

**PHYSIOLOGICAL INDEX OF STRAIN AND BODY
HEAT STORAGE IN HYPERTHERMIA**

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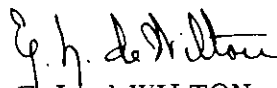
FOREWORD

This physiological research study was initiated by the Biomedical Laboratory, Aerospace Medical Laboratory, Wright Air Development Division. This report represents part of the internal research program being conducted by the Biothermal Section, Biophysics Branch, Biomedical Laboratory, under Project No. 7164, "Physiology of Flight," Task No. 71830, "Human Thermal Stress in Extended Environment."

ABSTRACT

Intra- and inter-individual, as well as group, variability of a Modified Craig index of physiological strain and body heat storage was determined and their relationship defined for 5 sitting, nonacclimatized subjects wearing 1 clo body insulation and exposed 5 times to each of three heat stress levels: 38° C, 54° C, and 71° C at 10 mm Hg vapor pressure. A linear relationship between physiological strain and thermal stress range studied is shown, although individual variation is marked, especially at higher stress levels. A statistically significant correlation between strain index and body heat storage is shown. Individual and mean variations in heart and sweat rates, and skin, rectal, and body temperatures as related to body heat storage, are illustrated. Data show usefulness of the correlation between strain and heat storage in comparing overall strain resulting from exposure to dissimilar thermal environments for different periods of time.

PUBLICATION REVIEW



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Contrails

PHYSIOLOGICAL INDEX OF STRAIN AND BODY HEAT STORAGE IN HYPERTHERMIA

INTRODUCTION

In recent years, studies of human physiological response to thermal stress have been directed to determining and expressing in quantitative form the total physiological strain. These studies included the work of Craig (ref. 4), who introduced a relatively simple though empirical strain index which he utilized in studies of working subjects. Heart rate and changes in rectal temperature and sweat rate are combined to give a single value: the index of physiological strain. Robinson (ref. 7) had previously developed an empirical index of strain for working men which, expressed as a ratio of strain in a given environment to maximum strain in the hottest tolerable environment, was termed the index of physiological effect. In this concept the criteria of heart rate, rectal temperature, skin temperature, and rate of sweating—all equally weighted—were used. They established tolerance contours essentially in agreement with those determined and described by Taylor (ref. 8) and Blockley et al. (ref. 1). However, this index was not applicable to nonacclimatized subjects. Recently Gold (ref. 6) developed a new index of physiological strain based on heart rate only. Applied to nonacclimatized, sitting-resting subjects over an extensive thermal exposure range (from 38° to 71° C), the heart rate showed a statistically significant correlation with body heat storage. A general review of the major considerations involved in environmental stress and the resulting physiological strain was presented by Carlson and Buettner (ref. 3).

A slight modification of the Craig index is routinely used in this laboratory in studies of human tolerance to heat and for evaluation of protective clothing. The experimental studies described in this report were performed to determine, in nonacclimatized, nonventilated, sitting-resting subjects: (a) the degree and statistical significance of inter- and intra-individual variability involved in using such an index, (b) the relationship between this index and body heat storage over an extensive thermal exposure range, and (c) the correlations between body heat storage and mean skin, rectal, and body temperatures, as well as heart and sweat rates. If accurately determined, the relationship between the index and body heat storage should be valuable in predicting human tolerance limits and degree of physiological strain resulting from exposure to the thermal stress range explored.

PROCEDURE

Seventy-five experiments were conducted on five healthy, nonacclimatized male subjects (table I). The sitting-resting subject wearing 1.0 clo body insulation was exposed 5 times to each of 3 heat stress levels (37.8°, 54.4°, and 71.1° C), all at 10 mm Hg vapor pressure. Exposure time was 180, 120, and 60 minutes, respectively, at these levels. No insulation was worn on head or hands. Leather shoes and light cotton socks were worn. Air-wall temperatures were equivalent and maintained within $\pm 0.5^\circ \text{C}$ during the experimental period. Vapor pressure was controlled within $\pm 2.0 \text{ mm Hg}$. Air motion was low (from 150 to 250 feet per minute) and turbulent in type. The heart rate was measured by electrocardiogram; the sweat rate, by nude pre- and post-experimental body weights; and the rate of rectal temperature rise, by rectal thermistor.

TABLE I

PHYSICAL CHARACTERISTICS OF SUBJECTS

<u>Subject</u>	<u>Age</u>	<u>Occupation</u>	<u>Height</u> (in)	<u>Weight</u> (kg)	<u>Surface Area</u> (m ²)
A	48	Airman	65	78.9	1.86
B	23	Project Officer	72	68.6	1.95
C	27	Administrative Officer	74	68.8	1.92
D	29	Airman	69	83.2	2.00
E	29	Medical Officer	70	73.9	1.92

Skin temperatures were continuously measured with 17 thermistors. Weighted mean skin and body temperatures were determined by the method of Burton (ref. 2). The subjects were weighed on a precision, platform-type balance, accurate to ± 4.0 grams. Skin temperatures were accurate to $\pm 0.2^\circ \text{C}$ and rectal temperature to $\pm 0.1^\circ \text{C}$. Prior to each heat exposure, control levels for skin, rectal, and heart rate were determined with the subject exposed to a comfortable environment (from 21° to 24° C).

Equations for calculating physiological index of strain (I_s) and body heat storage (q_s) are:

Modified Craig Index of Physiological Strain, I_s

$$I_s = \frac{HR}{100} + \Delta T_r + \Delta W_n$$

HR = the terminal heart rate

ΔT_r = the rise in rectal temperature ($^{\circ}$ C/hr)

ΔW_n = the sweat production (nude weight loss, kg/hr)

Body Heat Storage, q_s

$$q_s = \frac{WC_p}{A_b} \times \frac{\Delta T_b}{hr}$$

W = nude body weight (kilograms)

C_p = specific heat of body mass (0.83), cal/g/ $^{\circ}$ C

ΔT_b = change in mean body temperature, $^{\circ}$ C, per hour

A_b = surface area of body (m^2)

Metabolism was not measured since previous studies have shown a mean value for sitting-resting subjects of 50 Calories per square meter per hour, a generally accepted value for this activity level. Heat production of the experimental subject was assumed to be normal and representative of the specified activity level. Vapor pressure was purposely set and maintained at 10 mm Hg at each heat stress level to provide a relatively steep gradient for sweat evaporation. At the terminal mean skin temperature levels observed (from to 35.6 $^{\circ}$ to 39 $^{\circ}$ C), and assuming 95 percent saturation of the air at the skin surface, the vapor pressure at the skin is from 42 to 50 mm Hg.

RESULTS

The inter- and intra-variability of the physiological index of strain and the concurrently measured body heat storage at the three heat stress levels studied are presented in table II. The individual means and standard deviations for the five exposures of each subject and the group means and group standard deviations are included. In terms of mean index of strain, wide individual variation at each thermal stress level was observed and appeared randomly variable. No significant relationship between this variation and heat stress level was indicated. At different heat stresses the same individual may have a mean index either below or above the group mean. However, the results for body heat storage show a progressive increase in group mean value and in standard deviation as intensity of the thermal stress increases. At the lowest stress level (38 $^{\circ}$ C) the value of the group standard deviation is quite low (± 1.8 Cal/ m^2 /hr). This value may approximate the limit of accuracy and represent also the probable error of the body heat storage measurement method used. From the standard deviation values, the probable error involved in measuring this index of strain, or heat storage over the ranges examined, can be determined.

TABLE II

INDIVIDUAL AND GROUP VARIABILITY OF PHYSIOLOGICAL
INDEX OF STRAIN AND BODY HEAT STORAGE

Subject	ENVIRONMENTAL TEMPERATURE					
	38° C		54° C		71° C	
	10 mm Hg v. p.		10 mm Hg v. p.		10 mm Hg v. p.	
	I_s	q_s	I_s	q_s	I_s	q_s
	(Cals/m ² /hr)					
A mean	1.17	10.4	1.99	26.9	3.50	78.0
s*(±)	0.04	2.1	0.13	5.0	0.16	7.2
B mean	1.05	6.8	1.74	20.3	3.57	56.6
s(±)	0.10	1.7	0.53	4.7	0.20	8.7
C mean	1.31	9.4	2.07	21.0	3.79	62.6
s(±)	0.19	1.4	0.11	4.4	0.12	4.3
D mean	0.97	6.8	1.92	22.2	3.21	67.1
s(±)	0.13	2.5	0.25	7.7	0.32	11.7
E mean	1.10	10.2	2.09	24.4	3.40	59.1
s(±)	0.09	4.0	0.11	1.7	0.34	5.8
group mean	1.12	8.7	1.96	23.0	3.49	64.7
group s(±)	0.13	1.8	0.14	2.7	0.21	8.4

* s - standard deviation

In figure 1 the relationship between the physiological index of strain and the measured body heat storage is illustrated. The standard deviation in terms of both index of strain and body heat storage is shown at each of the respective heat stress levels. The best fit curve obtained statistically by the method of least squares shows a linear relationship between strain index and body heat storage over the thermal stress range studied. The equation for this curve in terms of strain index (I_s), the coefficient of correlation (r), and the standard error of the estimate (S_y) were determined and are shown in this figure. On the basis of the correlation coefficient, the results are statistically significant at the 1 percent level. At each thermal stress level the individual experimental results are plotted together with the group average. Degree of scatter at the lower and intermediate stress is significantly less than at the high stress level where wide variation is observed.

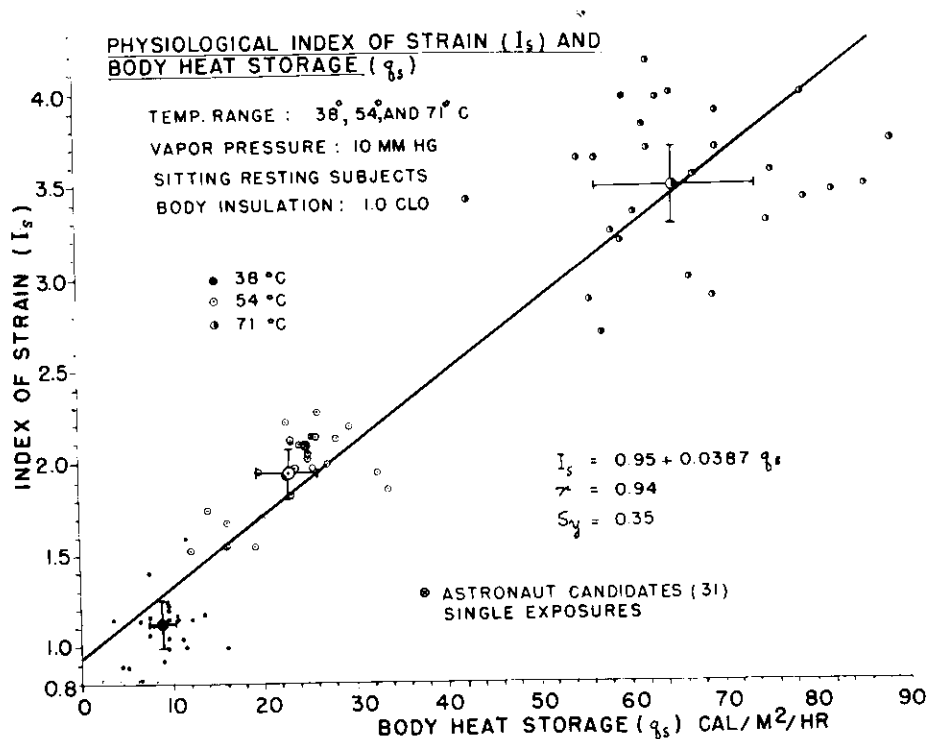


Figure 1. Relationship Between Physiological Index of Strain (I_s) and Body Heat Storage (q_s)

During the study we performed thermal evaluation studies on a group of 31 Astronaut candidates. Thus, our experimental observations were extended to a much larger population sample. The mean value for these 31 tests is also shown in figure 1. Each subject was exposed only once to the intermediate stress level (54° C). The mean value falls slightly above the best fit curve, these subjects showing a slightly higher strain index and correspondingly increased body heat storage. However, these differences are not significant since they lie within or approximate the probable error involved in measuring either strain or storage. In general, the agreement between these results and those of the original experimental group of 5 subjects gives added confidence with respect to the predictive value and general applicability of the plotted curve relating strain index and body heat storage.

Examination of the individual responses in terms of strain index or body heat storage shows no significant, consistent trend or performance pattern except perhaps in the cases of subjects A and B. On the basis of either strain or storage, subject B performed best: he had the lowest values in 4 of the 6 physiological criteria. In contrast, subject A performed poorest: he had the highest values in 4 of the 6 physiological criteria. This correlation is interesting since subject B was the youngest and subject A the oldest of the group tested. These results are in essential agreement with unpublished data of Gold* who has observed a good correlation between subject age and "effective body heat storage," a new concept also reflecting the individual's physiological adjustment to heat.

* Joseph Gold, Capt., USAF, MC, Biomedical Laboratory, Aerospace Medical Laboratory, Wright Air Development Division

Examination of each subject's pattern of variation with respect to the individual components of this strain index (heart rate, sweat rate, and rate of rectal temperature rise) also fails to indicate consistent trends or significant uniform patterns of response. Subject response especially at the higher stress appears highly individualized with each subject displaying a characteristic pattern. For example, subject B sweats profusely (mean value of $0.70 \text{ kg/m}^2/\text{hr}$) with low cardiac response to heat (119 mean terminal pulse), while subject C sweats significantly less ($0.56 \text{ kg/m}^2/\text{hr}$) and has a higher pulse. Subjects C and D display almost identical mean terminal heart rates and approximately equivalent sweat rates, yet differ significantly in rate of rectal rise, subject C showing a rate approximately twice that of D. These results emphasize that, under these heat stress loads, inherent biological variation is accentuated.

In figures 2 through 6, the individual and mean responses in terms of terminal heart rate, sweat rate, rectal, mean skin, and body temperatures are plotted. The standard deviation for each of these variables and for the body heat storage is also shown. The scatter is extensive in these plots, generally increasing in degree at the higher heat stress levels. All are curvilinear, with sweat rate (figure 3) most nearly approaching a straight line. In figures 7 through 10 changes in the above responses (excepting sweat rate) are plotted. Differences in initial or starting levels are eliminated and the rates of change in the physiological variables are illustrated. The plots are curvilinear as in figures 2 through 6 and the standard deviations are indicated in each. These also show, except for body temperature, a general increase in standard deviation (or probable error) with the higher heat stresses.

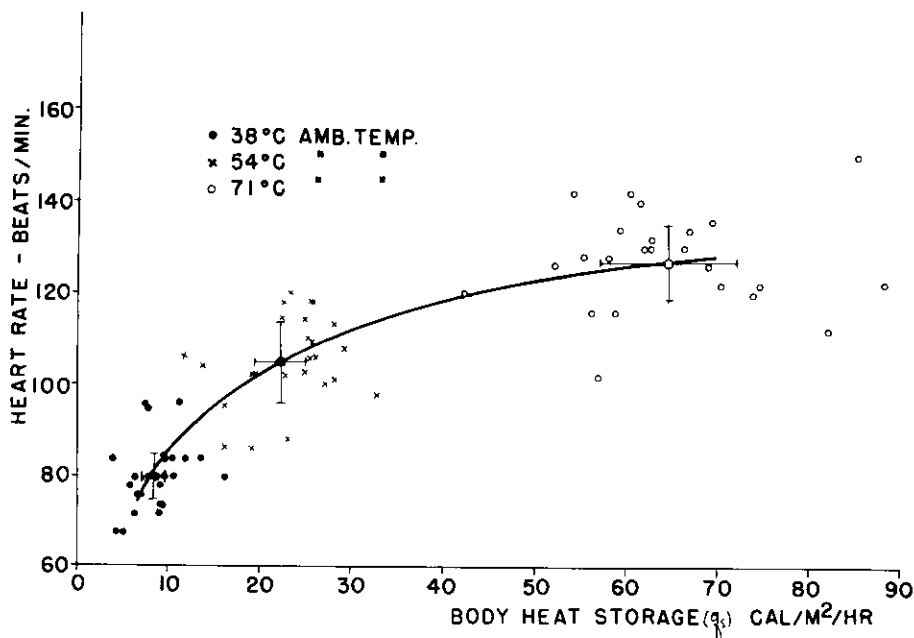


Figure 2. Variation of Heart Rate with Body Heat Storage

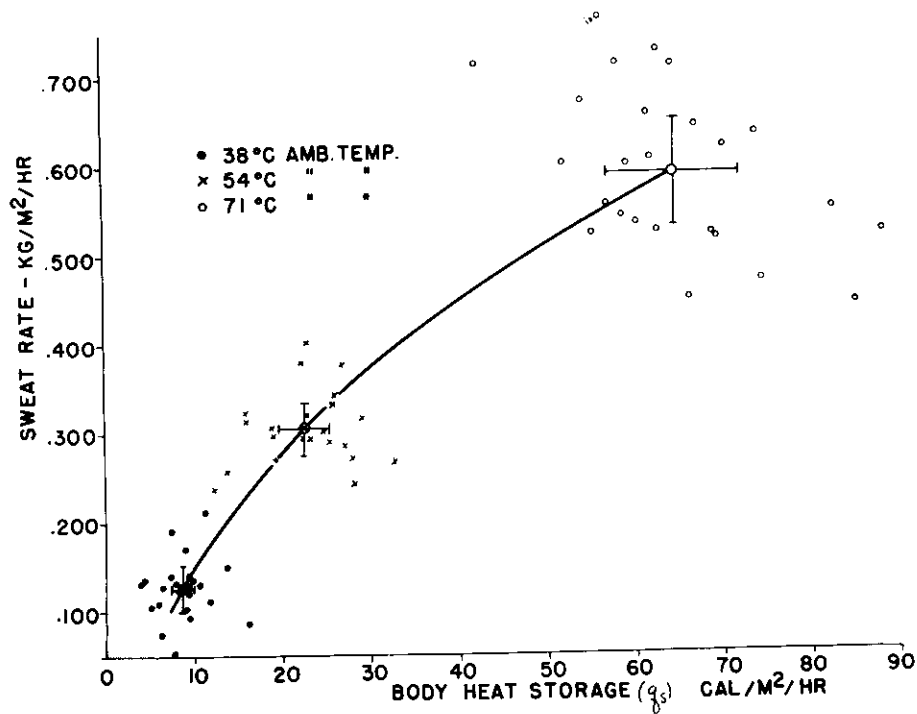


Figure 3. Variation of Sweat Rate with Body Heat Storage

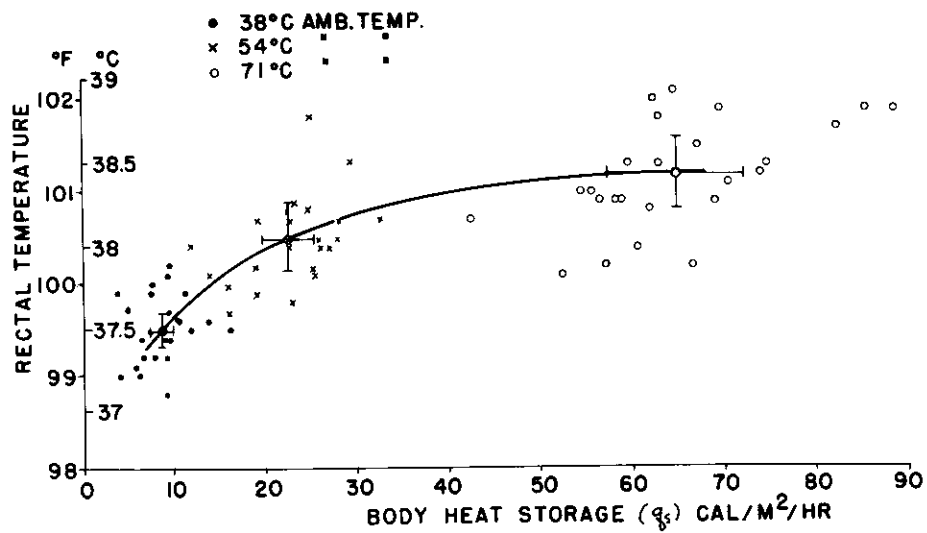


Figure 4. Variation of Rectal Temperature with Body Heat Storage

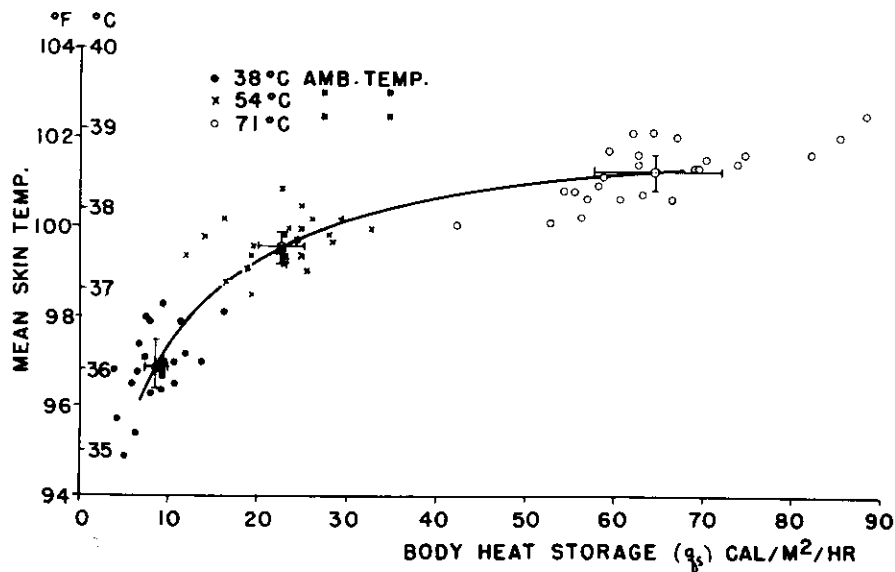


Figure 5. Variation of Mean Skin Temperature with Body Heat Storage

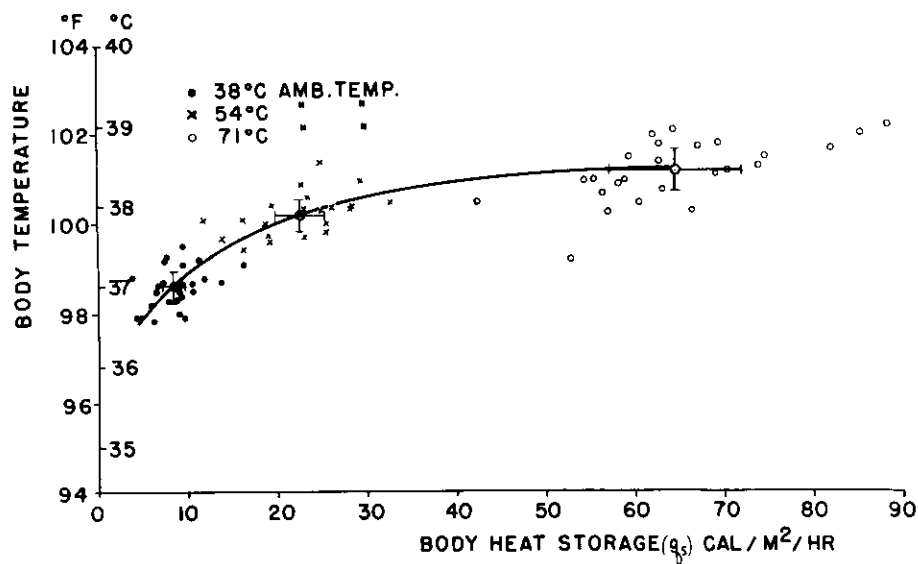


Figure 6. Variation of Body Temperature with Body Heat Storage

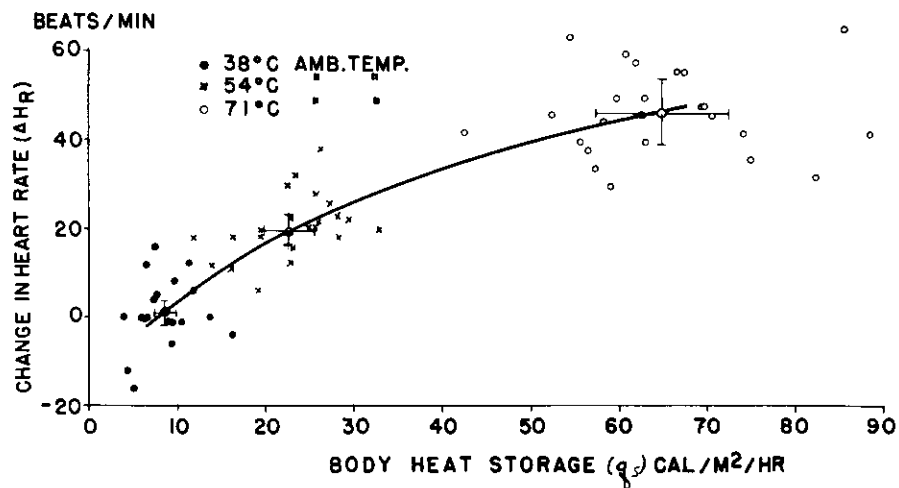


Figure 7. Rate of Change in Heart Rate with Body Heat Storage

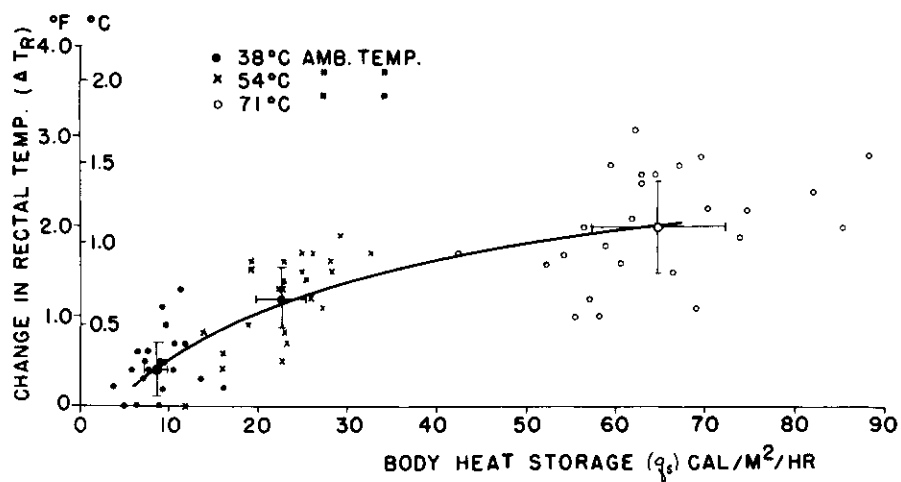


Figure 8. Rate of Change in Rectal Temperature with Body Heat Storage

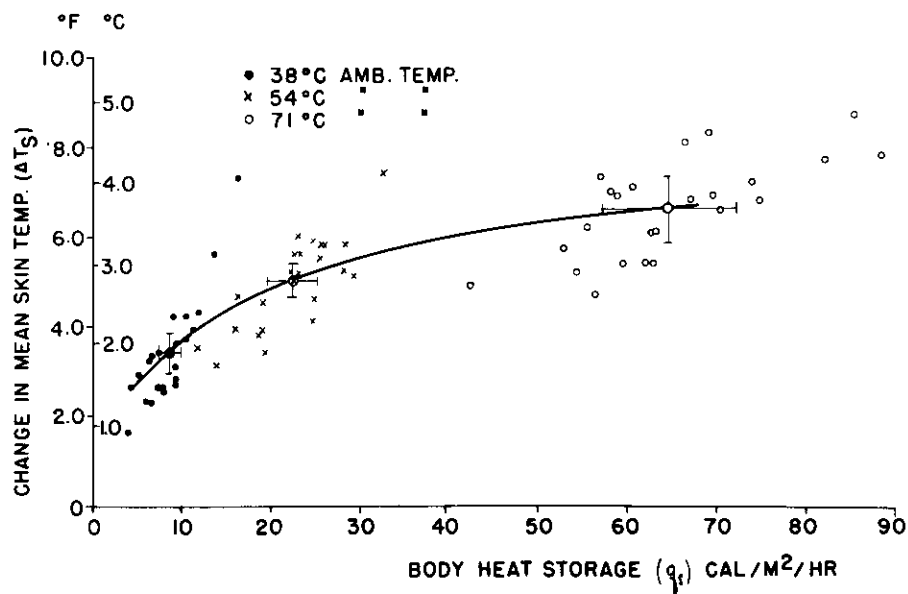


Figure 9. Rate of Change in Mean Skin Temperature with Body Heat Storage

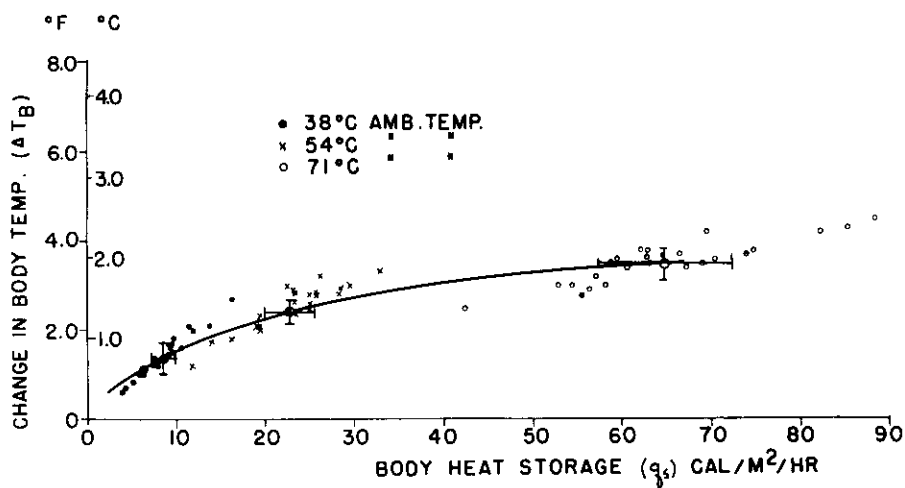


Figure 10. Rate of Change in Body Temperature with Body Heat Storage

DISCUSSION

For the environmental and human subject conditions reported (i.e., sitting-resting, nonacclimatized, 1 clo, and quasi-steady state), the curve in figure 1 establishes the relationship between this index of physiological strain and body heat storage. The degree of significant inter- and intra-individual variability and probable error involved in the use of these expressions is relatively small. For example, with the most variable subject (E) at the highest thermal stress (71°C), the index of strain with an error not exceeding ± 0.2 can be determined.

The problems involved in valid measurement of body heat storage and its relationship to rectal-skin temperature have been examined in detail by Gagge (ref. 5). Gagge described physiological and physical conditions contributing to errors in storage measurements. The probable error involved in the body storage measurement reported at the highest thermal stress level is approximately $6\text{ Cal/m}^2/\text{hour}$. Since these severe exposures are quasi-steady state exposure rather than steady state, the error in absolute calorimetric terms may be even greater.

Despite the limitations involved in calculating body heat storage and the empirical nature of the strain index, both expressions have many practical applications. They are potentially useful in determining if significant improvement has been achieved in the design of new protective clothing prototypes, or in determining the most thermally effective model from a group of similar protective clothing models.

The importance of using the same subject for any comparative thermal evaluation testing is apparent from table II. Intra-individual variation may often exceed the functional differences between protective clothing models and thus prevent a valid selection of the best item. Even with the same subject, if differences of protective clothing assemblies do not exceed the probable error of the method used (in terms of strain index or body heat storage at any given thermal stress level), no valid discrimination between different clothing types may be expected.

Statistical analysis of the data shows a significant correlation between this index of physiological strain and body heat storage. Further support of the predictive value for the curve is also given by the Astronaut data. These single tests performed on a much wider population might be expected to show a high degree of scatter. However, mean value as plotted falls within the probable error limits of the method. The curve has reasonably reliable predictive value in quasi-steady state thermal exposures of human subjects over the temperature range investigated (from 38° to 71°C). Its application is questionable beyond a temperature limit of perhaps 93.3°C , or to transient types of thermal exposures where the inertia of core (rectal) temperature change or skin pain threshold becomes a serious limiting factor.

The experimental results at the highest heat stress level (71°C) provide some evidence of the order of magnitude of the upper limits of human thermal tolerance in terms of strain index or heat storage for sitting-resting, nonacclimatized subjects. Present data of this experimental series, together with unpublished data from 25 human thermal tolerance exposures conducted at this laboratory, indicate the upper limit to be from 65 to 85 $\text{Calories/m}^2/\text{hour}$ and in the region of 3.5 to 4.5 strain index units. Precise definition of this upper thermal limit is difficult due to the subjective nature of a tolerance endpoint and marked individual differences in capacity to perform physiologically under heat stress. The latter is emphasized by the increased scatter observed in figure 2 as the thermal load is increased; i.e., as the individual approaches the upper limit of thermal tolerance. Further studies at extreme heat stress levels are required to establish this upper limit or zone more exactly.

Whether a single physiological variable may be used as an indicator of physiological strain due to thermal stress is an interesting question. Recent work at this laboratory has been directed toward such a goal. Some results have been reported by Gold (ref. 6). In these studies the heart rate was used as an indicator of strain due to thermal stress. We observed a significant degree of correlation between this variable and body heat storage over an extensive thermal exposure range (from 38° to 71° C). The simplicity of a single physiological variable as a heat strain indicator is an obvious advantage. However, whether such an index can reliably measure effects of low-level, long-duration stress exposures or those in which strong psychogenic or emotional factors are present needs to be determined.

The possible physiological strain equivalence of exposure to different thermal stress levels for different periods of time may be found by using the curve relating strain and body heat storage (figure 1). Thus, a broad spectrum of widely differing thermal environments may be physiologically equated. In 1945 Robinson (ref. 7), with the concept of index of physiological effect, E_p , advanced a generally similar approach and presented contour lines of equal physiological effect. However, these lines are applicable only to working, acclimatized subjects, and the amount of stored body heat was not directly related to the strain index. With the relationship developed between strain index and body heat storage as presented in these experiments some of these limitations are removed. For example, this data may be applied to sitting-resting, nonacclimatized subjects. A direct relationship between heat storage and strain index is shown. Upper or maximum limits for the respective physiological variables need not be determined. Using strain ratios for the respective variables is avoided.

The data in this report are based on thermal stress exposure times of 3 hours or less. However, 6 initial experiments involving long-duration exposures (from 6 to 12 hours) at low-heat load levels (32.2° C and from 15 to 25 mm Hg vapor pressure) yielded values agreeing with figure 1. These experiments conducted on ventilated subjects were conducted with various combinations of volume flow, humidity, and ventilating air temperature. Further study of the validity of the relationship between strain index and body heat storage at more extreme heat stress levels (93.3° C) and with both ventilated and nonventilated subjects is necessary.

With proper experimental design and systematic variation of the environmental variables of wall-air temperature, vapor pressure, and air movement, contour lines of equivalent physiological strain, with many useful applications, may be developed. Properly used in conjunction with reliably determined upper or maximum strain limits, these equivalent strain contour lines should be valuable in predicting human tolerance to thermal stress.

The data presented in figures 2 through 10 emphasize the extreme variability of human response to thermal stress, especially at the higher heat levels investigated in this study, and the approach to limiting values for the mean skin, rectal, and body temperatures. This asymptotic trend is definitely not observed with the sweat rate and only to a slight extent characteristic of the heart rate. These latter variables obviously can attain significantly higher values under more extreme heat-load conditions.

This data provides valuable basic information regarding mean human response to thermal stress over the ambient temperature range explored (38°-71° C) for sitting-resting, nonacclimatized subjects. At any given body heat storage or physiological strain index level within this range, prediction of response in terms of these variables (heart rate, sweat rate, and mean skin, rectal, and body temperatures) is possible. Evaluation of each human subject response with respect to the group mean is also possible.