Effect of Sweating and Changes in Blood Flow on Heating of Human Skin. (22441)

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Much of the experimental work on heat injury concentrates around the nature and quantitation of the stimulus and neglects the nature and quantitation of the tissue response. This report is an attempt to use a controlled intensity of thermal radiation and to examine the effects of sweating and changes in blood flow on the rate of heating of the skin.

Methods. Four cm^2 of the volar side of forearm was exposed to thermal radiations produced by 1,000 watt projection lamp. The intensity was 100 $mc/sec/cm^2$, with wave lengths of 0.5-3.8 μ with peak at 1.5 μ. Due to difficulties of determining reflection and absorption of normal human skin, the evaluation is limited to comparison of various physiological conditions. However, if the skin is painted with India ink, 96% of incident heat energy is absorbed at skin surface. Transmission from India ink into the skin is mainly by conduction. If intensity of incident radiation and temperature rise of skin are known, the thermal characteristics of skin can be calculated. A rapidly recording radiometer measured surface temperature of the skin(1). Heating of a body is determined by conductivity (k), density (ρ), and specific heat (c). The product of these heating characteristics was calculated from the formula: $k\rho c = \frac{1.13\ Q^2 t}{\Delta T^2}$, in which 1.13 = constant for blackened human skin; Q = intensity of incident radiation in $mcal./sec./cm^2$; t = time of exposure in sec.; ΔT = difference between skin temp. at time t and initial skin temp. in °C. The formula is based on Buettner's work(2) and indicates that, for a given intensity of radiation absorbed at tissue surface, the greater the $k\rho c$ the less will be the surface temperature rise over a given time interval (3). Heat loss by convection by flowing blood and by vaporization from the skin are not included in the formula. Therefore, the $k\rho c$ concept is used here as an indication of physiological changes. Subcutaneous temperatures were measured with steel-constantan loop thermocouple, ten thousandths of an inch in diameter, soldered end to end and drawn through the skin at a depth of about 1 mm. No attempt was made to measure subcutaneous temperature while skin was exposed to radiation. Subjects for these experiments were laboratory workers between ages 23-42 years. While one arm served as control, the following procedures were carried out on the other arm: 1. Changes of rate of sweating(4) produced by: a. Intradermal inj. of 0.1 cc of atropine (1.25 mg/cc to inhibit sweating; b. Intradermal inj. of 0.1 cc of acetylcholine (100 mg/cc) to increase sweating; c. Intradermal inj. of 0.1 cc of saline as control. The bleb formed by intradermal injection was about 0.5 cm diameter. The effect of the 2 drugs on rate of sweating covered an area considerably larger than 16 cm^2 field of experimental measurement. Changes of blood flow and blood content were produced by: a. Total obstruction of blood flow: arm was raised above heart level for 1 minute and pressure cuff applied above elbow with pressure of 200 mm Hg; b. Venous congestion: pressure in cuff was 80 mm Hg; c. Reactive hyperemia: on release of pressure cuff following procedures a and b, a deep flush of reactive hyperemia which persisted about 3 minutes.

Results. Influence of sweating on heating of skin. Fig. 1 shows the increase of skin temperature with time for a radiation intensity of 100 $mc/sec/cm^2$, and decrease of temperature when the heating was stopped upon reaching the pain threshold. With atropine (inhibition of sweating) rates of increase and of decrease are markedly enhanced. Acetylcholine (increased sweating) produces the opposite result. With acetylcholine, the $k\rho c$ was 82% higher, and with atropine 14%

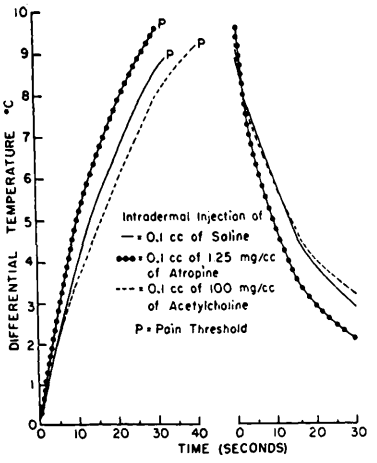

FIG. 1. Influence of pharmacologically induced sweating on heating of normal white human skin.

lower, than the control. The damaging effect of heat is a function of temperature and time of exposure of the skin above 45°C(5,6). Therefore, to determine injurious effects of heat, results are plotted in terms of temperature instead of temperature rise above initial skin temperature. This was done in Fig. 2. The initial skin temperature of the atropine experiment was higher, and that of the acetylcholine experiment lower than the control. This difference of initial skin temperature increases individual differences of heating curves. Even if no actual injury is produced in these experiments, the results are considered an indication that sweating has a protective value against thermal radiation injury.

Influence of changing blood flow and blood supply. Fig. 3 shows effect of total obstruction of blood flow with and without thermal radiation. Epidermal and subcutaneous temperatures during total obstruction of blood

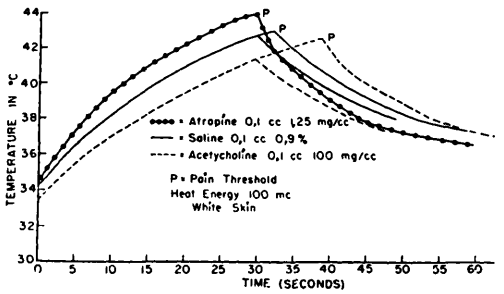

FIG. 2. Influence of sweating on temperature of normal skin exposed to thermal radiation.

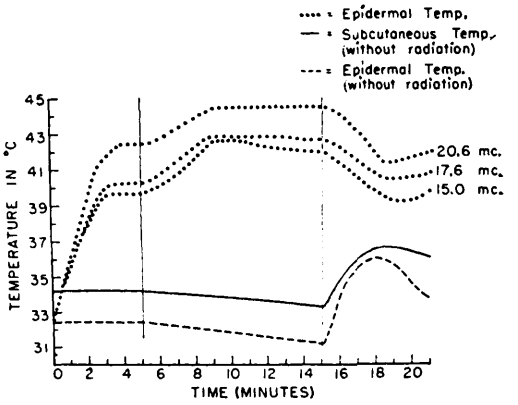

FIG. 3. Effect of prolonged total obstruction of blood flow on normal skin exposed to various levels of thermal radiation.

flow but without radiation are shown at bottom of the graph. Subcutaneous temperature in general follows the epidermal temperature, but to a less extent. Both fall on obstruction and increase on release of pressure cuff. If the arm is exposed to various levels of heat energy, a temperature change in the opposite direction occurs. Before pressure is applied, the temperature goes up and finally comes to an equilibrium. On occlusion, temperature rises again and comes to an equilibrium at a higher level. On release of the pressure cuff, there is a marked decrease in temperature. The $k\rho c$ value goes down during the obstruction and up again during the reactive hyperemia (Table I).

Fig. 4 shows a similar experiment on the effect of venous congestion. The epidermal and subcutaneous temperatures show very lit-

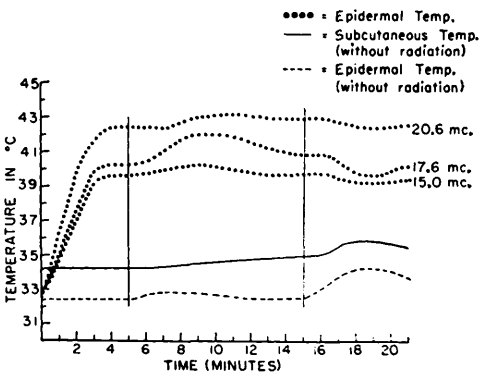

FIG. 4. Effect of prolonged venous obstruction on normal skin exposed to various levels of thermal radiation.

tle change during the experiment and a slight rise during the period of reactive hyperemia. The effects of thermal radiation are not very marked either. The $k\rho c$ in these 2 experiments was determined in 2 different ways: first, the skin (India ink) was exposed to 100 mc/sec/cm^2 of thermal radiation and the increase in skin temperature was determined; second, the skin was exposed to a constant radiation of 15 mc/sec/cm^2 and, intermittently, the energy was increased to 100 mc/sec/cm^2. As far as relative difference between control and various experimental procedures is concerned, the two methods agree fairly well (Table I). However, there is a difference in absolute level of the 2 methods of determination, indicating that heating of the skin increases the $k\rho c$, independent of the other experimental procedures.

TABLE I.* Influence of Blood Flow and Blood Content on Heating of the Skin.

	(1)	(2)	(3)			(4)	(5)	(6)	(7)	(8)
	Epidermal temp.	Subcut. temp.	Equilibrium skin temp. 14 mc/sec/cm^2	17.6 mc/sec/cm^2	20.6 mc/sec/cm^2	Pain threshold	Differential temp. (T_t-T_o)	Time to pain threshold (T_p-T_t),	$k\rho c \times 10^{-5}$ normal skin	$k\rho c \times 10^{-5}$ radiated skin
			°C					sec	cal^2/cm^4/°C^2/sec	
No. of determinations	12	4	4	4	4	8	8	8	8	4
(a) Control	32.4	34.2	39.6	40.2	42.4	44.2	11.8	40	77 ± 2.5	102
(b) Total obstruction	31.2	35.3	42.6	42.8	44.5	44.7	13.5	51	64 ± 2.9	99
(c) Passive hyperemia	34.6	35.9	39.2	40.4	41.3	44.9	10.3	37	85 ± 3.4	112
(d) Venous congestion	32.8	35.0	40.2	42.0	43.1	45.0	12.2	41.6	72 ± 4.7	102
(e) Passive hyperemia	34.2	35.9	39.2	39.6	42.4	44.6	10.4	34.6	78 ± 3.5	109
(f) $\frac{(b)+(d)\dagger}{2}$	32.0	35.15	41.4	42.4	43.8	44.85	12.85	46.3	68	100.5
(g) (d) − (b) Blood content	+1.6	-.3	-2.4	- .8	-1.4	+.3	-1.3	-9.4	+ 8	+ 3
(h) (e) − (f) Blood flow	+2.6	-.65	-2.2	-2.0	-2.5	+.05	-2.55	-9.3	+17	+11.5

* Each figure represents mean of 8 determinations. † Derived value for normal blood content without blood flow.

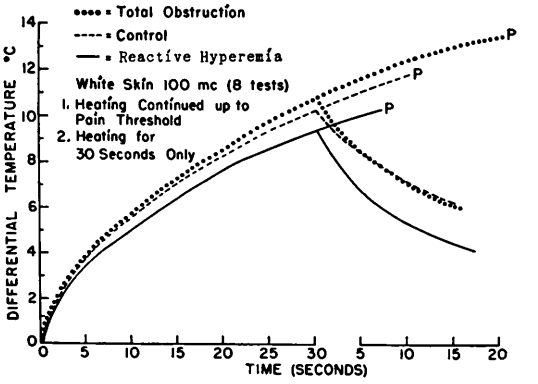

FIG. 5. Effect of blood flow on the heating of normal skin.

Fig. 5 gives the rise above initial skin temperature under the 3 experimental conditions, and the return towards normal after 30 seconds of heating. Reactive hyperemia with the highest $k\rho c$ shows the slowest rise of temperature, and total obstruction with the lowest $k\rho c$ shows the highest temperature. However, Fig. 6 indicates that the initial temperature is so high in reactive hyperemia and so low in total obstruction that the final tem-

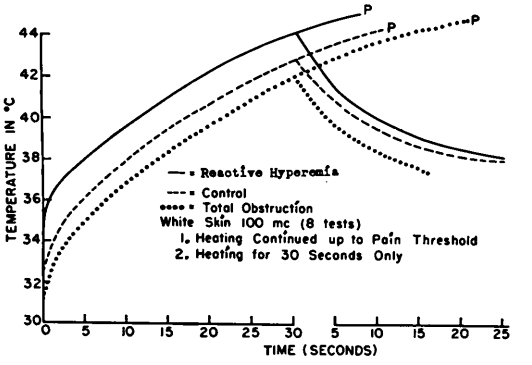

FIG. 6. Effect of blood flow on temperature of normal skin exposed to thermal radiation.

perature after 30 seconds of exposure is influenced more by the difference in the initial temperature than by difference in the $k\rho c$ values.

Discussion. As $k\rho c$ of water is higher than that of the skin(6), the increase of $k\rho c$ during sweating, in these experiments, was expected. This increase may also be explained by increased evaporation from the moist skin surface. To differentiate between these 2 factors, India ink painted skin was exposed to a radiated energy of 100 mc/sec/cm^2 with and without being wetted with tap water. The wet skin was about 3 degrees cooler throughout 15 seconds of heating and the first 15 seconds of cooling. In this experiment there was a continuous layer of moisture superficial to the India ink, while in the sweating experiments evaporation may actually be inhibited by the overlaying India ink. Therefore, it is felt that vaporization may account for some of the effects observed, but that changes of $k\rho c$ cannot be neglected. This idea is supported by changes observed after atropine, which are mainly due to change of $k\rho c$, with little change in vaporization.

In the blood flow experiments, we have to differentiate between blood content of tissues and blood flow through the tissues. In total obstruction, blood content is decreased and blood flow is stopped. In venous congestion, blood content is increased and blood flow is practically nil. Therefore, comparing these 2 conditions, we should get the effect of blood content of the tissues. This difference was calculated in line (g) Table I. This increase in blood content increases the $k\rho c$ 14% and the equilibrium skin temperature under radiation is lowered.

The most pronounced rise of skin temperature, indicating an increase of blood flow, was obtained after release of the pressure cuff following total obstruction. However, to compare this condition of increased flow with a condition of similar blood content but without blood flow, we have to take some state between total obstruction and venous congestion, as the blood content in reactive hyperemia is surely higher than in total obstruction and lower than in venous congestion. These derived values are given in line (f) Table I. The difference between reactive hyperemia (line (c) Table I) and the derived control (line (f) Table I), yields the effect of blood flow as shown in line (h) Table I. The changes found for the effect of blood flow are in the same direction as those found previously for the effect of changes of blood content, but they are more pronounced. In these blood flow experiments the initial skin temperature and the $k\rho c$ go in opposite directions. In the short time exposure given in Fig. 6 the difference of initial temperature determines final skin temperature, while in the long time exposure of Figs. 3 and 4 the equilibrium temperature is determined by difference of $k\rho c$. We can expect a similar reversal if, instead of prolonging the time, we increase the energy of radiation.

In reactive hyperemia, the slope of the temperature increase in time is very low. We would expect a correspondingly slow fall; actually the temperature decrease with cessation of radiation is fastest in reactive hyperemia. It is assumed that this is due to heat being carried away by the blood stream.

Column (4) Table I gives the pain threshold in terms of tissue temperature, which is slightly raised over the control. This increase is considered to be due to secondary pain caused by the procedure itself and no difference between the individual procedures was found. However, the temperature increase and the time to reach the pain threshold are dependent upon the initial skin temperature.

Summary and conclusions. 1. Acetylcholine-induced sweating decreases and atropine-induced inhibition of sweating increases heating effects of radiated heat energy. Increased blood content of tissues has a slight effect and increased blood flow a more pronounced effect on lowering the heating effect. 2. The effects of sweating appear to be due partly to vaporization of water at the skin surface and partly to a change in the thermal characteristics of the skin itself. 3. Increased blood flow through the skin raises the temperature and therewith increases the heating effects of low-energy, short-time radiation. However, the

thermal characteristics of the skin are changed in a way to combat these heating effects. Therefore, the harmful effects of high energy and long term radiation are decreased. 4. Pain threshold is frequently measured as temperature elevation or as reaction time, and then it is markedly affected by changes in blood flow and rate of sweating. However, if it is studied in terms of tissue temperature, it is independent of these physiological variables.

1. Hardy, J. D., *J. Appl. Physiol.*, 1953, v5, 559.

2. Buettner, K., *ibid.*, 1951, v3, 691.

3. Lipkin, M., and Hardy, J. D., *ibid.*, 1954, v7, 212.

4. Benjamin, F. B., *ibid.*, 1953, v5, 594.

5. ———, *ibid.*, 1952, v4, 907.

6. Henriques, F. C., and Moritz, A. R., *Am. J. Path.*, 1947, v23, 695.

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Antagonism of Diuretic Action of Thyroxine by Ethanol. (22442)

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Pretreatment with thyroxine causes an increase in the rate of excretion following the administration of a water load in the dog(1) and in the rat(2). Since ethanol also elicits a diuresis(3,4), these two substances were combined in an attempt to produce a diuretic response suitable for use in the biological assay of the antidiuretic hormone (ADH). Contrary to expectations, ethanol was found to abolish the diuretic action of thyroxine.

Materials and methods. Four groups of animals, each containing 12 female rats weighing approximately 200 g, were used in this experiment. The control groups and the rats that were pretreated with thyroxine were gavaged with distilled water or 8.5% ethanol in an amount equivalent to 7% of the body weight. The resulting diuresis was quantified by placing 4 rats in each urine collection cage and measuring the volume of urine from each cage at 15 minute intervals until the urine flow returned to normal. The cumulative volume of urine excreted by each group of rats was then converted to the per cent of the total water load excreted and plotted as a function of time. Pretreatment with thyroxine consisted of the daily intraperitoneal injection of 20 μg of thyroxine for 7 days prior to the gavage with distilled water or ethanol. Two groups of pretreated rats were given the water and ethanol loads intraperitoneally in order to determine if the ethanol was interfering with the absorption of the fluid from the intestine.

Results. As shown in Fig. 1, ethanol prolongs the diuresis following the administration of a water load whereas pretreatment with 20 μg of thyroxine per day results in an increased rate of excretion. Both of these treatments lead to the excretion of a greater percentage of the water load than that observed in the untreated controls. However, when pretreated rats are gavaged with ethanol, the diuretic response is similar to that observed in the rats which received no pretreatment with thyroxine. Thus the ethanol abolishes the diuretic action of the thyroxine.

Since the excretion of the water load by all 4 groups of animals is linear from 75 to 135 minutes after the gavage, the differences in the rates of excretion observed during this period were analyzed statistically using the Analysis of Variance (2 way classification) method(5). The rate of excretion of the water load by the rats pretreated with thyroxine differs significantly ($P<0.005$) from the rates exhibited by the other groups but

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