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SOME EFFECTS OF VARIATION IN EXPOSURE TIME AND INPUT PULSE SHAPE

IN THE PRODUCTION OF RADIANT ENERGY THERMAL BURNS

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SOME EFFECTS OF VARIATION IN EXPOSURE TIME AND INPUT PULSE
SHAPE IN THE PRODUCTION OF RADIANT ENERGY THERMAL BURNS

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ABSTRACT

This experiment was designed to evaluate some effects of exposure time, input pulse shape, and biopsy time on the severity of burns produced by radiant exposures of 10 cal/cm^2 . The differences between square and simulated field pulse burns were found to be much less than might have been expected from the necessarily great variations in exposure time and irradiance.

The different morphologic and staining characteristics of the burned dermal collagen have been rated according to the severity of damage. Production of a more superficial collagen burn at a short exposure time than at an intermediate one was again noted. Certain microscopic changes support the theory that steam bleb formation brings about this phenomenon.

An appreciable decrease in the depth of collagen damage was found to occur between 4 hours and 24 hours after burning, with much less decrease at 48 hours. This was apparently due to recovery of the deeply placed, less severely damaged fibers. In contrast, the depth of damaged epithelial cells in hair follicles increases between 4 hours and 24 hours.

INTRODUCTION

Workers in this laboratory have noted certain differences between the gross and microscopic appearances of burns produced by a short exposure to a high irradiance of radiant thermal energy (a "flash burn") and those produced by longer exposures to lower irradiances (1, 2, 3, 4). Factors other than exposure time which might affect the microscopic appearance of these burns include input pulse shape and time of biopsy.

These experiments have been designed so that the effects of exposure time, input pulse shape, and time of biopsy on the pathologic appearance and severity of burns produced by constant radiant exposures of 10 cal/cm² can be determined. In addition, the radiant thermal burns in this series can be compared with the hot metal burns of Leach, Peters and Rossiter (5), and with the hot air and hot water burns of Moritz (6).

METHODS

Young Chester White pigs, anesthetized with intraperitoneal Dial with urethane (Ciba), were the experimental animals. The skin of these animals was found by Moritz and Henriques (6, 7), and by workers in this laboratory, to resemble human skin closely and to respond similarly to thermal energy. The hair was closely clipped with electric clippers and the skin was gently washed with water and a liquid detergent. The ambient temperature in the burning room was controlled to minimize variations in the skin temperature of the anesthetized animals (8).

The heat source was a modified 24 inch army carbon arc searchlight (9, 10). A rotating slotted wheel between the source and the animal produced the simulated field pulse (11, 12).

In order to obtain moderately severe dermal burns all injuries were produced with a radiant exposure of 10 cal/cm². Exposure time of 0.3, 3.0 and 10.0 seconds were used for the square pulse, and the simulated field pulses involved exposure times of 1.8, 4.0 and 12.7 seconds. Biopsies were taken at 4, 24 and 48 hours, and at 4 or 5, 9 or 10 and 14 days after burning. These 36 treatments were randomly assigned exposure sites on an animal's side, and the treatment block was replicated 16 times for a total of 576 burns. Only the three shortest biopsy times are considered here. The others, used to compare healing times, will be reported subsequently.

The biopsies, which included adjacent normal tissue, were placed in 10% formalin and stained by Hinshaw's Method I (13). For microscopic evaluation, the central part of the burn where maximal damage occurs, was chosen for evaluating severity of the injury. In addition to a careful study of the individual cellular changes, the characteristics of each component of the skin were graded and tabulated to demonstrate similarities or differences.

The criteria for epidermal damage were differences in staining characteristics as evidenced by a color difference between the damaged and the undamaged cells and cellular and nuclear structural alterations. These differential points were also used to determine depth of damage in the hair follicles. Both color differences and disruption of glandular and cellular architecture not present in unburned areas were interpreted as damage to the glandular elements. One criterion of damage to the connective tissue of the dermis was its differential staining. Another was the depth of the

zone of increased interfiber spacing, interpreted as edema, beneath the differentially stained collagen. Because of the difficulties in recognition of the structures, and of damage to them, the vascular and neural elements were not evaluated in this study.

The following system for grading damage was used for comparison purposes:

I Dermal Collagen

- A. Fraction of the total dermis differentially stained.
 1. Less than $1/3$ total depth
 2. Between $1/3$ and $2/3$ total depth
 3. Greater than $2/3$ total depth
- B. Depth in millimeters of dermis differentially stained.
- C. Depth of dermal Edema.
 1. Full thickness of dermis or less
 2. Greater than full thickness of dermis
- D. The characteristics of the differentially stained dermal layer.
 1. Degree of color change
 - a. Marked: blue-black staining of entire fibers
 - b. Mild : partial or light blue staining of the fibers
 2. Type transition from normal to damaged tissue
 - a. Sharp
 - b. Gradual
 3. Coalescence of collagen fibers with uniform staining
 - a. With coalescence and uniform staining
 - b. Without coalescence or uniform staining

II Hair Follicles

- A. Less than 1/3 millimeter damage below differentially stained dermis
- B. Greater than 1/3 millimeter damage below differentially stained dermis

III Glandular elements

- A. With damage
- B. Without damage

IV Epidermis

- A. Complete separation from the dermis
- B. Partial microscopic separation from the dermis
- C. No separation.

RESULTS

Results from microscopic evaluation are given in Appendices I - IX.

A. Morphologic Changes Resulting from Radiant Energy Burns

The changes described by Moritz (6) and by Leach, Peters and Rossiter (5) from their conduction and convection thermal burns are also noted in these radiant energy burns. With increasing injury, the epidermal cells are noted to swell, to become stretched, and to show focal and extensive detachment from the dermis. Their nuclei concomitantly became swollen and, with increasing injury, pyknotic. With high irradiances, the epithelium is coagulated and little structural alteration occurs. Beneath the epidermis, interfiber edema is noted first; with further injury, the individual fibers swell with consequent decrease in the interfiber spaces. Loss of the fibrillary character of dermal collagen and formation of a rather homogeneous layer occur after even more severe trauma.

B. The Effect of Pulse Shape

Though the radiant exposure of the various square and simulated field pulses was 10 cal/cm^2 , the exposure times and irradiances were necessarily quite different. Nevertheless, the morphologic changes in the 3.0 sec. burn of the square pulse series resemble fairly closely those of the 1.8 sec. and 4.0 sec. burns of the simulated field pulse group. To a similar degree, the 10.0 sec. square pulse burn and the 12.7 sec. simulated field pulse burn resemble each other, but in some instances differ from the shorter exposures. The 0.3 sec. square pulse burns usually differ from all the longer exposures. Because of these noted similarities between the burns produced by the two pulse shapes, only the square pulse burns need be described in detail.

C. The Effect of Exposure Time

That the 3.0 sec. exposure time produces the greatest depth of differentially stained collagen, both by direct measurement with the micrometer scale of the microscope and also by estimation of the proportion of dermis damaged, is shown in Appendices I and II. A careful evaluation of the depth to which dermal edema extends beneath the dark staining burned collagen is given in Appendix III. In contrast, the 3.0 sec. and 10.0 sec. exposures result in approximately the same degree of damage; this is deeper than the injury in the 0.3 sec. burns. The damage to glands and hair follicles roughly parallels depth of edema (Appendices IV and V). In addition, hair follicles are injured to a greater depth than the surrounding collagen.

The 10.0 sec. exposure produces a large percentage of burns with light blue stained collagen fibers, with partially blue stained fibers, and with less superficial coalescence of the dermal collagen. This is in contrast to the dark blue, completely stained, coalesced fibers in the 0.3 sec. and 3.0 sec. burns (Appendices VI and VII).

Appendix IX shows the epidermis in most of the 0.3 sec. burns to be completely separated and elevated from the underlying dermis. In the 10.0 sec. burns minute areas of separation are present. In contrast, in the 3.0 sec. burns the epidermis, though damaged, is still in contact with the severely injured dermis.

D. The Effect of the Time Interval Between Burn and Biopsy

As the time between burn and biopsy increases, the measured depth of differentially stained dermis decreases, and this affects the proportion of the dermis damaged (Appendices I and II). In the 48 hour biopsies the burned areas are more sharply demarcated (Appendix VIII). A tendency toward lighter and less complete staining of the burned dermal collagen fiber is also seen at 48 hours (Appendix VI).

Fewer burns are found with edema greater than full thickness of the dermis at 48 hours than at four hours (Appendix III).

Those burns not initially showing deep hair follicle damage (0.3 sec.), frequently do so at 48 hours (Appendix IV). Glandular damage is also increasingly apparent in the later biopsies, especially in the burns produced with long exposure times (Appendix V).

After 48 hours, as contrasted with four hours, the 3.0 sec. exposure burns exhibit more detachment of the epidermis (Appendix IX).

DISCUSSION

A. Comparison of Radiation with Other Forms of Thermal Energy

When the characteristics of the microscopic appearance of these radiant energy burns are compared with those described by Leach, Peters and Rossiter (5) for hot metal burns and with those described by Moritz (6) for hot air and hot water burns, one is led to believe that these four methods of burn production cause no difference in the basic pattern of the structural damage. It should be emphasized that this is only an impression without entirely comparable experimental data and that the type of structural alteration may vary even with different methods of applying a single form of thermal energy.

B. Comparison of Pulse Shapes

Since variations in radiant exposure, irradiance, and exposure time each produce changes in the characteristics of a cutaneous burn, and since one can not produce a square and a simulated field pulse with all these factors in a comparable range, it is not possible to attribute to the pulse shape alone any differences observed between burns produced by these two pulses unless they should be of a greater magnitude or of a different type than could be explained by the known responses of skin to variations in these three factors. This experiment shows no differences of such magnitude. On the contrary, some similarities between burns produced with relatively great differences in exposure time and irradiance are quite striking. The 3.0 sec. burns of the square pulse series resemble fairly closely the 1.8 sec. and the 4.0 sec. burns of the simulated field pulse group; and the 10.0 sec. and 12.7 sec. burns are also similar to each other. The small differences observed between 1.8, 3.0, and 4.0 sec. burns and between the 10.0 and 12.7

sec. ones, if they be real differences, are adequately explained by variation in exposure time and irradiance. The somewhat greater variation among the extremely short exposure burn (0.3 sec.), the intermediate ones (1.8, 3.0 and 4.0 sec.), and the long exposure burns (10.0 and 12.7 sec.) are explainable in a like manner.

With exposures of 10 cal/cm², the differences between the square and field pulse burns are much less than might have been expected from such great differences in the characteristics of the burn-producing energy. We must conclude that the skin does not act as a passive receiver of radiant thermal energy but rather reacts to it, and the type of reaction varies depending both on the rate of delivery of the energy and on the total energy delivered.

C. Comparison of the Various Exposure Times

In these burns produced by a constant radiant exposure, one would expect from some of the previous studies that the depth of dermal collagen damage would be inversely proportional to exposure time. This is exemplified by the 10.0 sec. and 3.0 sec. burns when the differential staining reaction is used as a criterion of damage. But, as has been pointed out above, the 0.3 sec. exposure produces less damage than the 3.0 sec. one and this is contrary to the prediction. Others (4, 10) have reasoned that this phenomenon is due most likely to loss of a portion of the incident energy in the heat of vaporization of the tissue fluids as the "steam blebs" are formed. In addition, the heated fluids are removed from the skin surface; and, at times, the heated superficial layers of the skin are lost as a result of the effect of the surface reaction. Steam blebs occurred in all of the 0.3 sec. exposure burns, and the superficial layers appeared dehydrated even in the four hour biopsy specimens.

The explanation for the direct proportionality between exposure time, depth of edema, depth of damage in hair follicles and presence of damaged glandular elements is not at all clear. In fact, with these criteria the differences among burns produced by all three exposure times are quite small, and are especially so between the 3.0 and 10.0 sec. burns. Perhaps the accuracy of the methods has not been adequate to obtain a true picture of the results. It is also possible that edema is a reactive phenomenon not directly dependent on the depth of morphologic damage.

The presence of injured hair follicles in depths greater than damaged dermis would seem to indicate either enhanced heat conduction down the hair shaft, a greater sensitivity of the epidermal cells to heat, or both. Frequently, dermal collagen immediately about hair follicles at depths below the surface injury will show damage, thus indicating that increased conduction down the hair shaft is at least a factor in this phenomenon.

It is reasonably certain that the more superficial layers of these radiant thermal energy pig skin burns are the more severely damaged tissues. With this in mind, the following damage severity-color relationships are listed in the order of increasing severity:

1. Mild : light blue collagen fibers
2. Moderate : partial dark blue collagen fibers
3. Severe : complete dark blue collagen fibers
4. Very Severe : coalesced dark blue collagen fibers

When Appendices VI, VII and VIII are considered in this light it suggests that the 10.0 sec. burns show milder collagen changes and that the 0.3 and 3.0 sec. burns exhibit the more complete heat injuries. Therefore, with a

constant radiant exposure, high irradiances at short times would seem to produce greater or more complete denaturation of the superficial layers than do low irradiances at longer times. It is of clinical importance to know at what degree of protein alteration, as evidenced by the color of the differentially stained tissue, the body cannot repair the damage but will reject the damaged tissue as a slough. It is hoped this can be determined in a subsequent study.

The differences observed in degree of epidermal-dermal separation may be explained quite satisfactorily. The 0.3 sec. burn almost uniformly produces, with explosive-like rapidity, a large bleb. Other workers (4, 10) in this laboratory have felt that this was secondary to sudden formation of steam from tissue fluids in the neighborhood of the dermis-epidermis interface. Moritz (6) has described a disruption of the epidermal-dermal connections as a result of trans-epidermal injury with a subsequent collection of minute amounts of edema fluid beneath the epidermis; this is seen in our 10.0 sec. burns. On the other hand, in the 3.0 sec. burns, the sub-epidermal blood vessels have been coagulated so that no edema fluid can form in this area. The epidermis therefore remains in contact with the dermis.

D. Comparison at the Various Biopsy Intervals

There seems to be a loss of the capacity of more deeply placed damaged collagen to take on the blue-black color 24 and 48 hours after the burn. The gradual transition zone between burned and normal dermis is lost, and the demarcation line is sharper. All of the damaged collagen is less darkly stained. This could be due either to partial repair of some of the less severely damaged collagen, or to progressive destruction so that collagen no longer takes up the stain. Hinshaw (14) has postulated partial, repairable damage in the deeper layers of the burned collagen.

In those burns not showing initial deep hair follicle damage we see an apparent greater depth of damage to these structures at 24 and 48 hours. However, since depth of follicle damage has been measured as depth below dermal damage, and since dermal damage decreases with time, this may not be a real change in depth of follicle damage at all. Moritz (6) did note, however, the appearance of nuclear changes 6 - 12 hours post burn in mild epithelial burns which had shown no cellular alternation up to this time. In the 10.0 sec. burns, which are the only ones with only a moderate number of damaged glandular elements initially, increased damage is seen at 48 hours. These observations may indicate that mildly damaged epithelial cells undergo a progressive change which leads to necrosis in 48 hours. This is in contrast to a lack of progressive collagen damage after the burn.

It should be noted that the apparent decrease in the number of burns with dermal edema greater than full thickness (Appendix III) may be a deceptive one. It is quite possible that in some burns at 4 hours and 24 hours the demarcation zone between edematous and non-edematous dermis is not very readily detectable. These burns may have been unjustly included in the "greater than full thickness" category.

SUMMARY AND CONCLUSIONS

1. The effects of exposure time, input pulse shape, and time of biopsy in 10 cal/cm^2 burns were evaluated by comparing depth and character of damage which was made apparent by Hinshaw's Method I for differential staining of burned tissue. Burns with exposure times of 0.3 sec., 3.0 sec., and 10.0 sec. with a square pulse and of 1.8 sec., 4.0 sec. and 12.7 sec. with a simulated field pulse were biopsied at 4 hours, 24 hours and 48 hours.

2. No differences which were observed could be attributed to the variation in pulse shape alone. In fact, the 3.0 sec. square pulse burn and the 1.8 sec. and 4.0 sec. field pulse burn were very similar as were the 10.0 sec. and 12.7 sec. burns.
3. In the square pulse series, 3.0 sec. burns revealed a greater depth of damaged collagen than did 0.3 sec. and 10.0 sec. burns. The occurrence of routine steam bleb formation and apparent dehydration of the superficial layer of the 0.3 sec. burns gives support to the theory that a portion of the incident energy is dissipated at the skin surface with a consequent less severe burn at this exposure time.
4. There is enhanced conduction of heat along or around the hair shaft.
5. The differential morphologic and staining characteristics of the dermal collagen observed in the burns of this experiment are rated according to severity of damage.
6. The degree of separation of the epidermis from the dermis in burns deeper than the dermal-epidermal junction varies with exposure time when radiant exposure remains constant.
7. Depth of differentially stained collagen damage decreases appreciably between 4 hours and 24 hours after burning. In contrast, depth of epithelial damage in hair follicles increases during this same interval.
8. Skin does not act as a passive receiver of radiant thermal energy but reacts to it, and the type of reaction depends in part on the rate at which energy is delivered.

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APPENDIX I

DEPTH OF DIFFERENTIALLY STAINED DERMAL COLLAGEN

MEASURED AS FRACTION OF TOTAL DEPTH OF DERMIS

Exposure Time (sec)	Pulse Type	Biopsy Time (in hours post burn)	No. of Burns with Damage Less than 1/3 Total Depth	No. of Burns with Damage Between 1/3 and 2/3 of Total Depth	No. of Burns with Damage Greater than 2/3 Total Depth
0.3	Square	4	10	3	3
		24	16	0	0
		48	12	3	1
3.0	Square	4	1	10	5
		24	8	7	0
		48	11	4	1
10.0	Square	4	8	7	1
		24	14	2	0
		48	15	1	0
1.8	Simu- lated Field	4	6	7	2
		24	12	2	2
		48	12	2	2
4.0	Simu- lated Field	4	6	7	3
		24	10	6	0
		48	12	5	1
12.7	Simu- lated Field	4	8	6	2
		24	14	2	0
		48	16	0	0

APPENDIX II

DEPTH OF DIFFERENTIALLY STAINED DERMAL

COLLAGEN MEASURED IN MILLIMETERS

Exposure Time (sec)	Pulse Type	Biopsy Time (in hours post burn)	Depth of Damage in Millimeters
0.3	Square	4	.75
		24	.49
		48	.52
3.0	Square	4	1.02
		24	.75
		48	.71
10.0	Square	4	.66
		24	.45
		48	.32
1.8	Simulated	4	.85
	Field	24	.71
		48	.63
4.0	Simulated	4	.89
	Field	24	.63
		48	.59
12.7	Simulated	4	.71
	Field	24	.48
		48	.42

APPENDIX III

DEPTH OF DERMAL EDEMA

Exposure Time (sec)	Pulse Type	Biopsy Time (in hours post burn)	No. of Burns with Edema in Full Thickness of Dermis	No. of Burns with Edema greater than Full Thickness of Dermis
0.3	Square	4	5	11
		24	12	5
		48	14	2
3.0	Square	4	1	15
		24	6	9
		48	12	4
10.0	Square	4	1	15
		24	4	12
		48	10	6
1.8	Simulated Field	4	2	13
		24	6	10
		48	12	4
4.0	Simulated Field	4	1	15
		24	6	10
		48	11	7
12.7	Simulated Field	4	2	14
		24	3	13
		48	7	9

APPENDIX IV

DEPTH OF DAMAGE TO THE HAIR FOLLICLES

Exposure Time (sec)	Pulse Type	Biopsy Time (in hours post burn)	No. of Burns with Damage Less than 1/3 mm. Below Damaged Dermis	No. of Burns with Damage More Than 1/3 mm. Below Damaged Dermis
0.3	Square	4	12	4
		24	7	9
		48	6	9
3.0	Square	4	3	13
		24	1	14
		48	0	16
10.0	Square	4	2	14
		24	2	14
		48	2	13
1.8	Simulated Field	4	6	8
		24	3	12
		48	1	14
4.0	Simulated Field	4	7	8
		24	0	16
		48	2	15
12.7	Simulated Field	4	4	11
		24	1	15
		48	2	14

APPENDIX V

DAMAGE TO DERMAL GLANDS

Exposure Time (sec)	Pulse Type	Biopsy Time (in hours post burn)	No. of Burns With Damage	No. of Burns Without Damage
0.3	Square	4	1	15
		24	2	15
		48	2	12
3.0	Square	4	6	10
		24	8	7
		48	8	8
10.0	Square	4	6	10
		24	5	11
		48	11	5
1.8	Simulated Field	4	1	14
		24	4	12
		48	7	9
4.0	Simulated Field	4	4	12
		24	8	8
		48	13	5
12.7	Simulated Field	4	6	10
		24	11	5
		48	11	5

APPENDIX VI

CHARACTERISTICS OF THE DIFFERENTIALLY STAINED

DERMAL COLLAGEN: DEGREE OF COLOR CHANGE

Exposure Time (sec)	Pulse Type	Biopsy Time (in hours post burn)	No. Burns with Marked Change: Blue-black Staining of Entire Fibers	No. Burns with Mild Change: Partial or Light Blue Staining of Fibers
0.3	Square	4	16	0
		24	15	2
		48	11	4
3.0	Square	4	15	1
		24	14	1
		48	11	5
10.0	Square	4	7	7
		24	8	7
		48	2	14
1.8	Simulated Field	4	14	1
		24	14	2
		48	12	3
4.0	Simulated Field	4	15	1
		24	14	2
		48	14	14
12.7	Simulated Field	4	10	6
		24	8	8
		48	7	9

APPENDIX VII

CHARACTERISTICS OF THE DIFFERENTIALLY STAINED

DERMAL COLLAGEN: COALESCENCE OF COLLAGEN FIBERS

Exposure Time (sec)	Pulse Type	Biopsy Time (in hours post burn)	No. of Burns with Coalescence and Uniform Staining	No. of Burns without Coalescence and Uniform Staining
0.3	Square	4	13	3
		24	8	8
		48	11	5
3.0	Square	4	12	6
		24	7	8
		48	3	13
10.0	Square	4	1	15
		24	1	15
		48	2	14
1.8	Simulated Field	4	8	7
		24	6	10
		48	6	10
4.0	Simulated Field	4	10	6
		24	5	11
		48	4	14
12.7	Simulated Field	4	1	15
		24	1	15
		48	0	16

APPENDIX VIII

CHARACTERISTICS OF THE DIFFERENTIALLY STAINED DERMAL

COLLAGEN:TYPE OF TRANSITION FROM DAMAGED TO NORMAL TISSUE

Exposure Time (sec)	Pulse Type	Biopsy Time (in hours post burn)	No. of Burns with Sharp Transition	No. of Burns with Gradual Transition
0.3	Square	4	1	15
		24	11	6
		48	12	3
3.0	Square	4	0	16
		24	5	10
		48	11	5
10.0	Square	4	2	12
		24	9	6
		48	12	4
1.8	Simulated Field	4	3	12
		24	9	7
		48	12	3
4.0	Simulated Field	4	0	16
		24	9	7
		48	13	5
12.7	Simulated Field	4	5	11
		24	15	1
		48	13	3

APPENDIX IX

EPIDERMAL-DERMAL SEPARATION

Exposure Time (sec)	Pulse Type	Biopsy Time (in hours post burn)	No. of Burns with Complete Separation	No. of Burns with Partial Microscopic Separation	No. of Burns with no Separation
0.3	Square	4	14	0	2
		24	12	1	4
		48	13	1	2
3.0	Square	4	0	5	11
		24	1	3	11
		48	2	8	6
10.0	Square	4	0	12	4
		24	1	15	0
		48	0	14	2
1.8	Simulated Field	4	0	5	10
		24	0	4	12
		48	6	5	5
4.0	Simulated Field	4	0	4	12
		24	1	3	12
		48	2	7	9
12.7	Simulated Field	4	0	7	9
		24	0	11	5
		48	0	14	1