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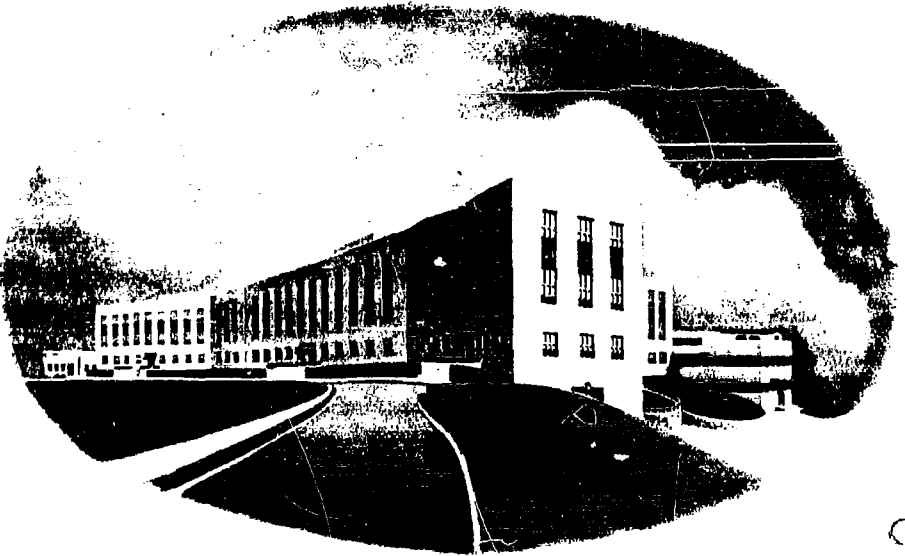## NAVAL MEDICAL RESEARCH INSTITUTE

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ELEVATION OF INTERNAL BODY TEMPERATURES
DURING TRANSIENT HEAT LOADS AND AT THERMAL EQUILIBRIUM

RESEARCH REPORT

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Report No. 1

ELEVATION OF INTERNAL BODY TEMPERATURES
DURING TRANSIENT HEAT LOADS AND AT THERMAL EQUILIBRIUM

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RESEARCH REPORT

ABSTRACT

Thermoregulatory responses of human subjects undergoing heat stress were studied utilizing a variety of environmental conditions, clothing, and work rates. Internal body temperatures were measured in the lower esophagus (t_o), ear (tympanic membrane) (t_e), and the rectum (t_r). Skin temperatures, heart rate, sweat rate, and metabolic rate were also measured. At low rates of heat storage (5 to 25 Cal/M^2 hr), the rates or rise of t_o, t_e, and t_r are approximately identical. During more rapid heat storage 50 Cal/M^2 hr), the rates of rise of t_o and t_e are about equal and more rapid than that of t_r. When heat storage is greater (89 to 90 Cal/M^2 hr), the rate of rise of t_o is greater than that of t_e. During work in the heat in which thermal equilibrium is attained, t_o and t_e reach equilibrium considerably sooner than does t_r, and the mean increase in t_r is 20 to 40% greater than that of t_e or t_o. It is concluded that t_o and t_e are more sensitive indicators of changes in internal temperature than is t_r during transient conditions, and t_r is a more reliable index of attainment of thermal equilibrium than are t_o or t_e.

INTRODUCTION

For several decades, investigators in the field of temperature regulation have utilized the concept of the body being separated into a "core" where temperature is held relatively constant and a peripheral "shell" consisting mainly of skin, subcutaneous tissues, and extremities, in which temperatures fluctuate relatively widely and which participates importantly through its vasomotor and sudomotor mechanisms in maintaining the constancy of the core temperatures. In the homeotherm, this constancy is maintained despite the wide swings in the temperature of the environment and changing patterns of activity. Nonetheless, it has long been known that even under resting conditions temperature gradients exist between central regions of the body (1). We have recently reviewed the literature describing regional internal body measurements at many different sites (2), including rectum (3-6, 11), mouth (3-7), lower esophagus (6, 8-10), stomach (11, 12), central vessels and chambers of the right heart (10, 13, 14), mucosa of accessory nasal sinuses and nasopharynx (15, 16), tympanic membrane (15, 16), jugular vein (13), jugular bulb (17), hepatic vein (13, 18), and liver parenchyma (18).

Under resting conditions, rectal temperature in man is one of the highest temperatures in the body core (table 1), being significantly higher than temperatures in central arteries and veins and equalled only by

Table 1

Internal Temperature Gradients in Resting Human Subjects Related to Rectal Temperature

Body Region	No. of Subjects	Temperature Gradient		Author
		°C	°F	
Mouth	46 [a]	-0.45	-0.81	Tanner (5)
	40 [a]	-0.35	-0.63	Cranston, Gerbrandy and Snell (6)
Esophagus	40 [a]	-0.24	-0.43	Cranston, Gerbrandy and Snell (6)
	6 [b]	-0.6	-1.08	Carlsen and Grimby (10)
	4 [b]	-0.26	-0.47	Minard and Copman (2)
Gastric	75 [a]	-0.07	-0.13	Graf (18)
Tympanic membrane	4 [c]	-0.18	-0.32	Minard and Copman (2)
Sphenoid sinus	1	-0.45	-0.81	Benzinger (16)
Nasopharynx (Rosenmuller's Fossa)	1	-0.45	-0.81	Benzinger (16)
Jugular vein:				
Jugular bulb [d]	·	+0.2	+0.36	Bazett (17)
Jugular v. (high)	4 [a]	-0.01	-0.02	Eichna et al. (13)
Jugular v. (low)	15 [a]	-0.22	-0.40	Eichna et al. (13)
Superior vena cava	19 [a]	-0.35	-0.63	Eichna et al. (13)
Right heart:	6	-0.6	-1.08	Carlsen and Grimby (10)
Artrium	24 [a]	-0.26	-0.47	Eichna et al. (13)
Ventricle	17 [a]	-0.23	-0.41	Eichna et al. (13)
Inferior vena cava:				
Low	7 [a]	-0.26	-0.47	Eichna et al. (13)
High	10 [a]	-0.22	-0.40	Eichna et al. (13)
5-8 cm below diaphragm	3	+0.4	+0.72	Mellette (14)
Liver	75 [a]	-0.21	-0.38	Graf (18)
Hepatic vein:	75 [a]	-0.125	-0.225	Graf (18)
Near Inf. vena cava	6 [a]	-0.09	-0.16	Eichna et al. (13)
Deep in liver	6 [a]	-0.03	-0.05	Eichna et al. (13)
Femoral artery	22 [a]	-0.22	-0.40	Eichna et al. (13)
Subclavian artery	3	+0.3	+0.54	Mellette (14)

a. See original article for standard diviation or standard error of the mean.
b. Standard deviation from the mean = 0.10° C (0.18° F) in 17 experiments.
c. Standard deviation from the mean = 0.10° C (0.18° F) in 21 experiments.
d. Related to external iliac artery temperature (not rectal temperature).

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the blood draining the liver (13) and the brain (13, 17). These two regions are thus cooled rather than warmed by arterial blood. Direct temperature measurements in the human brain have not been reported, but the warming of blood in its intracranial circuit indicates that the net thermal gradient is from brain tissue to blood. In experimental animals, temperatures in the hypothalamus are higher than rectal temperature and regional variations in temperature occur within the hypothalamus itself (19).

Under steady-state conditions, heat flows at uniform rates from the sites of its production to the cooler blood or to the surrounding tissues and external environment. Temperature gradients between regions of the body core and between core and surface thus remain fixed. Increased heat production or decreased heat loss results in changes in these gradients, and leads to thermoregulatory responses which establish a new body temperature equilibrium at a higher level when the heat loads are within tolerable limits.

Various investigators have noted unequal rates of change in regional temperatures of the body during nonsteady states, such as induced hyperthermia (20), muscular exercise (14, 18), induction and recovery from experimental hypothermia (11, 12) or hypothermia induced for surgical procedures (8, 9) in febrile responses to bacterial pyrogens (21), during the action of pharmacologic agents (18), following the digestion and absorption of food (18), and during external and internal heating and cooling of the body (15, 16, 22).

In general, results of these investigations have demonstrated regional differences in the rate of warming or cooling during transient heating or cooling of the body. Temperatures in the central veins and right heart respond more quickly than other regions, and rectal temperatures more slowly. Esophageal temperature is equal to right heart temperature at rest (10) and is more responsive than the rectal temperature.

Benzinger has shown that temperatures measured in accessory nasal sinuses, in the nasopharynx and at the tympanic membrane parallel one another closely during rapid transient heating or cooling, whereas the rectal temperature may lag well behind these temperatures (15, 16).

EXPERIMENTAL STUDIES OF INTERNAL TEMPERATURE GRADIENTS IN STEADY STATES AND DURING HEAT STORAGE

Rectal temperature (t_r) has long been used in most animal studies and almost all human studies as the index of core temperature. However, the validity of the use of t_r to represent internal body temperature in formulating theories of thermoregulation has recently been questioned, and the idea that perhaps other sites may be more suitable as an index of internal temperature has prompted the studies to be described below.

Experiments were designed to measure deep body temperature simultaneously in three sites (rectum, tympanic membrane, and esophagus) under the following experimental conditions: during thermal equilibrium at rest, after 1 to 2 hours of standard exercise, and following recovery; during slow storage of body heat in a resting subject following abrupt elevation of ambient vapor pressure; during moderately rapid storage of body heat in a resting subject which results when heat loss is completely blocked, and during very rapid heat storage in a subject performing extremely heavy work in the heat.

In addition, some results of an applied problem that was concurrently being studied in our laboratory, i.e., evaluation of the heat stress imposed on the wearer by an impermeable protective suit for use after an attack by radiological, chemical or bacterial warfare agents, were found to be applicable to the problem under investigation here since the physiological variables monitored were the same. Insofar as they are pertinent, some findings of this study are included in this report.

PROCEDURE

Subjects

All subjects were Naval personnel who had volunteered as thermal stress subjects. The subjects' initials, age, height, and weight are included in table 2. All subjects were physically fit but no special

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Table 2

Physical Characteristics of Thermal Stress Subjects

Subject	Age	Weight (kg)	Height (cm)	Surface Area (M^2)
CRL (CL)	26	71	169	1.84
RLO (RO)	33	89	178	2.04
LC	29	67	177	1.84
DM	49	80	180	2.02
RCH	21	67	172	1.79
RJL	21	73	177	1.86
ARD	29	87	185	2.12

acclimatizing procedures were used. Each subject was exposed to heat at least once and usually twice a week either as a subject or as a technical assistant or scientific observer.

Temperature Measurements

Rectal temperature (t_r) was measured by a copper-constantan thermocouple embedded in polyethylene and sealed in the copper tip of a 16 Fr. rubber cather inserted to a depth of 10 cm. beyond the internal sphincter.

Tympanic membrane temperature (t_e) was measured with a thermocouple in the form of a loop which was held in place by a standard rubber ear plug (figure 1). This modification of Benzinger's ear probe
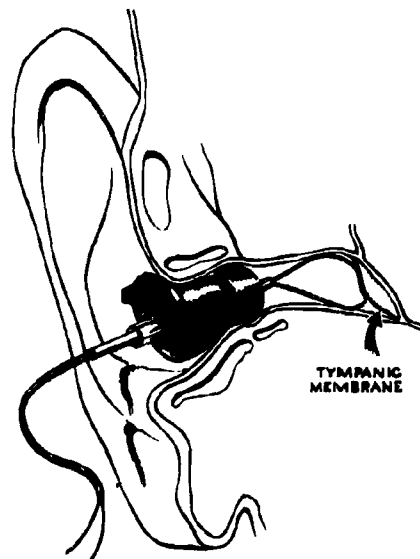
Figure 1. - Schematic representation of the thermocouple used to measure temperature at the tympanic membrane. The thermojunction is centered at the midpoint of the loop which can be advanced and retracted with the earplug seated in place.

permits the subject freedom of exercise and movement. In the later experiments, Benzinger's modified probe (23) was used (figure 2). Both designs were tested against each other and found to be equally

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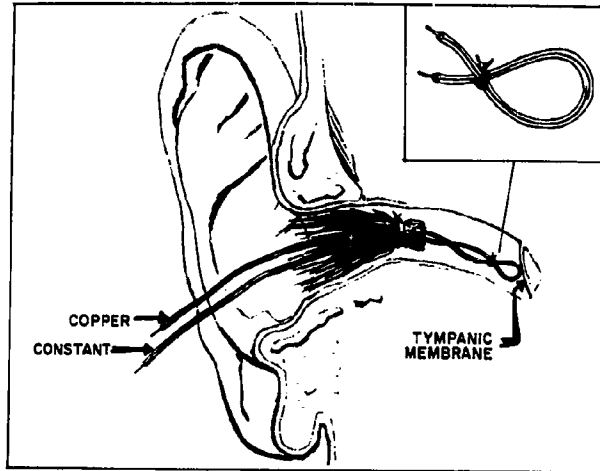
Figure 2. - Brush-type ear thermocouple of Benzinger (23). Without frame or plug, this thermocouple holds itself in place with mild pressure.

accurate, but that of Benzinger was more easily manipulated and better tolerated by the subject. The thermojunction is formed from 36 gauge copper and constantan wire soldered end to end with a short overlap and threaded through small gauge polyethylene tubing (0.6 mm o.d.), the thermojunction being accurately positioned at the midpoint of the loop. Additional thermal insulation was provided by a cup-shaped plastic ear defender (MSA Noisefoe Mark II) which covered the entire external ear. In later experiments, the cup-shaped rubber inner element was removed from the defender and used alone.

Esophageal temperature (t_0) was measured with a copper-constantan thermocouple embedded in the tip of a polyethylene tube, the thermojunction being located 43 cm. from the incisors.

In all experiments, skin temperature was measured at 10 points. Each point could be recorded individually or the mean skin temperature could be recorded as the unweighted mean of the 10 junctions, following a modification of the procedure of Teichner (24). Figure 3 illustrates the positions of the thermocouples in our experiments.

PHYSIOLOGICAL INSTRUMENTATION OF THERMAL STRESS
SUBJECTS (Human)

Figure 3. - Diagram illustrating placement of thermocouples in thermal stress experiments.

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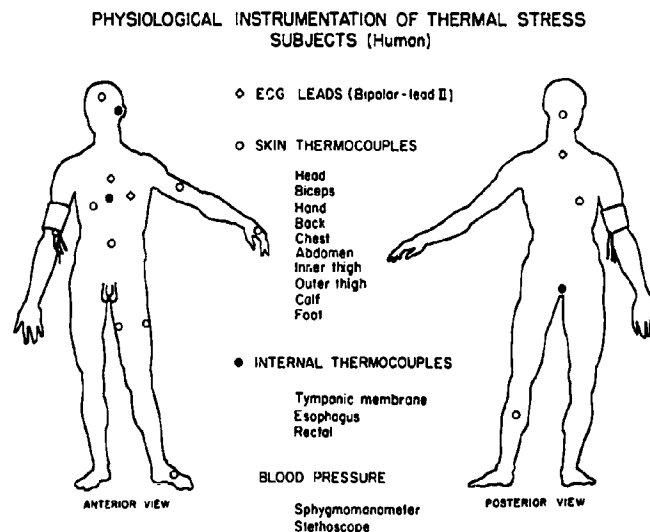Reference junctions were situated in a stirred water bath accurately regulated at 39.00° C (102.2° F). Bath controls created a temperature cycle of ± 0.01° C (± 0.018° F) which was damped out by positioning the reference junctions inside an open-mouthed 4-liter Erlenmeyer flask resting at the bottom of the stirred bath.

The thermoelectric emf from each of the three internal thermocouples was amplified 100 times by a stable breaker-type dc amplifier before being recorded on a standard multipoint 10 mv recording potentiometer. At the gain setting of the preamplifier, the 24 cm strip chart provided a recording range of 36.60 to 39.00° C (97.9 to 102.2° F). If the internal temperature exceeded 39° C, the zero baseline could be shifted from the left to the center of the record increasing the upper range to 40.4° C (104.7° F).

Environment

Air temperatures in the test chamber ranged from 23.9° C (75° F) dry bulb and 18.4° C (65° F) wet bulb, to 35.5° C (96° F) dry bulb and 27.8° C (82° F) wet bulb in different experiments. Air movement was minimal (< 50 fpm).

Heart Rate

Specially constructed cup-like electrodes made of Teflon were applied to the skin with collodion after filling the cups with electrode jelly. Depending on the electrical axis of the subject's heart, either the manubrium-xiphoid or manubrium-apex lead was employed in order to obtain an R-wave of maximum height. An electrode over the spinous process of the seventh cervical vertebra served as a ground lead. The input was led via a cable from the subject into a Waters Model C224 or C225 cardiotachometer. The output of this instrument was continuously monitored on the multipoint 10 mv recording potentiometer. Periodic ECG tracings were recorded on a Sanborn electrocardiograph. In recent experiments, a Telemedics RKG-100A telemeter was employed to transmit and record the electrocardiograph, using transthoracic or M-X positioning of the electrodes.

Metabolic Rates

Samples of the subject's expired air collected in a Tissot spirometer were analyzed and the metabolic rate calculated by indirect calorimetry. In the earlier experiments, the air was analyzed for oxygen and carbon dioxide by the Scholander method (25). In the later experiments, the air was analyzed for oxygen alone using a Beckman E-2 oxygen analyzer. Caloric equivalent was estimated using the Weir formula (26). Several comparisons using both methods showed no significant difference and justified using the latter method in this type of experiment.

Weight Loss

In most of these experiments, the subject was weighed at periodic intervals of 15 or 30 minutes using a Buffalo Model 1100 beam-balance scale, specially constructed for use with human subjects, accurate to ± 5 grams. In the suit experiments, the subject was weighed before entering and after removing the suit.

RESULTS

Rest, Work and Recovery

Figure 4 is an example of an experiment in which subject CRL sat at rest clothed in shorts and low shoes until attaining temperature equilibrium. He then worked one hour by stepping up two 6-inch steps and then back down 10 times per minute, the metabolic rate being 150 Cal/M^2 hr. He returned to the sitting position during recovery.

The time-course of temperature changes during transient heat storage at the beginning of work and at the start of recovery was quite different at each of the three sites of measurement. As seen in figure 4, after an initial dip t_0 rose rapidly at the onset of work, coming into equilibrium in about 20 minutes. Tympanic membrane temperature revealed less of an initial fall, rose more slowly than t_0, and came to an
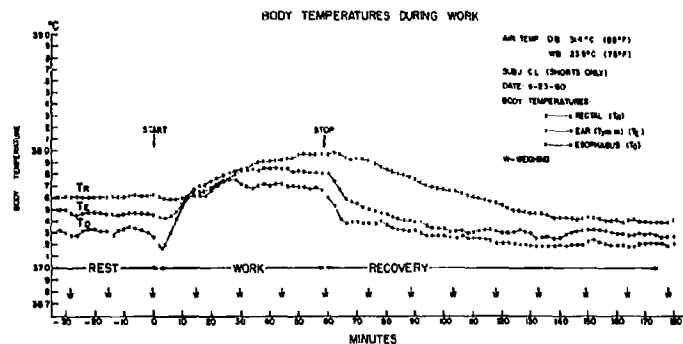
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Figure 4. - Subject C.R.L. Internal body temperatures recorded continuously for the last 35 minutes at rest, during performance of 1 hour standard work test, and during recovery showing relative speed of response and equilibrium conditions of temperatures measured at the 3 internal sites. During the preliminary rest period, equilibrium was attained only after 2 to 3 hours. Environmental conditions appear in the figure.

equilibrium level after 30 minutes. Rectal temperature showed no initial dip, rose more slowly than either t_e or t_o, and did not attain equilibrium until the final 10 minutes of work. Rates of recovery followed an inverse time-course, the rate of fall being in the order of $t_o > t_e > t_r$. Temperatures at the three sites bore the same relationship to one another after recovery as they did before work, although the equilibrium levels were slightly higher.

An analysis of 19 experiments in which subjects attained thermal equilibrium during work shows that the absolute change in temperature (Δt) of t_e and t_o were almost equal, whereas Δt_r was 20 to 40 percent greater, on the average, than Δt_e or Δt_o (table 3). There was wide individual variation, however. For

Table 3

Comparison of Mean Rise in Internal Temperatures Measured in Ear (Tympanic Membrane) (t_o), Esophagus (t_o), and Rectum (t_r) in Experiments in which Equilibrium was Attained During Work

Work Level (CAL./M² HR)	Ambient Temp (°F)		Number of Experiments	Mean Δt_e(°C)	Mean Δt_o(°C)	Mean Δt_r(°C)	Mean $\dfrac{\Delta t_r - \Delta t_e}{\Delta t_e}$
	DB	WB					
150	95	82	4	0.52	0.54	0.67	29%
100-130	95	82	4	0.53	0.52	0.75	42%
150	85	65 to 75	5	0.65	0.63	0.79	22%
150	78	65	6	0.64	0.72	0.84	31%
Total			19	0.59	0.62	0.77	30.5%

example in subject LC, Δt_r was usually more than 100 percent greater than Δt_e or Δt_o at thermal equilibrium during work whereas in the experiment shown in figure 4 the change in internal temperatures at the three sites of measurement were practically identical. In the average subject, however, Δt_r was about 30 percent greater than Δt_e or Δt_o under the conditions studied.

In these tests, the difference in heat tolerance between subjects was evident. For example, subject RLO was unable to attain thermal equilibrium under conditions in which CRL could attain equilibrium with relative ease, i.e., work rate 150 Cal/M² hr, DB 35° C, WB 27.5° C. When the work rate was reduced to 90 Cal/M² hr, subject RLO attained equilibrium under these conditions. The majority of the subjects used in the later tests were found to respond in a manner more similar to CRL in achieving thermal equilibrium during the work with relative ease under the conditions described.

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Figure 5 is a record of temperature gradients between the rectum (t_r), tympanic membrane (t_e), and esophagus (t_o) during a slow rise in body temperature of a resting subject (CRL), resulting from a reduction in evaporative heat loss caused by increasing ambient vapor pressure. Temperatures at the three sites of measurement were essentially parallel and nearly linear except that the rate of rise became slightly greater with the course of time. The average rate of rise in degrees per hour at the three sites was as follows: t_r, 0.18° C (0.324° F); t_e, 0.17° C (0.305° F); and t_o, 0.18° C (0.324° F). When ambient vapor pressure was restored to the original level, t_o responded first, followed by t_e, and finally by t_r. Full recovery is not shown in figure 5. The heat storage in this experiment, calculated by using the Burton (27) formula for mean body temperature (t_b) ($t_b = 0.67t_r + 0.33t_s$) was 5 Cal/M² hr.
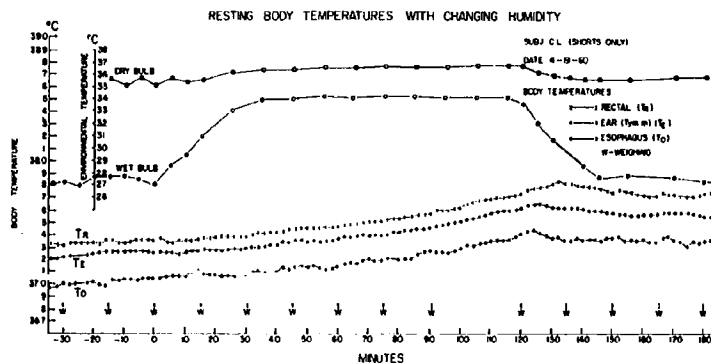
Figure 5. - Subject C.R.L. Rise in internal body temperatures measured at 3 sites during slow heat storage resulting from an elevation of ambient humidity. During gradual storage of body heat, the rate of rise of temperatures measured at the 3 internal body sites are seen to be almost identical.

Figure 6 depicts the internal body temperatures in two different experiments in a subject (RCH) wearing an impermeable protective suit, intended for use by members of a decontamination team. The outer garment consisted of a completely impermeable laminated rubberized parka and hood worn over overalls
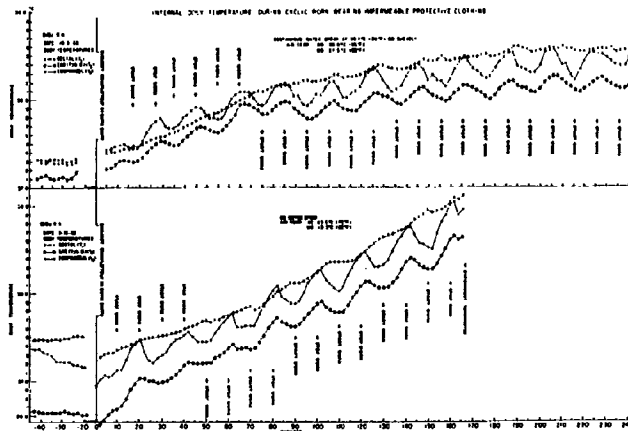
Figure 6. - Subject R.C.H. Internal body temperature during alternating 10-minute work (stepping) and rest (standing) periods while wearing impermeable protective clothing. At these rates of heat storage, the over-all slopes (rates of rise) of the 3 temperatures are almost identical. See text for details of these 2 experiments.

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made of the same material. The subject's face was covered by a Navy Mark V gas mask; in addition he wore rubber boots and gloves. Evaporative water loss, except through the respiratory tract, was completely blocked. Under these garments, the subject wore a semi-permeable impregnated parka and hood, overalls, and socks. He also wore ordinary T-shirt, undershorts, and shoes. Thus, the clothing had moderate insulative capacity. The subject alternately performed a stepping exercise at a metabolic rate of 150 Cal/M^2 hr. for 10 minutes, and then stood at rest for 10 minutes. At an air temperature of 23.9° C (75° F) dry bulb and 18.3° C (65° F) wet bulb with no external cooling, the subject reached the limits of his physiological tolerance in 165 minutes. However, if he was continuously sprayed with water at 26.7° C (80° F), he was able to continue the cyclical work schedule without undue difficulty for 4 hours at a higher ambient temperature [35.5° C (96° F) dry bulb and 27.5° C (82° F) wet bulb]. In the latter case, after a period of relatively rapid rise of internal temperatures lasting a little over 60 minutes, he came into a state approximating thermal equilibrium. The cyclic appearance of the internal temperatures is due to the alternation of work and rest. The amplitude of the temperature cycles is highest in the esophagus. The cycles in ear temperature are lower in amplitude and the onset of the rise lags behind the esophageal temperature. The cyclical pattern of the rectal temperature is hardly apparent, and the lag between onset of work and initial rise is the longest of the three internal temperatures. Nevertheless, the overall slopes of the three curves are almost identical. The rate of heat storage in the experiment with no external cooling, calculated using the Burton formula, was 25 Cal/M^2 hr.

Moderate Heat Storage

Figures 7 and 8 are records of deep body temperatures and skin temperatures (t_s) measured in subjects CRL and RLO in experiments in which the entire resting heat production was stored in the body by preventing its escape. This was accomplished by clothing the supine subject in a heavily insulated impermeable plastic garment, and by covering his head with a holyethylene hood, and his feet and hands with insulated vapor-impermeable boots and gloves. In addition, he lay upon, and was completely covered by, two layers of woolen blankets. He breathed air saturated at 37° C (98.6° F). Moreover, ambient air temperature was adjusted to levels above the initial temperature [35.5° C (96° F)] to keep pace with the rising skin temperature, thus maintaining a zero temperature gradient between skin and environment.
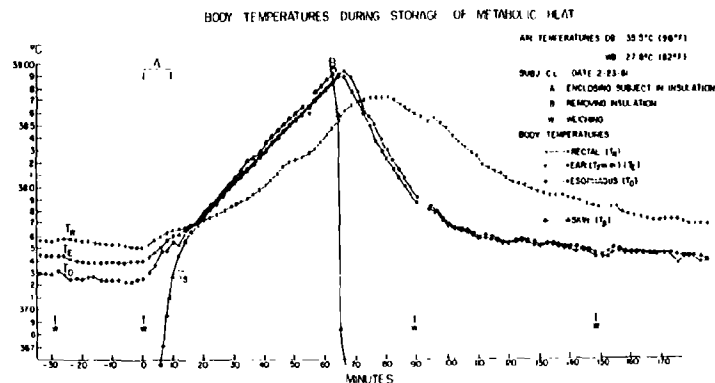
Figure 7. - Subject C.R.L. Internal body temperatures measured at the tympanic membrane, esophagus, and rectum and mean skin temperature during a test in which heat loss was blocked by enclosing the subject in impermeable insulating garments. Zero temperature gradient between skin and ambient air was maintained by adjusting air temperature to equal skin temperature during the period of rise. Arrows marked A and B indicate start and end of test respectively. Rate of heat storage was estimated to be 50 Cal/M^2 hr. (1 MET).

The patterns of heating in the two subjects are remarkably similar. In both t_e and t_o followed a rectilinear rise during the last 40 minutes of the experiment, the temperature of each region superimposing almost exactly upon one another. Skin temperature t_s rose rapidly and then followed the same time course

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BODY TEMPERATURES DURING STORAGE OF METABOLIC HEAT
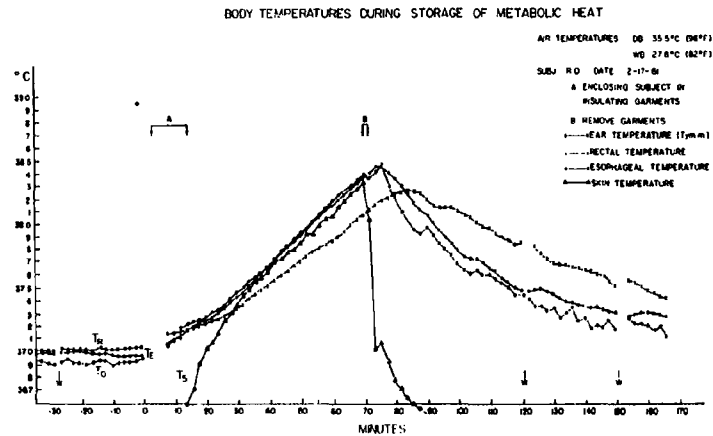
Figure 8. - Subject R.I..O. (See caption of figure 7 for procedure.)

as t_e and t_o. After an initial lag, t_r also rose in a linear fashion, but less steeply than the other three temperatures. Skin temperature was recorded as the unweighted mean of 10 skin junctions connected in series without intermediate amplification. The sensitivity was thus 0.415 mv/° C. The points for t_s in figures 7 and 8 are replotted to the same ordinates as the other three temperatures. Although the error in measurement of t_s is greater than for t_r, t_e, and t_o, which are directly recorded at 4.15 mv/° C, it is nontheless apparent that t_s is following t_e and t_o within the experimental error of measurement.

Table 4 is a summary of the results in the two experiments illustrated in figures 7 and 8. Esophageal temperature t_o is not tabulated, the rate of rise being identical with t_e and t_s. The predicted rise in mean body temperature t_m, if one assumes uniform distribution of stored heat throughout the body mass, is shown in table 4. Mean body temperature t_m is computed on the basis of the heat capacity of the body [weight x specific heat (0.83)], and an estimated heat production of 1 MET (50 Cal/M^2 hr). Actual heat production

Table 4

Rate of Rise (Degrees per Hour) in Tympanic Membrane (t_e), Skin (t_s), and Rectal (t_r) Temperatures Compared with the Predicated Rise of Mean Body Temperature (t_m)[a] During Total Storage of Metabolic Heat

Subject	Regional Temperature						Predicted Mean Body (t_m)	
	Tympanic Membrane (t_e)[b]		Skin (t_s)		Rectal (t_r)			
	°C	°F	°C	°F	°C	°F	°C	°F
CRL	1.57	2.83	1.57	2.83	1.19	2.14	1.50	2.70
RI.O	1.41	2.54	1.41	2.54	1.09	1.96	1.38	2.48
Mean	1.49	2.69	1.49	2.69	1.14	2.05	1.44	2.59

a See text for computation of t_m.

b The rate of rise of esophageal temperature (t_o) was identical with that of t_e.

measured in the rest period corresponded closely to this estimate. It is evident that measures of rate of change in temperature in the esophagus and at the tympanic membrane are only slightly higher than the predicted value. On the other hand, rectal temperature errs by a considerably greater margin on the low side.

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During the period indicated by arrows marked B in figures 7 and 8, the insulating garments were re-moved, and each subject was allowed to recover under the conditions of ambient temperature and humidity which prevailed initially. Unlike the curves during the period of heat storage, which are largely deter-mined by physiocochemical quantities, the recovery curves show marked individual differences which reflect the thermoregulatory characteristics of the two subjects. As noted above, these were quite different. Rate of cooling based on the linear portion of the recovery curve for ear temperature was 2.85° C (5.1° F)/hr. for subject CRL and 1.65° C (2.96° F)/hr. for subject RLO.

The inertia of t_r was evident in the recovery portion of these experiments. After removal of the suit, t_s fell immediately, promptly followed by t_o and then t_e. Rectal temperature continued rising for 20 min-utes after removal of the subject from the suit and then gradually began to decline.

Results in two other subjects, DM and LC, differ only in degree from those described for subjects CRL and RLO and substantiate the conclusions drawn from the latter.

Rapid Heat Storage

Figure 9 is a record of the internal temperatures in an experiment in which subject DM stepped rapidly up and down the two 6-inch steps at a rate of 20 round trips per minute. The ambient temperature was 35° C dry bulb and 27.5° C wet bulb. Working at this rate (365 Cal/M^2 hr.) in the heat, the subject reached his physiological limits in 25 minutes. The heat storage was 87 Cal/M^2 hr. The behavior of the
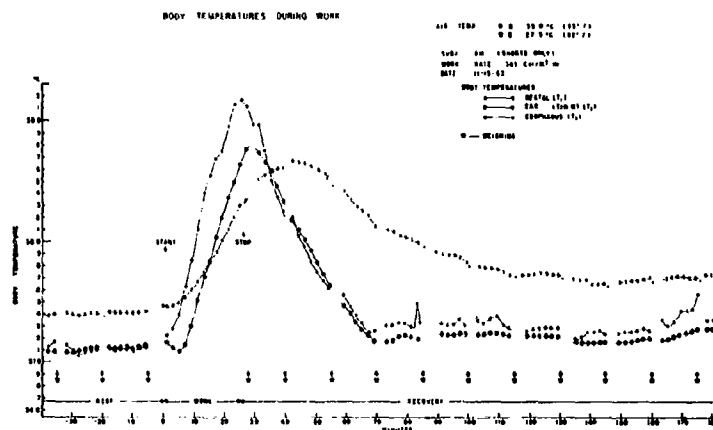
Figure 9. - Subject D.M. Internal body temperatures measured at the tympanic mem-brane, esophagus, and rectum at rest, during 25 minutes of strenuous work (365 Cal/M^2 hr.) and during recovery, showing relative rates of rise of these 3 temperatures during rapid heat storage (87 Cal/M^2 hr.) and relative speed of return to equilibrium levels during recovery. Environmental conditions appear on the figure.

three internal temperatures at this rapid rate of heat storage differs from that noted above. Esophageal temperature (t_o) rose almost immediately after onset of work, its rate of rise being most rapid of the three temperatures. After an initial dip, t_e began to rise, but at a rate slower than t_o. The onset of rise in rec-tal temperature was delayed for two or three minutes. The rate of rise of t_r was less than t_o or t_e. When work stopped, t_o began to fall immediately and reached a recovery equilibrium level first. Ear temperature followed after a minute, fell almost as rapidly as esophageal temperature, and came into equilibrium with-in a minute or two after t_o.

The rectal temperature continued to rise for 15 minutes after the cessation of work, then began a slow descent, not reaching equilibrium until 50 minutes after t_o and t_e.

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DISCUSSION

Temperature Gradients at Rest

The existence of temperature gradients between internal regions of the body at rest has long been known. Claude Bernard (1), in presenting his own findings, cites numerous references to the literature on this subject dating from the work of Haller in 1760. The possibility that the temperature of any single region of the body could be taken to represent average body temperature of the temperature of a "critical tissue" controlling thermoregulatory responses was considered unlikely by Eichna and his collaborators (13). However, temperature of blood in large arterial branches of the aorta was regarded by then as approximating that of the blood in the different vessels supplying a central receptor area. This view is shared by Benzinger (15, 16), who believes that changes in temperature measured in regions near, or supplied by, the internal carotid artery parallel changes in the anterior hypothalamus, which he regards as the site of central thermoceptors, or "critical tissue," to use the term employed by Eichna et al (13). For this reason he has questioned the reliability of the rectal temperature and has stated that it is misleading as an index of temperature in the brain, referring specifically to the hypothalamus. Instead, he has preferred to rely on temperatures measured at the tympanic membrane and in other cranial orifices. Studies by Rawson and Hammel (28) in the rhesus monkey have provided experimental support for the view that fluctuations in the temperature of the anterior hypothalamus measured directly parallel changes in the tympanic membrane temperature, although the latter was always slightly lower.

Equilibrium Conditions

The experiments reported here confirm the observation of Benzinger and a number of earlier investigators that the rectal temperature responds more slowly than other regions to transient heat loads. Under conditions where thermal equilibrium at work is attained, the rectal temperature comes into equilibrium last (figure 4) and Δt_r is usually greater than Δt_c or Δt_o (table 3). In studies on the physiology of thermoregulation, however, the question is often not the rate of change of a variable, e.g., sweat rate, during transient heating or cooling of the body, but rather its relative magnitude at two steady state levels of body temperature. In this case, the criterion that a true steady state has been attained would best be based on a temperature measured in the region which reaches equilibrium most slowly, which in this case is the rectum.

Zone of Transient Heat Storage

Heat storage index. - In the first decade after World War II, Blockley and Taylor and their associates (29-31) measured physiological strain and performance decrement in resting subjects exposed to dry heat at temperatures ranging from 60° to 120° C (140° to 248° F). At these levels of heat stress which the authors designated as the *zone of transient heat storage*, tolerance time is limited from a period less than 3 hours in length to one as short as 20 minutes. Because heat stress of this magnitude is not encountered in nature, such environments have been termed "supraclimatic" (32).

In the earliest studies, physiological strain was found to correlate well with skin temperature (29), but in the later reports (30, 31), change in mean body temperature (t_b) appeared to be a more satisfactory index of tolerance because under transient heat loads, t_b rose as a linear function of heat stress. The formula of Burton (27) was used to calculate t_b

$$t_b = .67t_r + .33t_s$$

From the rate of rise of t_b, heat storage (q_s) could readily be obtained from surface area, body weight, and specific heat. Although expressed as Cal/M^2 hr., the authors designated the resultant number as the "heat storage index," because they recognized that the particular weighting factors applied to t_r and t_s might not be precisely correct. For heat stress conditions tolerable from 3 hours down to only 20 minutes, during which t_b rises at a uniform rate, they concluded that the product of tolerance time and the heat storage index is constant, and may be expressed as follows:

$$\theta_t q_s = 77 \; Cal/M^2$$

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where θ_t = tolerance time in hours for subjects of normal heat resistance and q_s = average heat storage index (Cal/M^2 hr.). The constant was 55 Cal/M^2 for subjects of minimal heat resistance. Performance decrement became appreciable after about 75% of the total tolerance time had elapsed.

Hall and Polte (33) have found the heat storage index of Blockley and Taylor to correlate well with indices of heat strain. In their study, heat strain was based on a modification of Craig's formula (34) in which terminal heart rate, rise in rectal temperature and sweat production are combined in a single number. Both the index of strain, however, and the heat storage index include t_r as a variable, which would tend to reduce the validity of such a correlation.

In a report by Gold (35), curves of heat storage in a subject exposed to an ambient temperature of 71.1° C (160° F) and 17 mm Hg vapor pressure exhibit an upward inflection between 20 and 30 minutes. The author suggests that this is because sweat rate is declining. It is more likely, however, that the initial slow rise in the heat storage curve is the result of the lag in the rectal temperature during the transient heating, thus leading to an underestimate of the rate of heat storage in the early period of exposure.

Regional Temperature (t_o or t_c) as an Index of Heat Strain

Under conditions in which heat storage is rapid and continuous, our experiments indicate that rectal temperature is not a reliable index either of internal temperature or of mean body temperature. Deep temperatures measured in the esophagus or at the tympanic membrane, on the other hand, follow the predicted rate of elevation in mean body temperature more closely (see table 4). The slope of the temperature rise measured at these sites is only slightly steeper than predicted. Calculations based on experimental data in table 4 lead to the conclusion that under conditions of this experiment, t_e or t_o represent the temperature of over 80% of the body mass, whereas t_r represents less than 20%. The relatively slow rise in rectal temperature, which leads to this region becoming cooler than the skin itself in the experiments shown in figures 7 and 8, depends in part, perhaps, upon a diversion of blood away from the abdominal viscera during severe heat stress, and in part upon the heat capacity of the relatively avascular pelvic structure itself. Blood flow is maximal, on the other hand, through tissues which are the major sites of heat production and through the skin, subcutaneous tissue and muscle. It is the temperature of these highly perfused tissues which is measured by t_o and t_e.

When heat storage is very rapid, as in the experiment shown in figure 9, the esophageal temperature responds faster than the tympanic temperature. In cases of rapid heat storage, for example, rates greater than 80 Cal/M^2 hr., the temperature of the terminal esophagus is preferable as an index of change in internal body temperature. The most likely explanation for the rapid response of this region to changes in heat load is its proximity to the heart and great vessels.

It is stated by Blockley and Taylor and their associates (29-31) and also by Webb (32) and others (33, 35), that tolerance time is determined by the rate of heat storage, as estimated by the rate of rise in mean body temperature t_b calculated using Burton's formula. In our opinion, tolerance time in the zone of transient heat storage might better be related to the rate of rise in internal temperatures measured in the esophagus or at the tympanic membrane.

At heat loads exceeding those studied by Blockley and Taylor, Webb (36) has shown that tolerance time is limited not by storage, but by heating the skin to the pain threshold. In this case, the sensory receptors involved in limiting tolerance are those of cutaneous pain.

SUMMARY AND CONCLUSIONS

Gradients in internal body temperature exist in the resting human subject at thermal equilibrium. The rate of change in body temperature when equilibrium is upset (e.g., at onset of work) also varies from one internal region to another. If the total heat load is within tolerable limits, however, a new steady state is ultimately established.

Thermoregulatory responses of human subjects undergoing heat stress were studied utilizing a variety of environmental conditions, clothing, and work rates. Internal body temperatures were measured in the

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lower esophagus (t_o), ear (tympanic membrane) (t_e), and the rectum (t_r). Skin temperatures, heart rate, sweat rate, and metabolic rate were also measured. At low rates of heat storage (5 to 25 Cal/M^2 hr.), the rates of rise of t_o, t_e, and t_r are approximately identical. During more rapid heat storage (50 Cal/M^2 hr.), the rates of rise of t_o and t_e are about equal and more rapid than that of t_r. When heat storage is greater (80 to 90 Cal/M^2 hr.), the rate of rise of t_o is greater than that of t_e. During work in the heat in which thermal equilibrium is achieved, t_o and t_e reach equilibrium sooner than t_r, and the mean increase in t_r is 20 to 40% greater than that of t_e or t_o. During exposure to heat loads and during the subsequent recovery period, changes in heart rate tend more nearly to parallel changes in the more responsive temperatures. It is concluded that t_o and t_e are more sensitive indicators of changes in internal temperature than is t_r during transient conditions, and t_r is a more reliable index of time of attainment of thermal equilibrium than are t_o or t_e.

In the zone of transient heat storage, body temperature measured in a region which responds promptly to changing heat loads, such as t_o or t_e, may prove to be a more valid index of thermoregulatory strain than so-called mean body temperature, which is based on weighted readings of skin and rectal temperatures.

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