PHYSIOLOGICAL RESPONSES DURING WORK IN HOT HUMID ENVIRONMENTS

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Summary: Studies have been conducted on 6 young healthy Indians in simulated comfortable, hot humid and very hot humid condtions to evaluate the physiological reactions during work. Physiological responses like exercise oxygen consumption ($\dot{V}o_2$), pulmonary ventilation ($\dot{V}_E$) and heart rate (HR) were noted during sub-maximal fixed work rates of 400, 500 and 600 *kgM/min*. In addition, duration of continuous work at these three rates of work, in the three simulated environments was also noted. Physiological responses i.e. $\dot{V}o_2$, $\dot{V}_E$ and HR were noted every 15 minutes of work. Besides these responses, rectal temperature (T_r), mean skin temperature ($\overline{T}_s$) and mean sweat rate were also noted during the continuous work.

Results indicated a significantly higher oxygen cost ($\dot{V}o_2$) during 400 *kgM/min* of work in hot and very hot humid environments whereas, in the higher rates of work, the changes were not significant. The cardiac frequency showed a significantly higher rise during different grades of activities in hot and very hot environments except in the highest work rate in hotter environments, possibly due to attainment of maximum heart rate. The duration of continuous physical efforts in various grades of activities decreased significantly ($P<0.001$) in hot humid environments than in the comfortable temperature. During the progression of the work, the mean skin temperature decreased in comfortable temperature but increased in hot humid environments. The mean rectal temperature, increased during work in hot humid environment, and the rate of rise was much faster in higher work rates attaining the target temperature much earlier. The rate of sweating increased significantly as the heat load of the body increased. In hot humid environments, work performance decreased due to early attainment of maximum heart rate, reduction in $\dot{V}o_2$ max, disproportionate rise in rectal temperature, narrowing of the difference between the core and the skin temperature and attainment of maximum sweating rate.

INTRODUCTION

During work in heat, increased heat elimination is necessary and is met by an increase in blood flow through the skin (8,9,15,16). During heat stress, the blood flow through the skin is not always sufficient for the dissipation of heat. When the body is dehydrated the problem is aggravated by the gradual decrease in both circulating blood volume and sweating intensity. Since the thermal conduction of heat from the "Core" to the body surface is not sufficient (10) to eliminate all the heat during heavy work, sweat production is enhanced, the degree of which depends primarily upon environmental conditions (12). The circulation is put under stress when men are exposed to hot conditions as evidenced by cardio-accelaration with associated fall in stroke volume (26). However, there is no alteration in cardiac output and a-Vo_2 difference in heat (18,19). These reactions might alter maximum cardiac output in such a way that the individuals oxygen transport mechanism during maximal efforts suffers significantly. Therefore, the body temperature and heart rate are good indicators of individual tolerance to work in heat stress, (2,8). There is no single physiological parameters, which is prefectly correlated to the fatigue experienced during prolonged work in heat. A combined effect of all physiological responses can render a better concept for the termination of work in hot climate.

Further, we have observed (24) that work in humid climate imposes greater thermoregulatory strain on an individual than that in dry heat.

Since India is a tropical country, the ubiquitous high ambient humidity limits the possible evaporative cooling. Convective cooling is almost impossible without air movement. This inturn leads to limitations in work performance. Precise information regarding the physiological responses during work in hot humid climate is limited but is required for efficient planning of troops operation as well as utilization of man power in industry. Studies have, therefore, been conducted to know the effects of hot humid climate on physiological changes during prolonged sub-maximal works, as well as responses in continuous prolonged work.

MATERIALS AND METHODS

The studies were conducted on 6 young healthy Indian soldiers, well acclimatised to heat with a mean, age, height and weight of 21.7 *yrs*, 170.8 *cm*, and 61.0 *kg* respectively. Experiments were carried out in a climatic chamber, at 3 simulated environmental conditions classified as comfortable, hot humid (HH) and very hot humid (VHH) (Table I). The subjects reported to the laboratory in the morning on each test day after a light breakfast. After 30 min rest in the experimental conditions, the subjects were given a fixed sub-maximal exercise of 400, 500 and 600 *kgM/min* (65.4, 81.8 and 98.1 watts) for 6 minutes. Physiological responses like oxygen consumption ($\dot{V}o_2$), heart rate (HR), minute ventilation ($\dot{V}_E$) were recorded during the steady state (5th to 6th min) of exercise. For measuring minute ventilation the subjects breathed through a low resistence breathing valve (Collins) into a Cowan-Parkinson dry gasmeter. The mixed expired air samples were analysed for oxygen, and carbondioxide content by passing through calibrated Co_2 analyser (Beckman) and oxygen analyser (Servomex controls). The exercise heart rates were recorded in an electrocardiograph using chest leads. In addition, subjects were given 3 rates of continuous work of 400, 500 and 600 *kg/min* under three simulated environmental conditions, in a latin square design, on a mechanically braked bicycle ergometer. The pedal revolutions were maintained at 60 rpm and the work was continued till one of the following criteria is attained :

1. Cannot maintain the assigned rate of work even after best effort.

2. Attainment of heart rate of 180 beats/min or above.
3. Rectal temperature of 40°C.

TABLE I : Simulated environmental conditions during work.

S.No.	Thermal sensation	*Dry bulb* °C	*Wet bulb* °C	*R.H.* %	*Effective temp. (E.T.)* °C	*W.B.G.T.* °C
1	Comfortable (C)	27.0	22.0	60	24.4	23.5
2	Hot humid (H.H.)	37.0	29.0	60	31.4	32.0
3	Very hot humid (V.H.H.)	40.0	32.5	60	33.9	34 8

Besides the above physiological criteria, physical criteria of deterioration, leading to imminent collapse were also observed by an experienced medical officer. Work was also terminated because of signs of physical fatigue, feeling of warmth all over the body, unsteadyness, exhaustion and actual collapse. If the work was continued more than 90 min without the indication of above mentioned physiological and physical criteria the work was discontinued with the assumption that the individual can continue the work for a prolonged period. Physiological responses like $\dot{V}O_2$, V_E, HR, rectal temperature (T_r) mean skin temperature ($\bar{T}_s$) were noted every 15 min, during the continuous work. The skin and rectal temperatures were monitored by using a YSI telethermometer. The skin temperatures were monitored from four sites and the mean weighted skin temperature was worked out according to Ramanathan's equation (17). The sweat loss during the entire work period was noted by weighing the subjects nude in a sensitive human weighing machine (Avery) to the accuracy of 25 *g* before and after work, incorporating necessary corrections for fluid intake and urine voided if any.

RESULTS

The mean $\dot{V}O_2$, V_E and HR during sub-maximal fixed work rates of 400, 500 and 600 *kgM/min* are shown in Table II. The mean oxygen consumption during the work rate of 400 *kgM/min* was 1.264 lit at comfortable temperature but increased significantly to 1.360 and 1.442 lit in hot humid and very hot humid conditions respectively. During the higher work rates of 500 and 600 *kgM/min*, though the mean $\dot{V}O_2$ increased in hot humid and very hot humid conditions, these changes were not statistically significant. The mean exercise ventilation (V_E) during 400 *kgM/min* of work at comfortable temperature was 33.9 *l/min* but increased significantly to 40.5 and 43.1 *l/min* at hot humid and very hot humid conditions respectively. At the work rate of 500 *kgM/min* the V_E of 36.4 *l/min* in comfortable temperature increased insignificantly to 39.9 and 48.8 *l/min* in the two hot humid conditions. The exercise heart rate observed during 400 *kgM/min* of work at comfortable temperature was 123.7 beats/min but increased significantly to 155.7 and 171.3 beats/min at the two hot humid conditions. The increase in very hot humid compared to hot humid was also significant The similar trend of significant increase in heart rate during work in hot environment was observed at the work rates of 500 and 600 *kgM/min* also. However, the increases in heart rate during 600 *kgM/min* exercise, in hot humid and very hot humid, Conditions were not significantly different possibly due to the attainment of near maximal heart rates.

TABLE II : Mean (±SE) physiological responses during sub maximal fixed work in hot humid climate.

S.No.	Work rate (kgM/min)	Environmental condition	$\dot{V}O_2$ (LSTPD/min)	$\dot{V}_E$ (LBTPS/min)	H. Rate (beats/min)
1		Comfortable	1.264	33.9	123.7
			0.037	1.547	6.16
	400	Hot humid	1.360	40.5	155.7
			0.081	2.560	2.220
		Very hot humid	1.442	43.1	171.3
			0.065	4.307	2.170
			C Vs HH*	C. Vs HH*	C Vs HH*
			C Vs VHH**	C. Vs VHH*	C Vs VHH***
					HH Vs VHH*
2		Comfortable	1.427	36.4	136.7
			0.048	1.539	4.32
	500	Hot humid	1.462	39.9	160.0
			0.647	2.148	4.26
		Very hot humid	1.485	48.8	181.7
			0.061	4.314	1.82
					C Vs HH***
					C Vs VHH***
					HH Vs VHH*
3		Comfortable	1.767	46.4	153.0
			0.081	1.813	1.91
	600	Hot humid	1.798	49.4	172.0
			0.031	2.458	3.42
		Very hot humid	1.865	52.0	181.7
			0.051	2.358	1.06
				C Vs VHH*	C Vs HH*:
					C Vs VHH***

* = $P<0.05$, ** = $P<0.01$, *** = $P<0.001$

The mean durations in continuous physical efforts at different rates of work in the three climatic conditions are set-out in Table III. The mean duration while working at 400 *kgM/min* continuously in comfortable temperature was more than 90 minutes and possibly could have endured for 2-3 hrs. However, the same work could be endured only for 66 min in hot humid condition and 45 min in very hot humid condition. Similarly, while working at 500 *kgM/min*, the mean endurance time was 60 min and 36 min in hot humid and very hot humid conditions respectively. The highest work rate of 600 *kgM/ min*, was sustained more than 90 min in comfortable temperature but dropped significantly to 33 and 23 min in hot and very hot humid environments. To evaluate the reasons for the decrement in endurance work capacity in hot environments, the physiological responses during continuous work have been analysed. The heart rate responses during the progress of work in different thermal environments have been shown in Fig 1. It is observed, that

TABLE III : Duration (min) in continuous physical activity of varying severity in different hot environments.

S.No.	Thermal condition	Rate of work		
		400 kgM/min	500 kgM/min	600 kgM/min
1	Comfortable	More than 90 min	More than 90	Above 90
2	Hot humid	66" ***	60***	33***
3	Very hot humid	45" ***	36***	23***

*** Indicates highly significant (P<0.001)

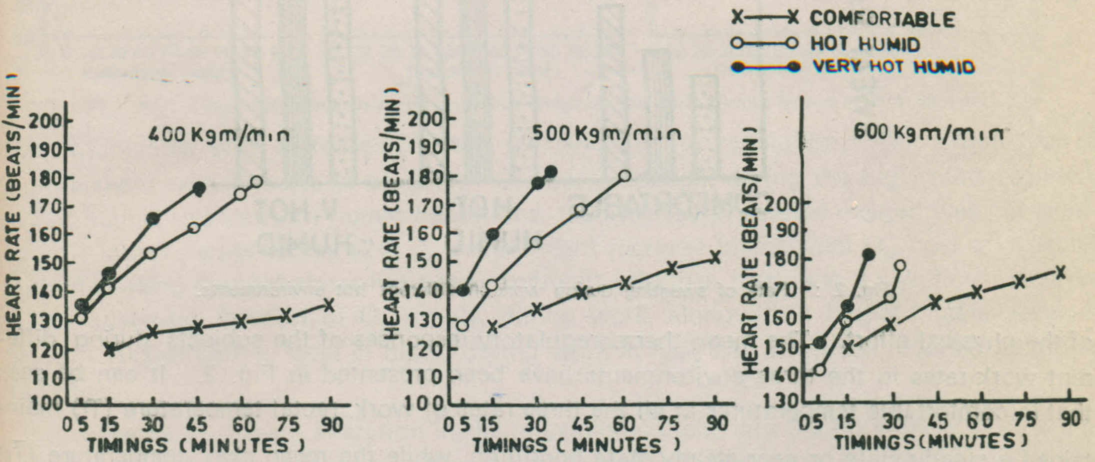

Fig. 1 : Changes in exercise heart rate during different thermal conditions.

the heart rate response is distinctly higher in hot environments than in comfortable condition. However, the progression of the heart rate towards the target maximum of 180 beats/min was much faster in hot humid and very hot humid conditions. For the regulation of thermal balance of the body, sweating and its evaporation is the principal mechansim of heat dissipation, more particularly during work in heat. As such, sweat rate is a good index of thermoregulatory efficiency. During work rates of 400, 500 and 600 *kgM/min* in comfortable temperature, the rates of sweating were 0.46, 0.60 and 0.82 *kg/hr* respectively (Fig. 2). While working continuously at 400 *kgM/min*, sweat rate increased significantly to 1.22 and 1.32 *kg/hr* in hot humid and very hot humid conditions. Similarly, significant increases in sweating rate occurred during higher work rates in hotter environments also. In very hot humid condition, the rate of sweating while working at 600 *kgM/min* was 1.98

kg/hr. This high rate of sweating cannot be maintained over a prologned period, with the result heat load on the body will start increasing at a faster rate, leading to termination

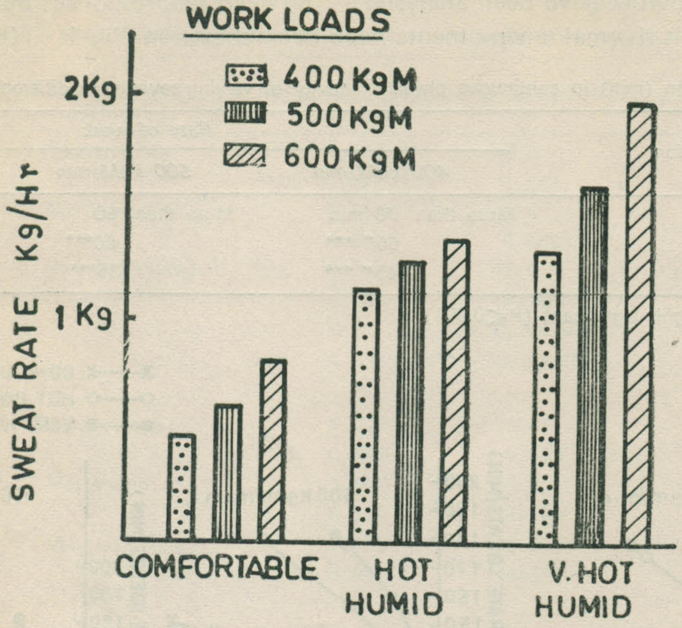

Fig. 2 : Rate of sweating during work in different hot environments.

of the physical effort. The mean thermoregulatory responses of the subjects during different work rates in the three environments have been presented in Fig. 3. It can be seen that in comfortable temperatures at all the three rates of work, rectal temperature (T^r) maintained a steady state or near steady state condition, while the mean skin temperature ($\bar{T}^s$) maintained a near steady state or slowly decreased on progression of work rate. In hot humid conditions at higher work rates the rectal (T^r) and mean skin temperatures ($\bar{T}^s$) increased progressively and the gradients between the two temperatures narrowed to a great extent.

DISCUSSION

A higher oxygen consumption during low rate of exercise has been observed in hot environments and this increase was more with the rise in the environmental severity. This indicates that thermal stress *per se* increases the energy requirements during work in heat. This finding is in agreement with the observations of Consolazio *et al.* (5), Kaufman *et al.* (11). In one of our earlier work also (7), the resting O_2 consumption was found to increase in hot environments. This increase in metabolic cost of work in heat may be due to various factors, such as increased demand on circulation for thermoregulation, increased activity of sweat glands and increased body temperature which in turn increases the biochemical reactions of the body (3, 4). This increased oxygen demand has also

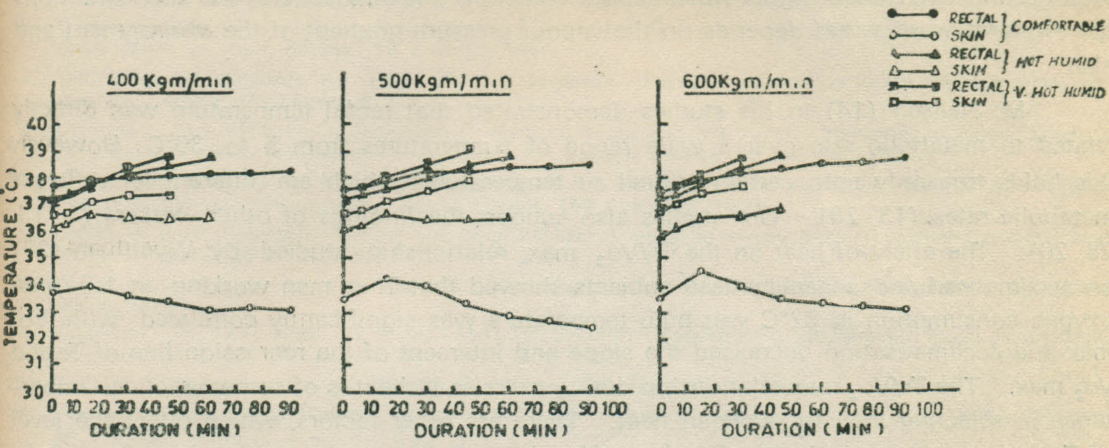

Fig. 3 : Mean responses in rectal and skin temperatures during work in hot humid climates.

been associated with increases in heart rate and minute ventilation. This observation is in agreement with Schulze *et al.* (21). Curiously enough, during the higher rates of work in hot humid and very hot humid conditions, the increase in aerobic oxygen was not significant. In our earlier works (24, 7) a significant increase in the total O_2, cost of exercise with increasing thermal stress has been observed. Further, there was a significant increase in the anaerobic fraction of O_2 supply, during work, alongwith a higher lactate level in blood. Higher lactate level in blood during work in heat has also been reported by others (6,26).

The most striking alteration in the physiological changes during work in heat is that of heart rate, which increased significantly at all levels of work till it neared the maximum. As such, the maximum heart rate is attained at lower levels of oxygen intake, in hot humid environments. It, therefore, follows that heart rate is increased and cardiac output is unaltered (18, 19) then the stroke volume must have been lowered. The higher heart rate in heat is therefore, a handicap and carries a premium. If for some reasons, the venous return to the right heart is restricted temporarily by a change of posture or due to any other reasons then the ability of the circulation to meet this emergency i.e. temporary accelaration of the heart can not occur in heat. Probably because of this fact, vasovagal faint in heat is common. Vasodilatation of blood vessels in the skin due to heat is well known. Skin blood flow in heat may be as high as 1.0 → 2.0 *l/min* (8). This amount of blood shunted away from muscle to skin would leave the muscle in a state of anoxia in heat.

In hot environments, maintainance of core temperature depends on the successful elimination of the body heat through, sweating and its evaporation, especially in the working individuals. Excess sweat produced runs off the body or drips and therefore is of little physiological benefit to the working men. In hot humid environments evaporation of sweat is impeded due to higher water vapour content in the atmosphere. In such situations the evaporation of sweat depends on the vapour pressure gradient of the environment and skin.

M. Nielsen (14) in his studies demonstrated that rectal temperature was directly related to metabolic rate over a wide range of temperatures from 5 to 30°C. However, this holds true only upto certain critical air temperatures which are different for different metabolic rates (13, 28). Our studies also support the findings of other workers (1, 13, 28, 20). The effect of heat on the Tr/Vo_2 max relationship studied by Wyndham (27) on acclimatised and unacclimatised subjects showed that Tr of men working at 1.0 *l/min* oxygen consumption in 32°C wet bulb temperature was significantly correlated with Vo_2 max and acclimatisation decreased the slope and intercept of the regression line of Tr and Vo_2 max. The Tr/Vo_2 max relationship during exercise in heat is of some practical importance in selecting men for work in heat. There are other factors, which effect the level of Tr during exercise in heat. Strydom (25) showed that men weighing less then 50 *kg* developed higher levels of Tr than heavier men when they worked at either 1.0 or 1.5 *l/min* O_2 consumption at 32°C wet bulb temperature. More importantly higher Tr was seen in men in dehydrated state than in the fully hydrated state or when they drink water *ad lib.*

There has been increasing evidence that in healthy young men, physical exercise in heat is a contributing factor in the development of heat disorders in industry and Armed Forces.

From the findings of the present studies, it seems probable to combine a number of physiological functions into a single index to predict the tolerance of work by men in hot humid environments.

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