the total depth of the dermis was divided into quarters. Appendix III gives, for all of the radiant exposures, the number of burns at each exposure time with damage extending into each of the four quarters. The category labeled "1/4" includes burns with dermal collagen damaged up to 1/4 full thickness, that labeled "1/2" includes those with damage from 1/4 to 1/2 full thickness, etc. In order to present this evaluation graphically, the total number of quarters of dermis damage in all 12 burns resulting from each exposure time-radiant exposure combination are added (Appendix IV and Figure 3). This again illustrates that maximal damage occurs at exposure times intermediate between the longest and shortest times investigated (Table 1).

The average depth of damage in the hair follicles is given in Appendix V and shown graphically in Figure 4. Table 1 shows the "critical exposure time" at which the greatest damage to the hair follicles occurs from each of the radiant exposures. It should be noted (Figure 4) that in the 16 cal/cm² and 20 cal/cm² burns, a number of the longer exposure times result in nearly the same depth of damage to hair follicle epithelium.

The exposure times which led to 4+ and 5+ burns (surface evaluation) are shown in Appendix I. If these times are compared with the exposure times at which maximal damage occurs (Table 1 or Appendices II, III, and IV) it is evident that the greatest depth of damage occurs at an exposure time just longer than the one at which only occasional 4+ burns are seen.

Appendix VI presents the number of burns with evidence of damage to the glandular elements of the dermis. Comparison of this Appendix and Appendices II through V shows that the glandular elements, usually located at a depth of 2.0 to 2.3 millimeters in the dermis, are damaged rather consistently

Figure 3.
Relationship Between Exposure Time and Depth of Dermal Collagen
Damage, Expressed as the Total Number of Quarters of Dermis
Damaged in 12 Replications.

Figure 4.

Relationship Between Exposure Time and the Average Depth of Hair Follicle Damage at Each Radiant Exposure.

when differentially stained collagen damage reaches depths of 0.75 millimeters and when hair follicle damage is at least 1.4 millimeters beneath the surface.

DISCUSSION

For each radiant exposure there is an exposure time at which maximal damage occurs, and this critical time increases as the total radiant exposure increases. The fact that maximal depth of damage occurs at exposure times just greater than those which produce 4+ superficial skin reactions is further evidence that there probably is a cause and effect relationship between the two. This supports the hypothesis that a reaction which produces steam and carbonized tissue at the surface of the skin utilizes a part of the incident energy, thus leaving a lesser amount available for dermal damage.

The two previous reports from this laboratory (1, 2) which produced the stimulus for the present work agree with the results presented here. The work by Hinshaw (1) on 16 cal/cm² burns predicted the maximal depth of collagen damage to occur at some exposure time between five seconds and ten seconds; in this experiment nine seconds was the critical exposure time. The preceding study of 10 cal/cm² burns (3) predicted a critical exposure time around three seconds, and this agrees with the results of this experiment. However, contrary to the results of the previous work with burns produced by 10 cal/cm² (3), in this experiment the hair follicles were damaged to the greatest depths at exposure times very near those which produced maximal collagen damage.

In the range from 0.15 sec. to 3.0 sec. there is no intermediate time at which maximal collagen damage occurred in burns produced by 5 cal/cm². However, there is a peak depth of the hair follicle epithelial alteration at the one second exposure time with this radiant exposure. It is possible that

with the shortest exposure times a slight amount of vaporization, insufficient to produce blebbing, has taken place, and that this has dissipated sufficient energy to decrease the damage to the deeper hair follicle epithelium. However, diversion of energy has been insufficient to be reflected in the depth of collagen damage. If this observation and the explanation of it are true, one can understand the findings of longer critical exposure times in some instances (10 cal/cm^2 , 20 cal/cm^2) from assessment of hair follicle damage than from assessment of dermal collagen damage. If the greatest damage occurs at exposure times just greater than those at which there is dissipation of energy through vaporization of a part of the superficial tissue fluid, and if depth of damage to hair follicle epithelium can reflect loss of a smaller increment of energy than the depth of dermal collagen damage, then the "critical exposure time" for maximal follicle epithelial damage would be expected to be slightly longer than that for maximal collagen damage.

The 16 cal/cm^2 and 20 cal/cm^2 groups of burns show very little decrease in depth of hair follicle damage at exposure times greater than the "critical exposure time." This indicates that at these greater radiant exposures a sufficient length of time has not been available for dissipation of energy. The result is the protection of the epithelial cells in the depths of the hair follicles. At still higher radiant exposures collagen damage would be expected to follow this pattern.

If, on a logarithmic scale, radiant exposure is plotted against the critical exposure time at which the deepest burn from that exposure will result, the points lie very nearly on a straight line (Figure 5). It would thus appear that, within the range of the radiant exposures investigated here, it

Figure 5.

is possible to predict at what exposure time a given radiant exposure will be most injurious. In other words, it is possible to predict the radiant exposure-exposure time combination which will be just insufficient to produce vaporization of tissue fluid in the superficial layers of the skin.

It should also be pointed out that at radiant exposures a little greater than 20 cal/cm² destruction of the full thickness of the skin will result with exposure times less than that expected to produce the greatest depth of damage.

SUMMARY AND CONCLUSIONS

1. The depth of damage to dermal collagen and hair follicle epithelium was measured microscopically in differentially stained sections of burns produced by radiant exposures of 5 cal/cm², 8 cal/cm², 10 cal/cm², 13 cal/cm², 16 cal/cm², and 20 cal/cm², each delivered during various exposure times.
2. With each radiant exposure (collagen damage from the 5 calorie exposure being an exception) maximal damage occurred at an intermediate exposure time rather than at the shortest exposure time.
3. The relationship between the "critical exposure times" at which maximal damage occurred and the exposure times at which 4+ and 5+ burns occurred indicates again that energy which is diverted by the vaporization of tissue fluids during very short exposures is responsible for the occurrence of maximal damage at intermediate exposure times.
4. This "critical exposure time" was longer and less discrete with the greater radiant exposures.

5. When these critical exposure times are plotted against radiant exposure on a logarithmic scale, all points fall very near a straight line. It is thus possible to predict what radiant exposure-exposure time combinations will be just insufficient to produce vaporization of tissue fluid.
6. In some instances the "critical exposure time" for maximal depth of hair follicle damage was greater than that for maximal depth of collagen damage. This is thought to be another indication that epithelium is more easily destroyed by high temperatures than is dermal collagen.
7. Glandular elements lying 2.0 mm. to 2.3 mm. below the epithelium showed histologic changes if collagen damage reached a depth of 0.75 mm. or if hair follicle epithelium was damaged to a depth of 1.4 mm.

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APPENDIX I

RELATIONSHIP BETWEEN EXPOSURE TIME AND SEVERITY OF DAMAGE EXPRESSED AS THE NUMBER OF BURNS WITH EACH OF THE FIVE GRADES OF SURFACE SEVERITY

Exposure Time (sec)	Radiant Exposure																												
	5 cal/cm ²				8 cal/cm ²					10 cal/cm ²					13 cal/cm ²					16 cal/cm ²					20 cal/cm ²				
	1+	2+	3+	4+	1+	2+	3+	4+	5+	1+	2+	3+	4+	5+	1+	2+	3+	4+	5+	1+	2+	3+	4+	5+	1+	2+	3+	4+	5+
.15			8	4																									
.25		1	7	4				4	8																				
.5			11	1				4	7					11	1														
1.0			11	1				8	4				4	8					1	1				8	4			2	10
2.0								12					10	2															
3.0		6	6				1	11					12					7	5										
4.0													12																
5.0							7	5									12					6	6				4	8	
7.0													12				12				1	10	1				1	11	
9.0						12											12					12					9	3	
12.0													3	9			12					12					12		
15.0																	12					12				1	11		
20.0																						12					12		
30.0																											12		

APPENDIX II

RELATIONSHIP BETWEEN EXPOSURE TIME AND AVERAGE DEPTH OF DAMAGE
TO COLLAGEN (EXPRESSED IN MILLIMETERS).

Exposure Time (sec)	Radiant Exposure (cal/cm ²)					
	5	8	10	13	16	20
.15	.22					
.25	.23	*.28				
.5	.20	*.40	**.40			
1.0	.17	*.52	*.57	**.58	**.60	**.80
2.0		.51	*.77			
3.0	.11	.49	.77	*1.00		
4.0			.78			
5.0		.32		1.20	*1.26	*1.62
7.0			.57	1.09	*1.51	*1.79
9.0		.22		1.09	1.58	*1.88
12.0			.28	.98	1.37	1.85
15.0				.69	1.41	1.86
20.0					1.25	1.75
30.0						1.51

* A fraction of the burns in these groups are of 4+ surface severity.

** All burns in these groups are of 4+ or 5+ surface severity.

APPENDIX III

RELATIONSHIP BETWEEN EXPOSURE TIME AND DEPTH OF DERMAL COLLAGEN DAMAGE AT EACH RADIANT EXPOSURE

(EXPRESSED AS THE NUMBER OF BURNS IN EACH OF SEVERAL FRACTIONAL PARTS OF THE TOTAL DERMAL THICKNESS).

Exposure Time (sec)	Radiant Exposure																														
	5 cal/cm ²					8 cal/cm ²					10 cal/cm ²					13 cal/cm ²					16 cal/cm ²					20 cal/cm ²					
	0	1/4	2/4	3/4	4/4	0	1/4	2/4	3/4	4/4	0	1/4	2/4	3/4	4/4	0	1/4	2/4	3/4	4/4	0	1/4	2/4	3/4	4/4	0	1/2	2/4	3/4	4/4	
.15	1	11	0	0	0																										
.25	4	8	0	0	0	0	12	0	0	0																					
.5	3	9	0	0	0	0	10	1	0	0	0	8	4	0	0																
1.0	4	8	0	0	0	0	6	6	0	0	0	7	5	0	0	0	5	5	2	0	0	6	5	1	0	0	2	8	2	0	
2.0						0	9	3	0	0	0	2	9	1	0																
3.0	9	2	0	0	0	1	8	3	0	0	0	2	9	1	0	0	0	8	3	1											
4.0											0	1	9	2	0																
5.0						2	8	2	0	0						0	0	6	5	1	0	0	4	7	1	0	0	1	5	6	
7.0											0	8	4	0	0	0	0	7	4	1	0	0	2	7	3	0	0	0	6	6	
9.0						5	7	0	0	0						0	0	6	6	0	0	0	4	4	4	0	0	1	3	8	
12.0											2	10	0	0	0	0	2	7	2	1	0	0	3	5	4	0	0	2	3	7	
15.0																0	6	5	1	0	0	0	2	6	4	0	0	0	2	10	
20.0																					0	2	5	2	3	0	0	1	7	4	
30.0																										0	0	4	5	3	

APPENDIX IV

RELATIONSHIP BETWEEN EXPOSURE TIME AND DEPTH OF DERMAL COLLAGEN DAMAGE AT EACH RADIANT EXPOSURE (EXPRESSED AS THE NUMBER OF QUARTERS OF BURNED DERMIS IN 12 REPLICATIONS).

Exposure Time (sec)	Radiant Exposure (cal/cm ²)					
	5	8	10	13	16	20
.15	11					
.25	8	*12				
.5	9	*12	**16			
1.0	8	*18	*17	**21	**19	**24
2.0		15	*23			
3.0	2	14	23	*29		
4.0			25			
5.0		12		31	*33	*41
7.0			16	30	*37	*42
9.0		7		30	36	*43
12.0			10	26	37	41
15.0				19	38	46
20.0					30	39
30.0						35

* Some of the burns in these groups are of 4+ surface severity.

** All burns in these groups are of 4+ or 5+ surface severity.

APPENDIX V

RELATIONSHIP BETWEEN EXPOSURE TIME AND THE AVERAGE DEPTH
OF DAMAGE IN THE HAIR FOLLICLES (EXPRESSED IN MILLIMETERS).

Exposure Time (sec)	Radiant Exposure (cal/cm ²)					
	5	8	10	13	16	20
.15	.52					
.25	.46	*.65				
.5	.49	*.77	** .97			
1.0	.63	*1.08	*1.00	**1.12	**1.15	**1.35
2.0		1.15	1.40			
3.0	.32	1.02	1.45	*1.68		
4.0			1.51			
5.0		.95		1.85	*2.03	*2.09
7.0			1.46	1.59	*2.06	*2.11
9.0		.72		1.69	2.06	*2.11
12.0			1.03	1.68	2.00	2.23
15.0				1.43	1.97	2.37
20.0					2.08	2.25
30.0						2.05

* Some of the burns in these groups are of 4+ surface severity.

** All burns in these groups are of 4+ or 5+ surface severity.

APPENDIX VI

RELATIONSHIP BETWEEN EXPOSURE TIME AND THE NUMBER OF BURNS
AT EACH RADIANT EXPOSURE WITH DAMAGE TO THE GLANDULAR ELEMENTS
OF THE DERMIS.

Exposure Time (sec)	Radiant Exposure (cal/cm ²)					
	5	8	10	13	16	20
.15	0					
.25	0	*2				
.5	0	*0	**3			
1.0	0	*0	*5	**6	**9	**11
2.0		4	*9			
3.0	0	1	11	*10		
4.0			10			
5.0		3		11	*12	*11
7.0			7	9	*10	*12
9.0		3		11	12	*12
12.0			7	10	12	12
15.0				9	11	12
20.0					12	11
30.0						12

* Some of the burns in these groups are of 4+ surface .
severity.

** All burns in these groups are of 4+ or 5+ surface severity.