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Heat Exchanges of Nude Men in the Cold: Effect of Humidity, Temperature and Windspeed

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ABSTRACT

IAMPIETRO, P. F., DAVID E. BASS AND E. R. BUSKIRK. *Heat exchanges of nude men in the cold: effect of humidity, temperature and windspeed.* J. Appl. Physiol. 12(3): 351–356. 1958.—Six healthy young men were exposed nude for 2 hours to various combinations of wind (< 1 and 10 mph), temperature (50° and 60°F) and relative humidity (30 and 95%). These conditions have been identified with cold-wet environments by meteorologists. Skin and rectal temperatures, oxygen consumption and subjective sensations were recorded. The results indicate that wind had the greatest impact on both the subjective and physiological responses; dry bulb had a marked although lesser effect. Relative humidity had little or no effect on any of the responses except heat production. Thus, under the conditions of this study, little evidence was found for an important role of humidity, per se, on either body heat exchanges or subjective sensations of cold.

THE SENSATION of being 'chilled to the bone' on a cold-wet day has been widely experienced both by the military and by civilians and it has generally been thought that this sensation was due to the high humidity on cold-wet days. Until recently, however, no serious attempts were made to quantitate the effects of high humidities and low temperatures on the subjective and physiological responses of subjects exposed to those conditions. Burton, Snyder and Leach (1) have described partial heat exchanges of unclothed men in 'damp-cold' environments. Their experimental conditions, however, may not have been representative of conditions ordinarily associated with cold-wet environments; relative humidity did not exceed 80% and air movement was negligible. Naturally occurring cold-wet conditions may be widely varied (2), but meteorological definitions include a wind of 5 mph or more, temperatures from 23 to 67°F and/or the presence of fog or precipitation.

The present study was designed to determine whether there are differences in body heat exchanges which could provide a physiological basis for the commonly experienced sensation of chill in cold-wet conditions.

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EXPERIMENTAL DESIGN

Six healthy young men were exposed nude in a constant temperature room to various combinations of the following:

Dry bulb: 60 and 50°F
Relative humidity: 95 and 30%
Windspeed: 10 and < 1 mph

All six men were simultaneously exposed to the same set of conditions on a given day. The order of exposure was randomized, and is shown in detail in table 1. Exposure to each environment was for 2 hours, preceded by 1 hour at a comfortable temperature (control).

During the course of each experiment the following observations were made: skin temperature (T_s), rectal temperature (T_r), and oxygen consumption ($\dot{V}O_2$). The physical characteristics of the test subjects are shown in table 2.

METHODS

Rectal temperatures were measured using a thermistor catheter and a portable bridge and were accurate to 0.1°F. Skin temperatures were measured continuously with copper-constantan thermocouples at 10 points on the body and the mean weighted skin temperature

(MWST) was recorded simultaneously as follows: MWST = .05 instep + .15 calf + .125 lateral thigh + .125 inner thigh + .125 back + .125 chest + .07 upper arm + .07 lower arm + .06 hand + .10 forehead. Sensations of cold and dampness of the various parts of the body were checked by the subjects on a questionnaire sheet at regular intervals. Oxygen consumption ($\dot{V}O_2$) was measured by collecting expired air in a Tissot spirometer and analyzing the expired gas for oxygen with a Beckman oxygen analyzer. Calculations of heat production were made according to Weir (3).

For convenience, the following shorthand notation will be used in describing environmental conditions: dry bulb/relative humidity/windspeed. For example, 50/95/10 signifies dry bulb of 50°F, relative humidity 95% and windspeed 10 mph. In instances where humidity is not important, but when dry bulb and wind are significant, the relative humidity will not be specified, e.g. 60/—/10. Comparison of the physiological responses to the various conditions was achieved by analysis of variance (4) and also by paired statistics where interactions were significant (table 3). Subjective responses were ranked and a 'U' test (5) was performed to determine the separate effects of temperature, windspeed and relative humidity.

TABLE 1. EXPECTED AND ACTUAL CHAMBER CONDITIONS

	Day 1	2	3	4	5	6	7	8
Dry bulb, °F								
Expected	50.0	60.0	50.0	60.0	60.0	50.0	50.0	60.0
Actual	50.4	61.7	49.8	57.5	59.0	51.8	50.2	60.0
Wet bulb, °F								
Expected	38.5	59.2	38.5	46.0	59.2	49.3	49.3	46.0
Actual	39.2	60.8	39.7	44.6	57.6	50.9	49.8	42.0
Relative humidity, %								
Expected	30	95	30	30	95	95	95	30
Actual	34	95	39	32	91	94	98	14
Vapor pressure, mm Hg								
Expected	2.8	12.6	2.8	3.9	12.6	8.8	8.8	3.9
Actual	3.1	13.5	3.3	3.8	11.6	9.2	8.9	1.7
Windspeed, mph								
Expected	1	1	10.0	1	10.0	1	10.0	10.0
Actual	1	1	7.2	1	10.5	1	10.0	10.4
Windchill, Cal/m²/hr.								
Expected	375	300	625	300	475	375	625	475
Actual	375	290	575	315	475	350	625	475

TABLE 2. SOME CHARACTERISTICS OF TEST SUBJECTS

Subject No.	Age yr.	Wt. kg	Ht. cm	Surface Area, m²	% Fat*
1	18	75.41	175.1	1.90	3.7
2	22	76.94	173.7	1.91	4.9
3	23	64.41	172.1	1.75	4.4
4	19	77.26	173.0	1.91	8.6
5	20	69.87	172.4	1.82	1.3
6	19	62.40	166.7	1.70	2.6

* From skinfold measurements.

RESULTS

Skin, Rectal and Mean Body Temperatures. Mean weighted skin temperatures (MWST) are shown in figure 1. These data show that in all environmental combinations there was

TABLE 3. ANALYSIS OF VARIANCE FOR MWST AT 100 MINUTES OF EXPOSURE, PEAK CHANGE IN T_r AND MEAN HEAT PRODUCTION

Source of Variation	A. MWST				B. T_r				C. Heat Production			
	S.S.	D.F.	M.S.	F[a]	S.S.	D.F.	M.S.	F[a]	S.S.	D.F.	M.S.	F[a]
Total	1629.370	47			14.5992	47			114318.9	47		
Subjects	217.588	5	43.518	7.0[b]	5.7642	5	1.1528	6.76[b]	1436.0	5	287.2	
Temp. (T)	182.130	1	182.130	29.1[b]	.4800	1	.4800	2.82[d]	25967.9	1	25967.9	59.7[e]
Windspeed (W)	985.547	1	985.547	157.5[b]	1.5408	1	1.5408	9.04[b]	56998.9	1	56998.9	131.1[e]
Rel. Humid. (H)	.005	1	.005	NS[c]	.1633	1	.1633	NS	7442.9	1	7442.9	17.1[e]
T × H	7.922	1	7.922	NS	.0208	1	.0208	NS	4627.8	1	4627.8	10.6[e]
T × W	7.140	1	7.140	NS	.0300	1	.0300	NS	3192.0	1	3192.0	7.3[e]
W × H	1.172	1	1.172	NS	.1633	1	.1633	NS	114.9	1	114.9	NS
T × H × W	15.735	1	15.735	NS	.0008	1	.0008	NS	1118.7	1	1118.7	NS
Residual	212.131	35	6.061		6.4360	35	.1839		14855.7	35	424.4	
Comb. error of nonsig. components	244.100	39	6.259		6.6509	39	.1705		16089.3	37	434.8	

[a] F (based on combined error). [b] $P < .01$. [c] Not significant ($P > .05$). [d] $P < .05$. [e] See text for probabilities.

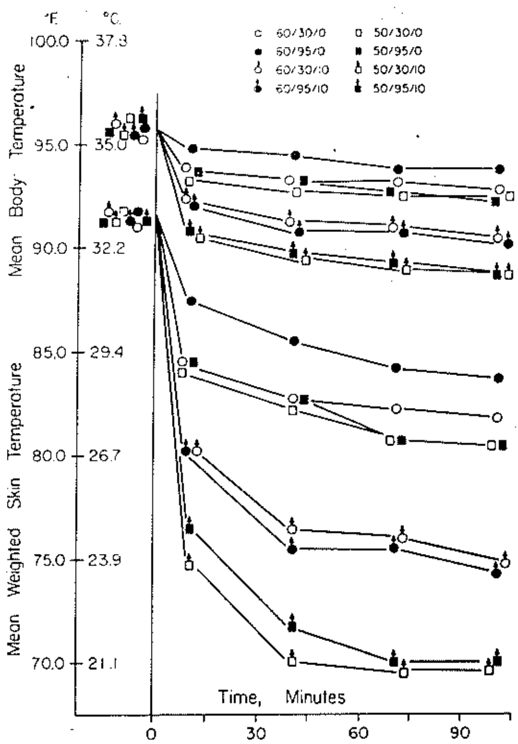

FIG. 1. Mean weighted skin temperature and mean body temperature of 6 men during exposure to cold.

a drop in MWST. From figure 1 there emerge three important points: *a)* wind was the prepotent factor, as evidenced by the fact that the four lowest MWST's were obtained with a 10 mph wind; *b)* dry bulb was a factor when wind was held constant, i.e. for a given windspeed the lower MWST occurred with the lower dry bulb; *c)* relative humidity had no apparent effect on MWST. The analysis of variance for MWST is presented in table 3*A*. The analysis shows a significant effect of windspeed and temperature but not for relative humidity.

Rectal temperatures, in general, rose to peak values within 40–80 minutes after entering the cold room; these peaks ranged from an increase of 0.2°F (above control) to 0.8°F at 60/95/0 and 50/95/10, respectively (fig. 2). The rectal temperatures dropped to or below control values during the remainder of the cold exposures. The same general pattern of a major impact of wind, with no effect of relative humidity that was found regarding MWST, was observed with respect to T_r. Table 3*B* shows the analysis of variance for T_r.

Mean body temperature (MBT) was calculated from the following formula:

$$MBT = 0.33\ MWST + 0.67\ T_r(6)$$

Control values for MBT were remarkably constant from day to day (fig. 1); the average control MBT for all men was 95.8°F. Mean body temperature decreased during all cold exposures; the decrease ranged from 2.5°F at 60/—/0 to 7°F at 50/—/10 (fig. 1). The relative order of importance of environmental factors on MBT was the same as that found for skin and rectal temperatures, viz wind and dry bulb had clearcut effects, with no discernible effect of relative humidity.

Heat Exchanges: Heat Production, Heat Debt and Heat Dissipation. From the data collected it is possible to estimate the effects of the various exposures on heat production, heat debt and total heat dissipation.

Heat production, calculated from $\dot{V}O_2$, increased in all exposures. The greatest increases were associated with the higher windspeed. Thus, there was approximately a threefold increase, from controls, at 50/10/10, and only a 25% increase at 60/95/0 (fig. 3). There was a significant overall effect of temperature, windspeed and relative humidity on heat production, as well as a significant interaction between relative humidity and temperature and temperature and windspeed (table 3*C*). These significant interactions make the choice

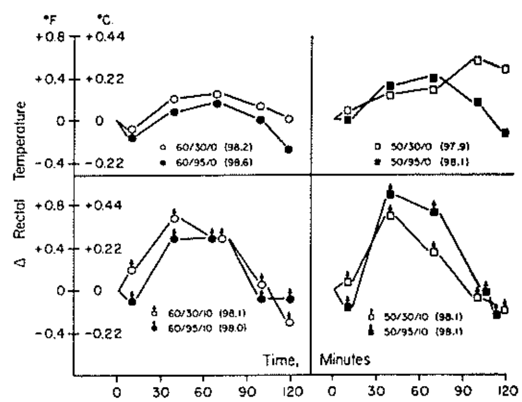

FIG. 2. Average change in rectal temperature of 6 men during exposure to cold. Numbers in parentheses refer to average rectal timperature during pre-exposure period.

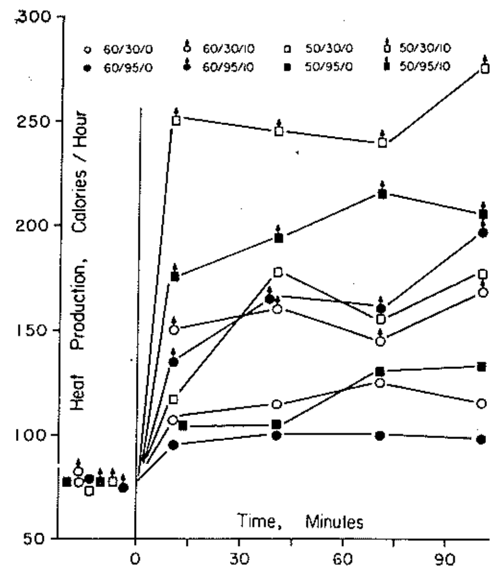

FIG. 3. Heat production of 6 men at various times during exposure to cold.

of the proper error term difficult. Analysis of the effects inside the interaction indicate that relative humidity was important in determining heat production under the following conditions: 50/—/10, 50/—/0, 60/—/0, but not at 60/—/10.

The significant interaction between temperature and relative humidity indicates that the magnitude of the difference in heat production is not the same for all conditions. The effects inside the interaction were analyzed by utilizing differences. It is clear from this analysis that the interaction was caused by the nonuniform effect of humidity within conditions.

The average differences in heat production between the two humidities at a given condition are:

Temp. °F	Windspeed mph	Relative Humidity 30% minus 95%	Probability of Identity
60	0	18.02	<.05
60	10	−7.48	ns
50	0	37.98	<.01
50	10	51.10	<.001
		Total	<.001

Since these differences are not uniform or equal this explains the observed interaction. The significance of this humidity effect is shown when a t test is performed on the differences. The two larger differences are significant beyond the 1% level and third largest is significant beyond the 5% level. In order to confirm the initial analysis of variance, the combined significance was computed and was less than .001. The combined significances of the temperature effect and windspeed effect were also less than .001. Individual differences, as computed within the temperature-relative humidity interaction, showed uniformity of variance. This indicates that the accuracy of the experiment was in no way affected by the experimental conditions.

Heat debt was calculated from the following formula:

$$\text{Heat Debt} = \Delta \text{ MBT } (0.83 \times \text{Wt.})$$

where 0.83 = specific heat of tissue and Wt. = body weight in kilograms. The largest heat debt was 230 Cal. and was incurred at 50/—/10. The smallest heat debt—75 Cal.—occurred at 60/95/0 (fig. 4, table 4). The major portion of the cumulative heat debt (50–75%) occurred during the first 10 minutes in all exposures (table 4). After the first 10

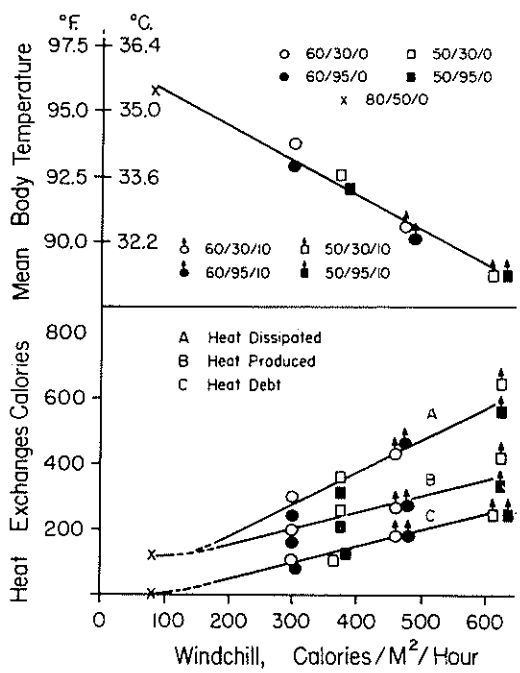

FIG. 4. Relationship of mean body temperature and heat exchanges of 6 men to windchill.

minutes, the rate of incurrence of heat debt was decreased and during the following 90 minutes the rate was constant.

Total heat dissipation was calculated from heat production and body heat debt; these calculations are given in table 4. Total heat dissipated after 100 minutes exposure to 50/30/10 was 650 Cal. This was approximately three times the heat dissipated during exposure to 60/95/0.

Insulation of Tissues. Insulation of tissues was calculated only for the whole body. The method of calculation was according to Burton's (1) equation:

$$I_T = I_A \times \frac{(T_r - T_s)}{1.21(T_s - T_a)}$$

Where I_A is the insulation of air and is dependent on air movement, T_r, T_s, and T_a are the temperatures of the rectum, skin (MWST), and ambient air, respectively. Values for the I_a were taken from tables in Carlson's monograph (7). I_a was considered to be 0.2 with a wind of 10 mph and 0.8 when the wind was minimal. Table 5 shows a comparison of our results with those of Burton (1). It is readily apparent that there is not good agreement between the two studies; the results of the present study indicate a degree of vasoconstriction only half that found by Burton. According to Burton's scale of 0.15 Clo units for full vasodilatation and 0.8 Clo units for full vasoconstriction, the subjects in the present study, under the most severe conditions, would be considered to be almost completely vasodilated ($I_T = 0.23$)! This may or may not be true since we had no independent method for assessing the extent of vasoconstriction or vasodilatation.

TABLE 4. HEAT EXCHANGES OF NUDE MEN DURING 100 MINUTES EXPOSURE TO COLD

Chamber Conditions	Heat Prod., Cal.			Heat Debt, Cal.			Heat Diss. Cal.		
	Time, Min.			Time, Min.			Time, Min.		
	10	50	100	10	50	100	10	50	100
60/30/0*	18	94	195	65	79	110	83	173	305
60/95/0	16	82	165	37	55	75	53	137	240
50/30/0	19	124	262	61	86	96	80	210	358
50/95/0	18	90	198	67	82	114	85	172	312
60/30/10	25	130	261	119	149	180	149	279	441
60/95/10	23	125	274	120	156	185	143	281	459
50/30/10	42	208	422	177	210	229	219	418	651
50/95/10	29	155	330	162	191	230	191	346	560

* 60°F dry bulb/30% relative humidity/0 wind.

TABLE 5. INSULATION OF TISSUES IN CLO UNITS AFTER 100 MINUTES EXPOSURE TO THE VARIOUS CONDITIONS

Chamber Conditions	Insulation of Tissues in Clo Units	
	Present study	Burton (1)
60/30/0*	.45	.85
60/95/0	.43	.84
60/30/10	.26	
60/95/10	.26	
50/30/0	.40	.85
50/95/0	.41	.80
50/30/10	.24	
50/95/10	.23	

* 60°F dry bulb/30% relative humidity/0 wind (mph).

TABLE 6. STATISTICAL ANALYSIS OF SUBJECTIVE SENSATIONS OF COLD

	Sum of Rankings for all Subjects	Total	Probability of Identity
Temperature, °F			
50	480.5		< .05
60	695.5	1176	
Windspeed, mph			
0	367.0		< .01
10	809.0	1176	
Relative humidity, %			
30	531.0		> .10
95	645.0	1176	

Subjective Sensations of Cold. The subjective responses for each of the six subjects for each of the 8 days of exposure were ranked from 1 to 48 (making allowances for ties) according to the magnitude of the response. It was then possible to perform a 'U' test (5) on the rankings. The data show that the subjects felt no colder when exposed to high humidity than when exposed to low humidity. The most important factor subjectively seemed to be wind, with temperature having a smaller but significant effect (table 6). It is interesting that the subjective response to the experimental conditions agrees with the physiological responses.

DISCUSSION

It is quite clear that of the three environmental variables used, wind had the greatest impact on both the physiological and subjective responses. Dry bulb also had a marked, although somewhat lesser impact. Relative humidity, however, had little or no effect on any of the responses except heat production. In this connection, we have calculated windchill for each of the experimental conditions (8). Figure 4 shows the relationship between windchill and total heat debt, total heat dissipation, total heat production and mean body temperature after 100 minutes of exposure. The correlation between windchill, which does not take humidity into consideration, and these parameters supports the foregoing statements.

Burton, Snyder and Leach (1) reported significant effects of humidity on rectal temperature (higher T_r with low humidity) and subjective sensations (more sensation of cold with low humidity), with low relative humidity eliciting greater responses than high humidity. They concluded that humidity per se had a physiological effect on unclothed men. The results of our study support this conclusion only in part, i.e. heat production.

The results of this study do not necessarily negate a physiological basis for cold-wet sensations. It may be necessary to study the clothed man in order to uncover these responses. On the other hand, despite the fact that we attempted to reproduce cold-wet conditions, based on a meteorological definition, it is possible that the conditions selected may not be representative of the outdoor ambient conditions which elicit cold-wet responses in the clothed man. One other factor which should be considered is whether it is possible to simulate cold-wet conditions in a chamber; even though wind, dry bulb and humidity can be controlled, it is doubtful whether radiation can be adequately simulated. For example, in our experiments, the radiation from the body to the walls and from overhead lights to the body were not measured and were probably not characteristic of outdoor cold-wet conditions, where solar radiation would normally be screened by a cloud cover and radiative loss from the body would be modified by clothing.

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