ANNALS OF SURGERY

Vol. 158 December 1963 No. 6

Rates of Insensible Perspiration Through Normal, Burned, Tape Stripped, and Epidermally Denuded Living Human Skin *

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THE HYPERCATABOLISM associated with mammalian thermal injuries is, under certain circumstances, somewhat related to the negative thermal load placed upon the burned, or scalded organism by the acceleration of insensible perspiration through the thermally injured skin.[7, 13] In order to make proper use of this knowledge in attempting further development of the treatment of burns and other debilitating diseases of the skin, much more needs to be learned about the quantitative relationships of cutaneous, insensible perspiration to the depth and stage of the thermal injury, to the stage of healing of donor areas, and to various dermatoses.

Because this paper is the first of a series, a review of insensible perspiration and its relationship to certain biologic parameters is included in this one, so as to constitute reference for subsequent articles.

The invisible passage of water without solute through the skin and the lungs from within the body into the air constitutes insensible perspiration. That water passes through the nonsweating skin in the form of water vapor is easily demonstrated in a cold room with a temperature of 4° C. or lower. After being in such a room long enough to be so thoroughly cold as to preclude sweating, one simply holds a 500 ml. flask filled with cold water in the cupped palm of the hand. The bottom of the held flask quickly becomes fogged by condensed water vapor over those parts of the bottom which do not touch the palmar skin. This water vapor passed through the skin outward, demonstrating that a vapor pressure gradient exists that is large enough to drive water vapor through the epidermis.

The vapor pressure of water in the wet internal mass of a living mammal is about

* Submitted for publication December 4, 1962.

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Supported in part by USPHS Grant RG-7787 (C1).

44 mm. Hg. However, the vapor pressure of water within, or just beneath the cutaneous water transpiration barrier is not exactly known but one can say that it is functionally about 20 mm. Hg because with water vapor pressures in the ambient air below 23 mm. Hg, water vapor passes from the epidermis to the air and with pressures of water vapor in air higher than 23, water vapor enters the epidermis from the air.[9, 10, 17]

By virtue of molecules of water vapor having higher kinetic energies than molecules of water, thermal energy must be supplied to water to convert it to vapor; 0.586 of a kilocalorie are required for the conversion of 1 Gm. of water at 37° C. to water vapor. Consequently, the escape of water vapor from the body through the skin and lungs represents loss of thermal energy. This energy comes from metabolism so long as the body is in an environment having a temperature lower than the body, or it is exposed to light sources imposing less absorbable radiation upon the skin than the skin is radiating outward.

These things being so, a definite relationship should exist between catabolic rate and the amount of thermal energy lost by the transpiration of water vapor through the skin and lungs within certain environmental limits. Benedict and Carpenter[1] demonstrated this, and many others have done so since. The water vapor transpirational loss of heat from a resting, fasting, normal man amounts to 19 to 30 per cent of total heat production[2] when he is exposed to the radiation from lights and radiators needed to light the calorimeter and keep its air temperature between 24 and 30° C. However, the relationship between the rate of heat loss through insensible perspiration, and total heat production varies with the environmental temperature. In quiet, normal, fasting rats living in spaces having air temperatures of 24, 28 and 32° C., the vaporizational heat loss respectively accounts for 17, 22, and 34 per cent of the total heat production.[7]

The rates of insensible transpiration have been measured indirectly and directly. Sanctorio, in 1614,[16] using a delicate balance to weigh himself, determined that insensible perspiration of a man amounted to 34 ounces during a night. During ensuing years, various balances such as those devised by Lombard and by Sauter were used for the same purpose. The Lombard balance was so rugged and sensitive that fine large graphic recordings of the changes in weight accompanying single breaths were easily made. Benedict and Root,[2] by collecting all of the water vapor given off by a man in a calorimeter, ascertained that the combined pulmonary and cutaneous insensible perspiration proceeded at rates of 25 to 40 Gm. of water/hr. They estimated that about 12 to 20 Gm. (49%) of this was cutaneous.

Kuno[11] was first to develop a direct method for the measurement of cutaneous insensible perspiration. He covered a 20 cm.^{2} area of skin with a celluloid dish. A current of dry oxygen was led continuously through this dish, and the moisture picked up by the oxygen was determined by weighing every five minutes. Kuno found the rate of movement of water vapor into the oxygen from the skin over most of the trunk and extremities (excluding soles and palms) was 1.2 to 2.9 Gm./M.^{2}/hr. Pinson[15] using a similar method, found a much higher rate of water vapor movement from the skin and discovered that the rate of insensible perspiration doubled for each 10° C. rise in ambient temperature.[15] These studies were done upon subjects whose sweat glands had been rendered locally nonresponsive to heat.

Burch and Winsor[5, 6] exposed 5 cm.^{2} of skin under a brass cup to a flow of dry oxygen for 10 minutes. The moisture in the oxygen was collected by freezing. They found that living and dead skin transmitted water at similar rates; and that the stratum

TABLE 1. *Human In Vivo Cutaneous Insensible Transpiration* (*Gm.* $H_2O/M.^2/hr.$)

	No. Tests	Mean Rate	Stand. Dev. (Gm.)
Normal skin	73	4.3	0.8
Preoperatively prepared skin	7	5.5	0.5
Donor site of split-thickness graft (6 mo. old)		5.6	
Mixed partial and full thickness burn		310. (6 da. after burn) 212. (11 da. after burn)	

corneum was most important in inhibiting water transpiration.

These studies were undertaken to develop a practical and reliable method for the direct *in vivo* measurement of water transpiration through normal and abnormal skin, and to measure the rates of insensible perspiration through burned skin, donor sites, preoperatively prepared skin, and skin afflicted by various dermatoses.

Methods

Three rotary pumps of a Benedict multiple chambered indirect calorimeter immersed in paraffin oil were used to circulate air in three separate closed systems through plastic hemispheres individually covering 120 cm.^{2} of skin. In each system the air was first passed through a U-tube containing Drierite (calcium sulfate, No. 8) to remove any moisture before exposure of the air to the skin. After exposure to the skin, the air was passed through another absorption bulb containing Drierite. The weight gain of the absorption bulbs was measured with an electromatic chain balance with an accuracy of 0.2 mg. Each air circuit system was connected to its own spirometer in order to detect any leak of air into or out of the system that might occur during the tests. A preliminary test period of 15 to 30 minutes was done before every measurement in order to remove the water vapor from within the apparatus and any water that might have been on the skin. The actual measurements were conducted for one hour upon normothermic resting men exposed to a room temperature between 21 to 24° C. The hemispheres were placed over the skin of the abdomen and thighs, and held in place with rubber straps. A light layer of grease was applied to the rim of the hemispheres before applying them in order to effect an airtight seal between them and the skin. One-half inch diameter polystyrene * tubing with walls 1.0 mm. thick was used throughout to connect the various parts of the systems. It was found on repeated test runs with the cups sealed to glass plates that the individual circuits gained 8 to 11 mgm. (.66 to .83 Gm./M.^{2}) of water per hour. This leak could not be eliminated. All modifications of the apparatus that were tried did not reduce the leak. *With rubber tubing connections the leak was 5 to 10 times faster*. This may account for the high rates of cutaneous insensible perspiration measured by Pinson.

First, a large number of measurements were conducted on skin previously shaved, washed with alcohol, acetone or ether, scrubbed with Septisol, and coated with tincture of iodine. The effects of stripping the stratum corneum from skin by repeated applications of scotch tape upon insensible perspiration were then ascer-

* In later work, the more flexible polyethylene tubing 2 cm. in diameter and 2 mm. thick was used.

TABLE 2. *Human in Vivo Insensible Transpiration (Gm. $H_2O/M.^2/hr.$) After Adhesive Tape Stripping of Skin*

Individual	Rate After 1st Strippings	Rate After Restripping
1	50.3	
2	49.1	
3	39.6	
4	25.7	68.9
5	15.5	21.9
6	11.6	
7	10.2	

tained. Biopsy specimens were used to ascertain the depth of the stripping by the scotch tape. Finally, the cutaneous transpiration rates were measured through mixed partial-full thickness burns and donor sites of split-thickness skin grafts.

Results

The data are given in Tables 1 and 2 and Figures 1 to 4.

Discussion

The examination of the effects of preoperative preparation of the skin by shaving, washing with detergents, and alcohol, and ether or acetone; and the application of the weak tincture of iodine was performed in order to ascertain whether any of the postoperative hypercatabolism might be attributable to an acceleration of the transcutaneous movement of water vapor through the preoperatively prepared skin. Obviously these experiments have ruled out such a possibility because such preoperative preparation of the skin did not affect the rate of insensible perspiration.

The rate of insensible transpiration of water vapor through normal human skin, excluding that covering the palms and soles,** is remarkably slow; it is only about 1/75th as fast as the rate through epidermally denuded dermis. A man 175 cm. in height, weight 75 kilograms, loses per hour only 6.5 to 10 Gm. of water through the skin, exclusive of that which passes through the palms and soles. This is only 160 to 240 Gm./day. It constitutes a relatively small part of the daily gross ex-

** The rate of movement of water vapor through the palms and soles is about 10 times faster than it is through the rest of the skin.[11]

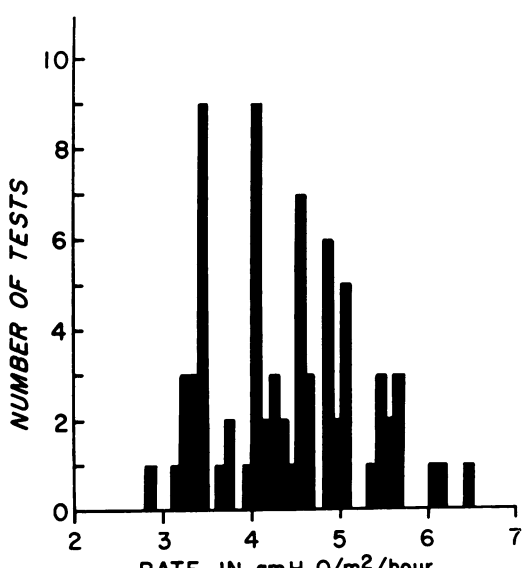

FIG. 1. Variance of cutaneous insensible transpiration through normal human abdominal skin.

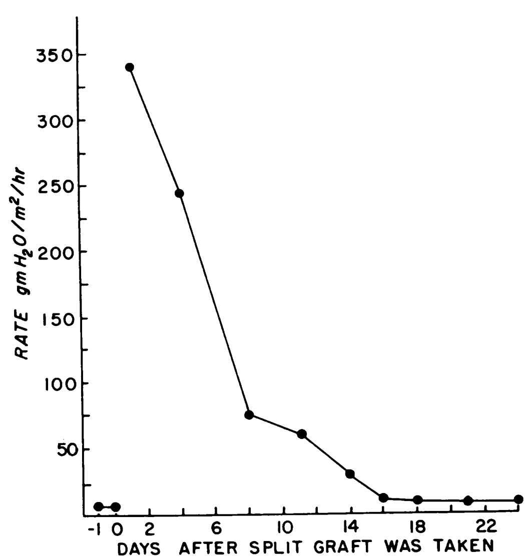

FIG. 2. Cutaneous insensible transpiration through epithelially denuded dermis—*donor site*—dog.

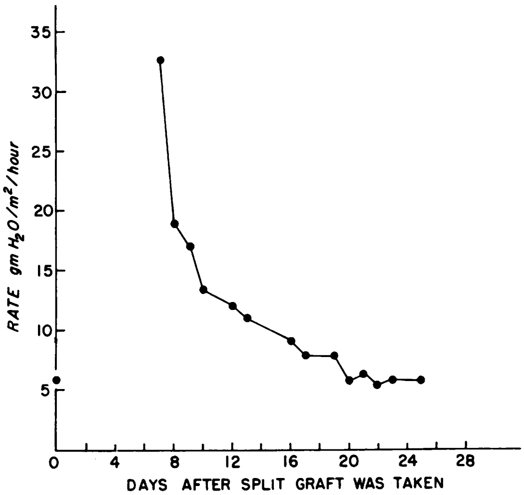

Fig. 3. Cutaneous insensible transpiration through epithelially denuded dermis—donor site—man.

cretion of water and represents a loss of heat of only 95 to 140 calories.

The rate of movement of water vapor through burned skin is very rapid. Although the burned skin was palpably and visibly dry when the measurements were made, the burned skin transmitted water vapor outward seventy times faster than normal skin during the sixth day after the burning. The rates with which water vapor is transmitted through dry burned skin and through granulation tissue approach the rates of transmission of water through epithelially denuded living dermis up to the sixth day after a split graft has been taken from it (Fig. 2, 3). These rates of transmission also approach the rate of evaporation from an open dish of Ringers'-lactate solution.[14] In other words, even dry burned skin (eschar) has essentially lost its water vapor barrier, and offers very little resistance to the passage of water vapor through it. Consequently, the badly burned person's need for water may be very great. This is shown in Table 3 which was constructed on the basis of actual measurements of cutaneous transpiration of water through dry burn eschars.

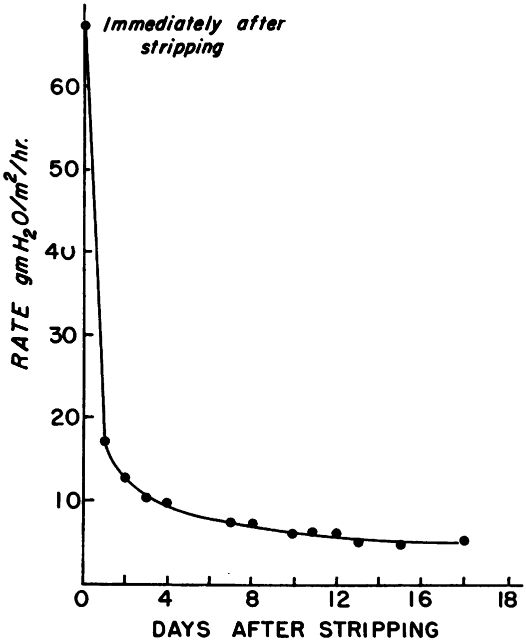

Fig. 4. Cutaneous insensible transpiration after adhesive tape stripping of human skin.

Actually, extra renal losses of water amounting to as much as eight liters daily have been measured in men with burns covering more than 70 per cent of the body while the wounds were exposed or dressed in massive dressings.*** The metabolic consequences of this rapid loss of water through the burned skin are not defined yet. However, it is known that sufficient acceleration of vaporizational heat loss is lethal for mammals kept in air having temperatures between 22 and 26° C. and water vapor tensions much lower than within the animal, conditions which are productive of steep negative thermal and vaporization gradients between animal and the environment. This was discovered earlier in this laboratory by Lieberman and Lansche[12] during the performance of experiments directed toward discovering the relationships between the rates of oxygen consumption and carbon dioxide production (catabolic rates), and the rates of vaporizational heat

*** Unpublished data.

TABLE 3. *Man—75 kg., 175 cm. height, body surface 1.9 M.² (19,000 cm.²)*

Burn % Body Surface	Parts of Body Burned	Area of burn M.²	Insensible transpiration through burned skin ml./24 hr.*	Approx. Kilocalorie equivalents 24 hr.
20	One leg, one thigh and buttock	0.38	2,700	1,600
25	One hand, one foot, one leg, one thigh and buttock	0.475	3,400	2,000
30	Two hands, two forearms, two arms, neck, face and anterior chest	0.57	4,100	2,400
35	One leg, one thigh and buttock, anterior and posterior abdomen	0.665	4,800	2,800
40	Two legs, two thighs and buttocks	0.76	5,500	3,200
45	Two legs, two thighs and buttocks and lower anterior abdomen	0.855	6,200	3,600
50	Two legs, two thighs and buttocks, and anterior abdomen and lower chest	0.95	6.800	4,000
55	Two legs, two thighs and buttocks and anterior and posterior abdomen	1.045	7,500	4,400

Part of Body	% of Body Surface
Foot	— 3
Leg	— 6
Thigh and buttock	—14
Trunk	—28
Hand	— 2
Forearm	— 3
Upper arm	— 5
Neck	— 2
Head	— 5

log surface area = log wt. kg. $\times$ 0.425 + log ht., cm $\times$ .725 + 1.8564

* Calculated from observed rate of 300 mls/M.²/hr. through burned human skin, see Table I.

loss through burns and cutaneously denuded areas of a mammalian body.

A part of their data is reproduced in Table 4. Within three hours after excising 30 per cent of the skin from an anesthetized rat, the vaporizational heat flow from the animal increased 509 Cal./M.²/day while total heat production increased only 178 Calories. Seventeen hours after the excising, total heat production was 432 Calories greater than before the skinning and the vaporizational thermal loss was 906 Cal./M.²/day larger than normal. During these 17 hours the rectal temperature dropped 2.8° C. and within the next 5 hours, it fell another 1.9° C. During the next 31 hours (17th to 48th) that the animal lived both total heat production and vaporizational heat loss decreased a little and the rectal temperature fell to 32° C. However, the total heat produced per unit time was still 157 Cal./M.²/day above normal although the speed of chemical reactions within the animal should have decreased by at least one half, assuming a Q_{10} between 2 and 3 (Van't Hoff's Law). The animal was quiet, sat tightly hunched-up and no longer shivered after the tenth hour so that muscular hyperactivity could not well account for the maintained high consumption of oxygen in the face of what should have been materially slowed rates of chemical reactions per unit concentration of reactants. At times a picture similar to the above

TABLE 4. *Changes in Catabolic Rate, Vaporization Heat Loss and Rectal Temperature Following Removal of 30 Per Cent of the Skin from an Anesthetized Rat*[12]

	Before Excising	Hours After Excising			
		3	17	24	48
Metabolic rate (Cal./M.^{2}/24 hr.)	954	1,132	1,386	1,180	1,111
Vaporization heat loss (Cal./M.^{2}/24 hr.)	246	755	1,152	1,020	974
Rectal temperature ° C.	36.8	36.5	34	32.1	32
		Dead at 50 hours			

Catabolic rate calculated from O_2 consumption and CO_2 production. Vaporization heat loss calculated from insensible perspiration, measured gravimetrically.

is seen in badly burned infants and young children. They shiver and have fever for some hours or a day or two, then their temperatures become subnormal, falling to 32 to 34° C., shivering stops, and they die.

Why did the skinned rats die? Oxidations were measurably proceeding at normal rates and the animals, although hypothermic, were in thermal equilibrium for at least 20 hours before dying. Is mammalian life dependent upon the maintenance of a narrow range of relationship between the rate of chemical reactions and entropy? If the rates of cellular chemical reactions were half normal, by virtue of the decline in body temperature of 5° C., then entropy needs increase remarkably in order that heat production shall proceed at normal rate. There is another possibility: Is mammalian life dependent upon the maintenance of a limited proportionality between concentrations of chemical reactants and internal body temperature? A sufficient increase in the concentrations of chemical reactants while body temperature decreases could sustain the rate of oxidation and heat production without change in entropy. Should this be the case, enzyme concentrations, or activities should increase as body temperature falls consequent to an acceleration of vaporizational heat loss during negative environmental heat loading. Dr. Falls B. Hershey is now investigating this possibility.

Whatever might be the case, the fact remains that the loss of the cutaneous water vapor barrier by burned, or scalded skin might well be one of the major factors leading to the death of a badly burned mammal.

A number of other questions naturally arise: Where is the cutaneous water barrier located and what is its nature? How rapidly is it regenerated after its physical removal?

The barrier is located in the stratum corneum.[3-6, 8, 14] Simple stripping of epidermis of a part of the stratum corneum by repeatedly applying scotch tape to and quickly pulling it away from the skin materially accelerates the cutaneous insensible transpiration of water vapor.[4] We have confirmed this (Table 2). Within three to six days after stripping, the skin regains its normal resistance to the passage of water vapor through it (Fig. 4). The complete removal of the transpiration barrier by taking a thin, split graft from the skin is attended by an increase in the rate of cutaneous insensible transpiration of 60- to 70-fold. The restoration of the barrier, after a graft is taken, takes place rapidly in the dog and human being; within eight to 16 days after the epidermis is cut away from the dermis with a knife, the barrier has been regenerated (Fig. 2, 3). Barrier regeneration and reepithelization take place simultaneously. The water vapor barrier generated after epithelization of a donor site is permanent (Table 1).

The fact that the water barrier in the stratum corneum is not affected by subjecting the stratum corneum of excised, isolated skin to temperatures of 100 to 400° C., unless steam-blisters effect widespread physical ruptures of the stratum corneum,[14] indicates that leaving blisters alone, and replacing partially torn-off surfaces of burn bullae should materially reduce the rate of loss of water vapor through partial thickness burns and scalds.

Water vapor impermeable plastic films such as Saran Wrap have been found to stop the supernormal transpiration of water vapor through epithelially denuded partial thickness burns and through burn eschars and granulation tissue,[12] but because such films are impermeable to bacteria and pus, they soon constitute the outer walls of abscesses. Spray-on paraffin films have the same infection drawback and in addition, they break with such ease and quickness that they do not for long serve as a water barrier. Thick vaseline (grease-gauze) dressings applied to burn wounds tend to told water vapor in the body, but they too hold in pus and bacteria. Obviously, the restoration of the water vapor barrier to burned skin before re-epithelization is effected, requires the definition of the chemical nature and mode of action of the normal cutaneous water vapor barrier.

Until such time as this is accomplished, the only way to easily and safely stop the very rapid loss of water vapor through burned skin while maintaining normal concentrations of solutes that exchange across the eschar * is to submerge the injured parts in warm Locke's solution.[13] Maintenance of the sterility of the Locke's bath is a problem that to date has not been solved. Continuous filtration through large millipore filters is now being tried. The application of preserved, or fresh cutaneous homografts to open wounds reduces insensible perspiration through the wound to normal.

* Most notably: Na^+, K^+, Ca^+, Mg^+, HCO_3^-, Cl^- and $H_2PO_4^-$.

Summary

A simple gravimetric method for the measurement of the rate of cutaneous insensible perspiration in human beings was developed.

The rates of cutaneous insensible perspiration were measured through normal, burned, stripped, and preoperatively prepared skin; and through epithelially denuded dermis.

Skins preoperatively treated with shaving, scrubbing with a liquid soap and water, washing with alcohol, acetone and ether, and covering with weak tincture of iodine transmitted water vapor at normal rates.

Dry burn-eschar transmitted water vapor to the air 75 times faster than normal skin; as also did epithelially denuded dermis.

Donor sites for split thickness grafts recovered normal resistances to the passage of water through them in eight to sixteen days.

Stripping a part of the stratum corneum from the skin with an adhesive tape accelerated insensible perspiration 10- to 20-fold. Tape-stripped skin fully regained its water vapor resistance in three to six days.

Some of the possible biologic connotations of large accelerations of cutaneous insensible perspiration and methods of reducing the rapid rates of loss of water through burned skin are discussed.

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