STUDIES OF THERMAL INJURY

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—*Editor*

STUDIES OF THERMAL INJURY

I. THE CONDUCTION OF HEAT TO AND THROUGH SKIN AND THE TEMPERATURES ATTAINED THEREIN. A THEORETICAL AND AN EXPERIMENTAL INVESTIGATION *

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I. INTRODUCTION

Never before in the history of man has heat energy been so important a cause of disability and death as during World War II. The need for precise knowledge regarding the thermal tolerances of living tissue and the nature of the cellular and somatic changes induced by hyperthermia was felt by those responsible not only for the protection and medical care of our own military personnel but also for the development and use of such thermally effective weapons as the flame thrower, the atomic bomb, and various other incendiary or explosive missiles.

Although thermal injury has always constituted a problem of medical importance, the requests of various branches of the Armed Forces for precise and quantitative information disclosed a dearth of basic facts relating to the casualty-producing effectiveness of heat energy. Remarkably little information was available concerning the mechanism by which hyperthermia leads to irreversible cellular injury, the reciprocal relationships of time and temperature in the production of either cutaneous or systemic injury, the relationship between environmental heat, surface temperature and the slope of the transcutaneous thermal gradient, the pathogenesis of cutaneous burns, or the physiological mechanisms by which external heat may be responsible for acute disability or death.

In an attempt to elucidate some of these problems and to satisfy some of the more pressing needs of the Armed Services for quantitative data, a series of studies was undertaken. It became apparent that the information thereby acquired was of such fundamental importance to an understanding of the problem of thermal injury from a civil as well as from a military standpoint that its publication in the open literature was authorized.

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This report, which is the first of a series, is concerned in part with a general consideration of the physical laws that relate to heat transfer and temperature change and in part with a quantitative experimental study of the rate of heat transfer through skin at different surface temperatures and the effects of different rates of energy transfer on the subsurface temperature gradient.

II. THEORETICAL CONSIDERATIONS

THE NATURE OF HEAT

The concept of temperature arises from the sensations of hotness and coldness. Experience has shown that when a group of substances of different temperature are kept free of outside disturbances, the hotter bodies will get colder and the colder bodies hotter, and, ultimately, these substances will reach a state of complete thermal equilibrium (identical temperature). The hotter bodies are said to have lost heat and the colder bodies are said to have gained heat. This concept of heat becomes quantitative by defining a unit of heat, the calorie, as the amount of heat gained by 1 gm. of liquid water under atmospheric pressure when the temperature increases from 14.5° to 15.5°C.

A gain in heat, which is discernible through a rise in temperature, is associated with an increase in the intra-molecular and inter-molecular motion. Thus, heat can be considered as the energy stored in a substance by virtue of the state of its molecular motion. Certain manifestations of this increase in energy are readily observable; for example, melting, vaporization, decomposition, and alteration in rate of diffusion and chemical reaction.

Beside the definition of a calorie, there are other physical concepts pertaining to heat which are requisite to an understanding of the general problem of thermal injury, namely, heat capacity and heat transfer.

Heat Capacity, C_p

Heat capacity, or specific heat, of a substance is the amount of heat which is required to raise its temperature by 1°C.

The importance of heat capacity in relation to thermal injury is readily seen by considering the respective propensities for production of injury of 1 gm. of water ($C_p = 1.00$) and 1 gm. of silver ($C_p = 0.06$) both at 100°C. and in contact with 1 gm. of thermally insulated skin ($C_p \approx 0.7$) at 35°C. After equilibrium is reached in the former case, the temperature of the skin is increased to 73°C., whereas in the latter case it is increased only to 42°C.

It is apparent that if the skin were to equilibrate rapidly enough when placed in contact with a hot body, there is insufficient heat in 1 gm. of silver at 100°C. to produce injury to 1 gm. of skin. Actually, of course, the skin, due to its thermal insulating properties, does not equilibrate rapidly enough and the portion of skin nearest the silver does reach a sufficiently high temperature to produce injury before thermal equilibrium is reached. Hence, another physical property of importance in the problem of thermal injury is heat transfer.

Heat Transfer

In certain experiments to be described in ensuing articles,[1,2] heat was transported to the skin by three methods: convection, radiation, and conduction. With convection and radiation,[1] heat reached the skin under such circumstances that the uptake of heat was primarily determined by the heat source. With conduction,[2] the amount of heat absorbed by the skin was primarily determined by the properties of the heat absorber, the skin itself.

Convection. Convection is the mechanism by which hot air transports heat to a cooler surface due to the eddying currents that arise. The air velocities of the eddy currents are about 1.6 km. per hour. An equation has been developed for the transfer of ambient heat by natural convection from a large envelope of hot air surrounding cylindrical objects about 30 cm. in diameter.[3,4] This equation shows that q, the caloric uptake per minute per sq. cm. of surface, can be expressed as follows:

$$q = 0.0026\,(T_a - T)^{\frac{5}{4}} \tag{1}$$

where T_a is the air temperature in °C. and T is the surface temperature in °C. Thus, using a skin temperature of 40°C., air at 100°C. and at 400°C. will transport to the skin about 0.4 and 4 calories per sq. cm. per minute, respectively. It is also apparent that as this heat is absorbed by the skin, the surface temperature of the skin will rise and the caloric uptake of the animal will decrease with time.

It is of interest to compare the caloric uptake rate of skin at 40°C. when an atmosphere of steam maintained at 100°C. is substituted for the air. Under these conditions, about 300 calories per sq. cm. per minute would be absorbed by the skin,[3] if the surface temperature could be maintained at 40°C. This 800-fold increase in caloric bombardment as compared to air is due to the latent heat of condensation of steam. This, of course, is why steam is an enormously greater hazard than hot air in the production of heat injury.[5]

Radiation. All substances give off heat in the form of radiant energy in amounts that are predetermined by their surface temperatures. When this radiation impinges upon another body a certain fraction is absorbed and is changed into heat. Thus, if two substances at different temperatures are placed in an enclosure, there is a continual exchange of energy; the hotter body radiating more energy than it absorbs and the colder body absorbing more heat than it radiates. In the special case of an animal completely enclosed in a large box of source temperature, T_r, in °C., the caloric uptake rate, q, of the animal, due to this interchange of radiant energy between the skin and the wall of the box, is expressed by the following equation: [3,4]

$$q = sef\,[(T_r + 273)^4 - (T + 273)^4] \tag{2}$$

where s is the radiation constant and is equal to 8.2×10^{-11} calories per sq. cm. per T^4 per minute, e is the effective emissivity of the hot walls of the box, and f is the absorptivity of the skin to radiation emitted at T_r. Under experimental conditions to be described, the product, ef, can be taken as about 0.8. Thus, when the skin temperature is 40°C., the hot walls at 100° or 400°C. will radiate to the skin about 0.7 or 13 calories per sq. cm. per minute, respectively.

Conduction. Conduction is defined as the transfer of heat from the hotter portion of a substance to a colder portion of the same substance, or from a hot body in physical contact with a cold body, when in each case there is no appreciable displacement of any of the molecules comprising these substances. It is this restriction that differentiates conduction from convection.

In certain experiments to be described, heat was conducted from either a hot solid or a hot liquid [2] to the skin. In these experiments, the purpose of both the solid and liquid heat source was to maintain the temperature of the skin surface at a predetermined constant value and hence the conduction of heat through the heat source need not be considered. In hot air experiments,[1] thermal conduction through air is small as compared to convection, and this small contribution is included in equation 1. Thus, conduction of heat through the skin only need be considered.

In all cases of heat flow by conduction, a temperature gradient must exist within the substance. If this temperature gradient varies with time, the rate of heat flow will also vary with time. This type of heat flow in which temperature is a function of both position within the body and time is called heat conduction in the unsteady state. Heat conduction in the steady state refers to all cases in which the temperature at any point within a substance does not depend upon time. Under these conditions the amount of heat flow through the medium is determined by this temperature gradient and by the ability of the body to conduct heat (thermal conductivity). It is the latter case which will be considered first. The equation for steady state heat conduction inside a rectangular homogeneous body is based upon Fourier's law [3,4,6] and is given by:

$$q = \frac{K}{L}(T_1 - T_2) \qquad (3)$$

where K, the thermal conductivity, is expressed in calories per minute per sq. cm. perpendicular to the direction of heat flow per unit temperature gradient, °C. per cm. length of path. L is the path length through which the heat flows and T_1 and T_2 are the temperatures in °C. at the beginning and end of the path respectively; q has been previously described.

This equation makes possible the experimental determination of the *in vitro* thermal conductivity of the four respective sections of cutaneous and subcutaneous tissues: epidermis, dermis, fat, and muscle, and also of any combination thereof.

GENERAL THEORY OF HEAT FLOW THROUGH SKIN

By making use of the above brief definitions of the various physical factors involved in the transport of heat to and through the skin, it is possible to consider how the application of heat affects the time-temperature relationship within a given cutaneous site. It is apparent that in order to make heat flow inward from the skin surface it is necessary to raise the temperature of the skin surface to an extent that overcomes the normal existing gradients. This can be accomplished by means of an external source of heat through conduction, convection, or radiation. Once the temperature of the skin surface is sufficiently high, the heat will start to flow inward, resulting in a general rise in temperature within the skin site.

This initial heat flow inward, *and thus the rate of temperature rise within,* will depend primarily upon two physical factors: (a) the heat capacity of the skin or the ability of the skin to absorb the heat, and (b) the thermal conductivity of the skin or the ability of the skin to transport the heat. After a certain interval of time the amount of heat entering the skin site will be balanced by the amount of heat leaving the skin site, and the skin will be "heat saturated." In this state, the new temperature distribution within the skin site will become nearly invariant with time, and the amount of heat flowing through the skin will depend only upon (b) and the skin surface temperature.

It is to be recognized that the above picture involves not only the solution of the steady state of heat conduction, but also the solution of the initial unsteady state of heat flow. In order to solve even the above "idealized" picture, it would be necessary to know the initial temperature gradients within the tissues, the thicknesses, densities, thermal conductivities, and heat capacities of the various layers, and the skin surface temperature as a function of time.

The solution of such a problem involves the following Fourier heat equation:[6]

$$\frac{K}{PC_pL^2}\left(\frac{d^2T_{xt}}{dx^2}\right) = \frac{dT_{xt}}{dt} \tag{4}$$

where T_{xt} is the temperature at the time, t, at a distance, x, within the skin measured from the skin surface. P is density, and the remaining symbols have been previously defined.

The solution of equation 4, subject to the above-mentioned conditions, is exceedingly complicated. Yet, superimposed upon this are the numerous indeterminate *in vivo* factors which arise when we go from the "idealized picture" to the living animal. It is useful to enumerate the most important of these various indeterminate factors:

(a) Site variations in the respective thickness of epidermis, dermis, fat, and muscle.

(b) Variation of existing temperature gradients within the skin with respect to time and/or position of site.

(c) Unknown average rate of blood flow through the various skin layers, and the unknown variations of the unknown rate of flow with respect to position of site and temperatures within the site.

(d) The appearance of edema fluid in variable quantities which brings forth indeterminate alteration in the density, heat capacity, thickness, and thermal conductivity of the various layers of skin so affected.

It is obvious from the above discussion that any general solution of the time-temperature relationship within a skin site, when heat is applied, is not possible. However, with certain of the experiments to be described in detail,[1,2] it is possible *to derive to a first approximation the time-temperature relationship in the layer of basal epidermal cells.** These experiments were either (i)[2] conducted so as to bring the skin surface immediately to, and maintain it at, a predetermined temperature level until the threshold of irreversible epidermal injury was reached; or (ii)[1] the entire animal was surrounded com-

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* Actually, these time-temperature relationships can also be estimated at either the skin surface or at any distance within the epidermis. The basal epidermal layer has been specifically chosen since increases in temperature of these cells are of the most import in the production of epidermal injury by heat.

pletely by an envelope of ambient (air) and radiant heat. These experimental conditions at the boundary of the skin surface and source of heat are expressed by the following equation:

$$q = H\,(T_s - T) \tag{5}$$

where q and T have been previously defined (equations 1 and 2). T_s is the temperature of the heat source in °C. and H, in calories per sq. cm. per minute, is known as the heat transfer coefficient. Conditions under experiments i were tantamount to an infinite heat transfer coefficient ($H = \infty$); and with experiments ii the heat transfer coefficient is finite and the numerical value is readily obtained by combining the radiant and ambient contributions to heat transfer coefficient as computed by equations 1 and 2, respectively. In order to solve equation 4 under the boundary condition expressed by equation 5, it is necessary to assume that the ratio of the total tissue thickness to the epidermal thickness (about 80 μ) is infinite rather than finite. This assumption will lead to slightly longer time intervals for "heat saturation" of the epidermis than are to be experimentally expected. The integration[6] of equation 4 under the above conditions results in equation 6:

$$\frac{T_s - T_t}{T_s - T_o} = \theta\left[\frac{\gamma}{\sqrt{t}}\right]\left\{ e^{\frac{HL}{K}\left(1 + \frac{HLt}{4\gamma^2K}\right)}\right\}\left\{1 - \theta\left[\frac{\gamma}{\sqrt{t}}\left(1 + \frac{HL}{2\gamma^2K}\right)\right]\right\}$$

where

$$\theta\,[Y] = \frac{2}{\sqrt{\pi}}\int_0^Y e^{-x^2}dx \tag{6a}$$

and γ is computed by means of equation 6b.

$$\gamma = \frac{L}{2\sqrt{\dfrac{K}{PC_p}}} \tag{6b}$$

T_t is the temperature of the basal epidermal cells at the time, t, in seconds. T_s is the temperature of the heat source. T_o is the temperature of the skin surface previous to the exposure to heat. L is the distance of the basal cells from the skin surface. P is the density of the basal epidermal layer. The other symbols have been previously defined and are experimentally determinable. The integral that defines $\theta\,[Y]$ (equation 6a) is respectively equal to $\sqrt{\pi}/2$ and zero when Y is infinite ($t = 0$) and Y is zero ($t = \infty$). For other values of Y, the numerical value of the integral is tabulated.[7]

The time-temperature relationships at the basal-epidermal layer during an exposure of the animal to a source of constant ambient and radiant heat will be evaluated by means of these equations in section IV.

In experiments in which the skin surface was brought immediately to, and maintained at, a predetermined constant temperature, H, the heat transfer coefficient, is nearly infinite, and equation 6 reduces to

$$\frac{T_s - T_t}{T_s - T_o} = \theta\left[\frac{\gamma}{\sqrt{t}}\right] \tag{6c}$$

where, as before, γ is given by equation 6a. It is to be noted that in this case T_s can be taken as the skin surface temperature during the entire heat exposure, since the temperature of the heat source is identical with the surface temperature once heat exposure begins.

Equation 6c results in a basal layer temperature which becomes, after a certain time interval, essentially identical with the skin surface temperature. Actually, there will always exist a small but finite temperature gradient between the surface and the basal cell layer. This steady state gradient can be experimentally determined by means of equation 3, and the true temperature of the basal layer can be quite accurately computed for any time, *t*, by using equation 6c until the steady state temperature obtained through equation 3 is reached. Computations using equation 6 to ascertain basal epidermal temperatures will be given in section IV.

III. AN EXPERIMENTAL INVESTIGATION OF THE QUANTITIES INVOLVED IN BOTH THE STEADY AND UNSTEADY STATE OF HEAT CONDUCTION THROUGH THE SKIN

Determination of the Heat Capacity of the Four Pertinent Tissues

The apparatus used for the determination of the heat capacity of these cutaneous and subcutaneous tissues need not be described in detail, since the well known method of mixtures was used.[8] Briefly, this procedure consisted of heating a known weight (about 10 gm.) of each tissue in a thin brass container and rapidly dropping it into a water calorimeter. The heat capacity of the tissue was readily computed from temperature rise of the water as measured by a Beckmann thermometer.

In order to obtain pure epidermis for these determinations, the following method was used. After the hair was shaved as closely as possible, the pig was immersed in the water at 55°C. for about 1 minute, then withdrawn and the skin carefully dried. It was then possible to remove strips of pure epidermis by scraping with a knife. The remaining tissues were readily obtained in a relatively pure state by dissection.

The values of the heat capacities of the respective tissues of two pigs are given in Table 1.

TABLE I

Heat Capacity of Cutaneous and Subcutaneous Tissues of the Pig in Calories per Gram per °C.

	Epidermis	Dermis	Fat	Muscle
Heat capacity, C_p	0.887 0.845	0.785 0.753	0.538 0.573	0.890 0.926
Average value, $\overline{C_p}$	0.86	0.77	0.55	0.91

In view of the known similar heat capacities of dry tissue, the variations of the different tissues as shown in Table 1 are probably due to the water content. In this respect, the high value for epidermis (0.86) is understandable since it was found experimentally that the water content of epidermis, in spite of the presence of the cornified layer, averaged about 76 per cent.

Determination of the Thermal Conductivities of Cutaneous and Subcutaneous Tissues of the Pig

The experimental determinations of the thermal conductivities of cutaneous and subcutaneous porcine tissue were based on equation 3. The respective tissues were placed on a copper cylinder, 5 cm. in diameter and 10 cm. high. The temperature of this tissue-cylinder interface was measured by means of an iron-constantan thermocouple soldered into the face of the copper cylinder and a type K2 potentiometer.* The automatic recording caloric applicator[9] was then placed over, and in contact with, the exposed face of the tissue. This apparatus provided a means of automatically recording the vertical rate of caloric flow from the applicator through the tissue to the copper cylinder as functions of the temperatures of both tissue surfaces. Thus, when the tissue became "heat saturated," knowledge of the caloric input into the tissue, of the temperatures of the tissue-applicator (about 48°C.) and of tissue-cylinder (about 30°C.) interfaces, and of the thickness of the tissue made possible computation of thermal conductivity. The average tissue thickness was determined

* Leeds & Northrup, Philadelphia, Pa.

by measuring the distance between the face of the applicator and the face of the cylinder. The thermal conductivities of all tissues except epidermis were obtained by this procedure, since in view of the thinness of epidermis the above method was not feasible.

The method of difference was used with epidermis. A section of well shaved skin tissue consisting of dermis and epidermis was rigidly clamped to the copper cylinder, water at 55°C. was poured over the skin, and the excess water was removed by blotting. The clamps prevented lateral contraction of the heated tissue and the hot water facilitated subsequent removal of the epidermis. The conductivity determination was then made, the epidermis scraped off, and the determination repeated. As a further check, in certain experiments a strip of intact epidermis was placed over the denuded dermis and the measurement repeated. The thickness of numerous pig epidermal strips was determined with a micrometer. The thickness was about 80 ± 10 μ.

TABLE II

In Vitro Thermal Conductivities, K, of Pig Tissues

$$K = \frac{\text{calories} \times \text{cm.}}{\text{cm.}^2 \times \text{minutes} \times {}^\circ\text{C.}}$$

	Epidermis	Dermis	Subcutaneous fat	Subcutaneous muscle
K	0.036	0.054	0.021	0.064
K	0.023	0.053	0.024	0.062
K	0.032	0.051	0.023	0.073
K	0.03	0.053	0.023	0.066

At least triplicate determinations were made on each of the four tissues of three different pigs (about 10 kg.). The average values of the thermal conductivities obtained are given in Table II.

In view of the thinness and uncertainty as to thickness of the epidermis, the wide variation in the epidermal thermal conductivity was to be expected. The data pertaining to the other tissues were considerably more reproducible.

It is of interest to compare some of these data with those of Breuer,[10] who determined the respective thermal conductivities of both muscle and fat of cow, horse, pig, and dog. This investigator found that the conductivities of pig muscle and fat, expressed in the above units, were 0.060 and 0.021, respectively; furthermore, essentially the same values were found for the muscle and fat of the other three animals. In view of the excellent agreement between Breuer's value and ours for pig muscle and fat, it is difficult to understand the value, 0.03, that Hardy and Soderstrom [11] reported for both cow muscle and fat. Unfortunately, no description of their experimental method was given. In order to investigate this discrepancy, the thermal conductivity of beef muscle was redetermined and an average value of 0.057, which agrees with the results of Breuer, was obtained.

In view of the numerous indeterminate factors (section II) which enter into the *in vivo* conduction of heat through pig skin, the *in vitro* thermal conductivities of these four tissues are not of themselves very useful. However, they do serve as a baseline in the interpretation of certain experiments to be described.

In Vivo Observations of Caloric Uptake of Pig Skin and the Rise in Temperature at the Dermis-Fat Interface as a Function of Both Time and Skin Surface Temperature

It was of interest to ascertain the caloric uptake of the skin when the epidermal surface was maintained at various temperature levels between 45° and 100°C. Numerous such experiments have been performed and, as was to be expected (see section II), the data varied widely and were extremely difficult to interpret in detail. Therefore, only a small fraction of these data will be reported and the variations to be expected will be indicated.

During these experiments the temperature at the dermis-fat interface also was ascertained. A pig under nembutal anesthesia was clipped and shaved. The no. 27 gauge needle thermocouple[9] was introduced laterally into the dermis-fat interface in the following manner: Through experimentation it was found possible to insert laterally a no. 22 gauge trocar along the natural cleavage plane of the dermis-fat interface, until a point directly underneath the surface area to be exposed to heat was reached; then the no. 27 gauge thermocouple needle was inserted into the no. 22 gauge trocar until skin resistance could be detected. The no. 27 gauge needle was then withdrawn about 1 cm. The temperature (millivolts) of this needle couple was measured either intermittently with a type K2 potentiometer * or continually with a photo-electric recording potentiometer.†

After the determination of the skin temperature at a chosen site by means of the fine wire thermocouple,[9] the automatic recording caloric applicator[9] was applied, and a continuous record of the caloric uptake rate of the skin at a predetermined epidermal surface temperature was obtained.

After the heat exposure was terminated, the skin was cut to expose the hypodermic needle thermocouple and the distance from the dermis-

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* Leeds & Northrup, Philadelphia, Pa.

† General Electric Co., Schenectady, N. Y.

fat interface to the skin surface was ascertained with a depth gauge. This depth before the application of heat was ascertained by control experiments on neighboring sites.

Caloric Uptake Rate of Pig Skin

Typical caloric uptake data as a function of time and epidermal surface temperature are presented in Table III. These data were a composite of at least three determinations on the lateral thoracic area of different pigs; five pigs in all were used. As was expected, in view of the numerous factors that determine the caloric uptake in a living animal (section II), the experimental variations inherent in duplicating exposures were considerable. Thus, these data served only as a rough guide (± 30 per cent) to the caloric uptake rate of pig skin.

TABLE III

A Guide (± 30 Per Cent) to the Caloric Uptake of Pig Skin as a Function of Time and Surface Temperature as Determined by the Automatic Recording Caloric Applicator[9]

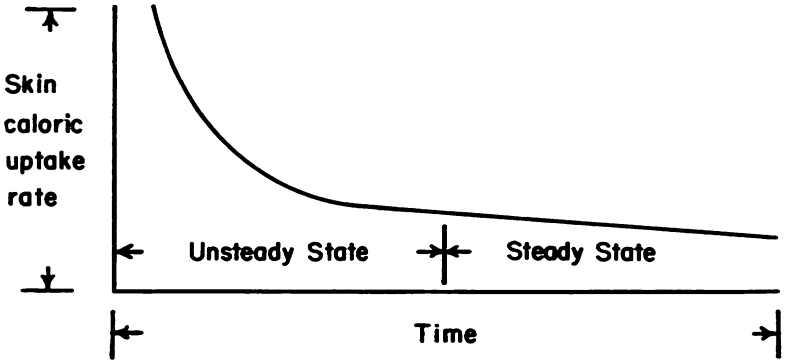
Time interval	Skin surface temperature during heat exposure				
	45° C.	50° C.	55° C.	60° C.	65° C.
(*minutes*)	Caloric uptake rate of lateral thoracic skin in calories per minute per sq. cm.				
0 –0.2	6.0	9.5	12.0	15.0	17.0
0.2–0.4	2.2	3.7	4.9	6.9	8.4
0.4–0.6	1.8	2.8	3.8	5.6	6.7
0.6–0.8	1.7	2.5	3.1	5.1	5.9
0.8–1.0	1.6	2.3	2.7	4.7	5.4
1 –1.5	1.5	2.0	2.6	4.3	4.8
1.5–2	1.4	1.8	2.4	4.1	4.5
2 –3	1.2	1.6	2.3	3.7	4.2
3 –5	1.1	1.5	2.1	3.2	3.8
5 –7	1.0	1.4	2.0	2.8	3.5
7 –10	0.9	1.3	1.9	2.5	3.2
	Total caloric uptake in calories per sq. cm.				
0 –1	2.7	4.2	5.3	7.5	8.7
0 –5	7.5	10.7	14.3	21.8	25.2
0 –10	12.2	17.4	24.0	34.9	42.7

It was noted that the average caloric uptake rate of pig skin during the first 0.2 minute was about six-fold greater than the average caloric uptake rate during the steady state period (7 to 10 minutes). This six-fold difference was due to the initial necessity of heat saturating the tissue and was primarily a heat capacity effect. After the first few minutes the skin tissue was essentially heat saturated and the ***in vivo*** thermal conductivities of the various layers of pig skin primarily determined the caloric uptake rate.

When the data given in Table III are plotted against time, the curves obtained will conform in type to that shown schematically in Text-Figure 1. A mathematical analysis of the general form of these curves based on equation 5 showed that during the first 2 to 3 minutes of the heat application, the skin can be considered as an infinite body with a ratio of thermal conductivity to heat capacity that was approximately the same as that computed from the *in vitro* determinations tabulated in Tables I and II. This agreement was probably due to the fact that the ratio of the thermal conductivity to heat capacity (equation 6b) was not nearly as sensitive to these indeterminate *in vivo* factors as the individual quantities themselves.

The Interface Temperature at the Junction of Dermis and Fat

The dependence upon time of the dermis-fat interface temperatures during exposure of the skin surface to a predetermined temperature between 45° and 90°C. is given in Table IV. These values were a composite of at least two experimental determinations on two different pigs (four determinations in all). As with measurements of the caloric uptake, the variations in duplicating experiments were considerable, and these data serve only as a rough (± 20 per cent) guide to the time-temperature relationship at the dermis-fat interface. These data together with other experimental observations indicate the following:



Text-Figure 1. The time dependence of the rate of heat flow through skin when the surface is immediately brought to, and maintained at, a constant temperature.

(a) The junction of the fibrous dermis and the subdermal fat in the lateral thoracic area of a 10 kg. pig lay about 2 mm. below the skin surface. Ten minute exposures to surface temperatures of 50° to 70°C. increased, significantly, the thickness of the dermis. This increase in thickness was due to the accumulation of edema fluid in the dermis and the effect was maximal when the skin surface was maintained at about 60°C. Skin surface temperatures equal to, or greater than, 80°C. denatured the corium so rapidly that these mechanisms were destroyed.

(b) Although the continual caloric uptake by the skin tended to increase the dermal temperature, the appearance of relatively cool edema fluid tended to decrease it. At skin surface temperatures of 50° and 70°C. these two effects nearly counterbalanced, and after the first minute of heat exposure, the dermis-fat interface temperature remained essentially constant. With skin surface temperatures between 55° and 65°C. the rapid appearance of a large amount of edema fluid more than compensated for caloric uptake, and the temperature at the interface between dermis and fat was temporarily lowered. This effect was maximal when the skin surface was maintained at about 60°C.

(c) When the skin surface temperature was maintained at 45°C., and probably at all other temperatures that fail to cause edema, the dermis became "heat saturated" after about 5 minutes of exposure.

TABLE IV

The Dependence on Time of the Dermis-Fat Interface Temperature (± 20 Per Cent) During Exposure of the Surface of Pig Skin to Predetermined Temperatures

	Skin surface temperature in °C.							
Initial	35.0	34.8	34.8	35.2	34.9	34.3	34.2	34.5
During exposure	45	50	55	60	65	70	80	90
Time	Dermis-fat interface temperature in °C.							
(*minutes*)								
	34.7	34.5	34.6	35.0	34.7	34.2	34.4	34.8
0.2	36	38	39	43	46	52	53	56
0.5	38	43	45	46	52	62	65	66
1.0	39.5	45	47	48	53	65.6	71	74
1.5	40	47	48	47	53	66.5	72	77
2.0	40.5	47	49	46	54	67	74	79
3.0	41	47	48.5	45	56	67.5	75	79
5.0	42	47	47.5	44.5	58	67.5	77	
7.0	42	46.5	47.5	47	58			
10.0	42	47	48	49	59			
	Average thickness of corium in mm.							
Initial	2	2	2	2	2	2	2	2
At termination of exposure to heat	2	2.5	3.2	4.2	3	2.5	2	2
	In vitro thermal conductivity of dermis at termination of exposure							
	0.06	0.1	0.09	0.10	0.16			

When edema fluid was produced, the time for dermal heat saturation was essentially indeterminate, but it apparently was not much greater than 10 minutes.

(d) Histological examinations showed that complete primary injury to the dermis immediately following heat exposure was obtained in all of these experiments when the skin surface temperature was maintained at 65°C. or above. The limited (five) time-temperature-injury data at the dermis-fat interface tended to indicate a quantitative relationship not at variance with that found for epidermal injury.[2,12]

(e) By making the reasonable assumption that the dermis was essentially "heat saturated" at the end of a 10 minute exposure, the *in vitro* thermal conductivities of dermis can be computed by substituting the approximate caloric uptake (Table III), dermis-fat interface and skin surface temperatures, and the final dermal thickness in equation 3; neglect of the epidermal temperature drop introduced no appreciable error. Table IV also shows the results of these calculations. A comparison of these values with the experimentally determined *in vitro* value of 0.053 (Table II) for pig dermis indicates that the presence of edema fluid increased the thermal conductivity of dermis two- to three-fold. This increase in conductivity, however, was slightly more than compensated by the swelling of the dermis, and thus an edematous dermis was a somewhat better heat barrier to the underlying tissues than normal dermis. A comparison of the *in vivo* thermal conductivity of dermis obtained at 45°C. with the *in vitro* value tended to indicate that intact circulation probably increased the effective thermal conductivity of dermis by about 15 per cent.

IV. Estimation of the Temperature Changes at the Epidermal-Dermal Interface During the Exposure of the Skin Surface to Heat

In view of the thinness ($\sim 80\ \mu$) of the pig's epidermis, experimental measurement of the time-temperature relationships at the epidermal-corium junction was not feasible. There are certain facts, however, that allowed the estimation of this time-temperature relationship with a considerable degree of certainty. In view of the extreme thinness of epidermis, the temperature of the basal layer was largely determined by skin surface temperature. This is most readily seen by solving heat conduction equation 3 for the steady state temperature of the basal epidermal layer. Of the four necessary experimental quantities; namely, skin surface temperature, epidermal thickness (about 80 μ), epidermal thermal conductivity (Table II), and caloric uptake of the skin at the requisite skin surface temperature (Table III), only the last two were subject to considerable variation (± 30 per cent). Fortunately, even variations of this magnitude result in uncertainties of less than 0.2°C. in the steady state temperature of the basal epidermal layer.

Basal Epidermal Temperatures When the Skin Surface Is Immediately Brought to, and Maintained at, a Temperature between 45° and 100°C.

Before the steady state temperature is attained, the time-temperature relationship at the epidermal-dermal junction is given under these conditions to a good approximation by equation 6c, where γ has the numerical value

$$(7) \qquad \gamma = 0.15$$

if the time, *t*, is expressed in *seconds*.

The numerical constant, 0.15, is not subject to the experimental uncertainties of the quantities requisite to computation by equation 6b, since this value was empirically determined [12] with considerable accuracy from data on experimental temperature-time-epidermal injury.[2] An identical value for γ can be directly computed also by substituting into equation 6b the heat capacity, thermal conductivity, and thickness of epidermis, and assuming an epidermal density of 0.8 gm. per cc., a most reasonable value. In view of the two completely independent methods, one of which was *in vivo* and the other *in vitro,* considerable confidence can be placed in the adaptation of the "infinite body picture" (section II) to the solution of the time-temperature relationship at the epidermal-dermal junction during the unsteady state period of heat flow.

TABLE V

The Computed Time-Temperature Relationships for the Epidermal-Dermal Interface When the Skin Surface Is Immediately Brought to, and Maintained at, a Specific Temperature

	Surface temperature during heat exposure				
	45° C.	55° C.	65° C.	80° C.	100° C.
Time	Temperature at basal epidermal layer*				
(*seconds*)					
0	35.0	35.0	35.0	35.0	35.0
0.01				36.3	37.0
0.02			38.9	40.9	43.4
0.05		41.8	45.2	50.3	57.1
0.1	40.1	45.2	50.3	57.9	68.2
0.2	41.3	47.6	53.9	63.3	75.9
0.5	42.7	50.4	58.1	69.6	85.1
1	43.3	51.6	60.0	72.4	89.1
2	43.8	52.6	61.4	74.6	92.3
5	44.2	53.5	62.7	76.6	95.1
10	44.5	53.9	63.4	77.6	96.6
30	44.7	54.4	64.1	78.6	98.0
60	44.8	54.6	64.4	79.0	98.6
120	44.9	54.9	64.5	79.4	99.2
300	44.9	54.9	64.7	79.5	99.3
600	44.9	54.9	64.8	79.7	99.6
Steady state†	44.8	54.5	64.2		

* Computed by means of equations 6b, 6c, and 7.

† Computed by means of equation 3 and experimental data of Table II.

The computation of the temperature of the basal cell layer of the epidermis as a function of both time and skin surface temperature is given in Table V. These data show that there was a rapid rise in the temperature of the basal epidermal layer when the skin surface was immediately brought to, and maintained at, a specified constant temperature. A comparison of the data of the unsteady state computed from equation 6c with those of the steady state obtained by means of equation 3 shows that the epidermis under the above conditions became essentially "heat saturated" after a heat exposure of 0.5 to 1.0 minute's duration.

It must be re-emphasized that these data apply only to situations in which the heat transfer coefficient, H, from the temperature source to the skin surface can be considered as infinite. In all cases where H is finite, an analysis similar to that given below is required.

Basal Epidermal Temperatures When the Entire Animal Is Surrounded by an Envelope of Ambient (Air) and Radiant Heat between 80° *and* 175°C.

In the previous discussion, the time-temperature relationships at the epidermal-dermal junction depended only upon the rate of heat transfer through the skin and the constant temperature of the heat source. To this must now be added the slow rate at which heat is transported from its source to the skin surface via air conduction, air convection, and infra-red radiation. The mathematical solution of this problem is given by equations 6 and 7 where the only quantity that requires further consideration is H, the heat transfer coefficient from the heat source to the skin surface. This quantity is readily computed through the substitution of equation 1, heat transfer by convection, and equation 2, heat transfer by radiation, into equation 5. The numerical values of the heat transfer coefficient which were obtained at particular source or air temperatures are shown in Table VI. A comparison of these values of H, 0.015 to 0.026 $\frac{\text{calories}}{\text{sq. cm. per minute per °C.}}$, with epidermal thermal conductance, K/L (Table II), numerically equal to 4 in these units, indicates the slow rate at which ambient and radiant heat was transferred to the skin surface as compared to the rate at which this heat flowed through the epidermis.

Table VI gives also the estimated temperature of the basal epidermal layer as function of source or air temperature as calculated by means of equation 6. These data show the extreme slowness of temperature rise at this epidermal-dermal junction. In fact, under these conditions, the epidermal temperature even after a heat exposure of 15 minutes was far lower than the temperature of the heat source, and actually an animal would succumb to hyperthermia[1] long before the temperature of the skin approached that of the air.

Although the data for the time-temperature relationships at the skin surface are not given, they can be readily computed by putting L (the epidermal thickness) equal to zero in equation 6. If this be done, it will be found that except for the first 20 seconds of heat exposure, the skin surface temperature was not significantly different than the values recorded in Table VI for the basal-epidermal temperature. This is due to the fact that under the conditions specified, heat transfer to the skin was the controlling factor. Thus, these data can be taken also as the temperature of the skin surface as a function of time.

A comparison of Tables V and VI indicates the importance of the mode of imparting heat to the skin surface in the epidermal time-temperature relationships. In fact, for a given source temperature, a mechanism that enables the surface temperature to be immediately brought to, and maintained at, the source temperature has, on a time basis, at least a thousand times greater propensity to injure the epidermis than a heat source which raises the skin temperature by means of radiation, and conduction and convection of relatively immobile air.[1,2,12]

TABLE VI

The Computed Time-Temperature Relationships at the Epidermal-Dermal Interface When an Entire Animal (~ 30 cm. Diameter) Is Surrounded by an Envelope of Ambient Air and Radiant Heat That Results from a Constant Temperature Source

	Circumambient temperature				
	80° C.	100° C.	125° C.	150° C.	175° C.
	Heat transfer coefficient,* H, in calories per sq. cm. per minute per °C.				
	0.015	0.019	0.021	0.024	0.026
Time	Temperature at basal epidermal layer†				
(*seconds*)					
0	35° C.	35° C.	35° C.	35° C.	35° C.
10	37	39	40.5	44	46
20				46.5	49
30	38.5	41.5	44	49	52
40				51	54.5
50	39.5	43.5	46.5	53	57
70	40	44	48	56	60
100	41	45.5	50	59	64
130	42	47	52	61	
160	42.5	48.5	54.5	63	
200	43	50	56	65	
300	45	52.5	59		
400	46	55	63		
500	47				
600	48				
800	50				
1000	50.5				
1200	51				

* In order to make these data directly comparable to the published experimental investigations,[1] the radiant contribution to H was computed by using a radiant temperature 20% in excess of the air temperature.

† Computed by means of equations 1, 2, 5, 6, 6a, 6b, and 7. Due to both the thinness of the epidermis and the slow rate of heat transport to and through the skin, there is no appreciable difference between these temperatures and those of the skin surface after the first 20 seconds of heat exposure.

V. SUMMARY

The various physical factors which determine the transfer of heat energy to and through the skin and the temperatures attained thereby have been defined and discussed. A general theory of heat flow, which enabled the estimation of the time-temperature relationships within the epidermis during exposure to heat, was developed.

The thermal conductivities and heat capacities of epidermis, dermis, and subcutanous fat and muscle were measured *in vitro*.

Experimental observations pertaining to the rate at which thermal energy is taken up by the skin, during surface exposures of varying intensity, and the sub-surface thermal gradients established therein, have been presented.

The time-temperature relationship at the dermal-epidermal junction was computed under two greatly different experimental conditions: (i) when the skin surface temperature was immediately brought to, and maintained at, the temperature of the heat source, and (ii) when the entire skin surface was exposed to specified circumambient and circumradiant temperatures. These data indicate the extreme importance of the mode of applying heat to the skin surface in the time-temperature relationships within the epidermis.

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