Alterations of Cardiac Output, Stroke Volume, and Heart Rate during 3 Hours of Exercise in Different Ambient Temperatures

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Abstract The alterations of cardiovascular responses during 3 hours of treadmill walking in five thermal conditions, 20, 25, 30, 35, and 40°C, were studied in eight normal young men. Cardiac output (determined with the CO₂ rebreathing method), heart rate, oxygen uptake, rectal temperature, and mean skin temperature were measured at 10th minute, 1st hour, 2nd hour, and 3rd hour of exercise. Cardiac output in the 40°C showed a tendency to be higher than in the lower temperature conditions. Cardiac output did not change significantly in all environments during 3 hours of exercise. It might be thought a significant decrease in stroke volume during exercise compensated by a significant increase in heart rate. The most marked decrease in stroke volume and the most marked increase in heart rate occurred in the 40°C. A significant correlation between stroke volume and rectal temperature was found as a whole, and the relationship between them did not change during exercise. The analysis of covariance showed the relationship between heart rate and rectal temperature significantly altered during exercise.

The human adaptability to the thermal environments may be one of the most important subjects in the anthropological field. To investigate the man's responses to the thermal environments may be the primary step for the research of this subject.

When man is exposed to a hot environment, his heart rate increases in comparison with the values attained under the comfortable environment (e.g., Rowell et al., 1966). However, it has not been well established whether cardiac output in a hot environment differs from that in the comfortable environment or not. In fact, Nadel et al. (1979) found the increase in cardiac output above the normal responses during exercise in a hot environment. However, MacDougall et al. (1974) observed during exercise that cardiac output was not significantly altered in a hot environment from a comfortable condition. On the other hand, Rowell et al. (1966) found the decrease
in cardiac output below normal responses during exercise in a hot environment. Differences of findings concerning cardiac output in the hot environment seem to justify a further investigation into the cardiovascular responses to the thermal environments.

Furthermore, there have been very few works concerning the cardiovascular responses during the prolonged exercise in the various ambient temperatures. It is presumed that the cardiovascular responses alter with the time course of the exercise, and also the relationships among the physiological responses for the cardiovascular and other functions change with time. Therefore, it may be of value to study the effects of the prolonged exercise in the different ambient temperatures on the cardiovascular responses.

The purpose of this study is to investigate these problems during 3 hours of exercise in the different ambient temperatures.

**METHOD**

The subjects were eight normal males, 22-28 years of age. Their physical characteristics are shown in Table 1.

They performed 3 hours of treadmill walking at a constant speed of 5.6 km/h and a grade of 2.5% under five ambient temperature conditions, 20, 25, 30, 35, and 40°C, with relative humidity kept at 50%.

Heart rate, oxygen uptake, rectal temperature, cardiac output, and skin temperature were determined at the 10th minute, the 1st hour, the 2nd hour, and the 3rd hour of exercise. Heart rate was counted from the recordings of electrocardiograph. Oxygen uptake was determined by the collection of expired air into Douglas bags, and the analysis of gas was performed with a Respilyzer (Fukuda Irika). Rectal temperature was recorded with a thermistor inserted about 10 cm into the rectum. Cardiac output was determined by the CO2 rebreathing method: the mixed venous CO2 pressure was estimated by the methods as described by Defares (1958), Jernérus et al. (1963), and Klausen (1965), and the arterial CO2 pressure was assumed to be the same as in the end-tidal air. For the CO2 analysis a rapid infrared CO2 meter (Godart Capnograph) was used. Stroke volume was calculated from the values of cardiac output and heart rate. Skin temperature was recorded with thermocouples and a potentiometer, and mean skin temperature was calculated along the method of Ramanathan (1964). The results of analysis on skin temperature were reported elsewhere (Takasaki et al., 1979).

The subjects wore swimming pants, shorts, sleeveless undershirt, socks, and running shoes. Each subject walked once

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K. I.</td>
<td>25</td>
<td>169.9</td>
<td>55.4</td>
</tr>
<tr>
<td>T. K.</td>
<td>28</td>
<td>169.3</td>
<td>56.1</td>
</tr>
<tr>
<td>Y. T.</td>
<td>25</td>
<td>181.7</td>
<td>58.2</td>
</tr>
<tr>
<td>Y. F.</td>
<td>23</td>
<td>176.5</td>
<td>61.3</td>
</tr>
<tr>
<td>K. P.</td>
<td>22</td>
<td>166.9</td>
<td>70.8</td>
</tr>
<tr>
<td>S. Y.</td>
<td>23</td>
<td>166.9</td>
<td>69.9</td>
</tr>
<tr>
<td>K. Y.</td>
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<td>169.5</td>
<td>58.9</td>
</tr>
<tr>
<td>H. Y.</td>
<td>23</td>
<td>182.0</td>
<td>70.2</td>
</tr>
</tbody>
</table>
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a week under each of five ambient temperature conditions in randomized order. Experiments were carried out from July to early September.

The results were analyzed by computing the analysis of variance and t values. The analysis of variance was performed with respect to ambient temperature, exercise time, and different individuals.

RESULTS AND DISCUSSION

Analysis of variance concerning rectal temperature showed that the factor of the exercise time had a statistically significant influence ($P<0.005$), suggesting rectal temperature increased with time. The largest difference in rectal temperature was observed between the 10th minute and the 1st hour of exercise in all environments as shown in Fig. 1. In the environments below $30^\circ C$, there was no significant increase in rectal temperature after 1 hour of exercise. In the environments above $35^\circ C$, rectal temperature significantly ($P<0.05$ to $P<0.001$) increased through the exercise time, and the final rectal temperature at $35^\circ C$ and $40^\circ C$ reached $38.24\pm 0.18^\circ C$ and $39.02\pm 0.32^\circ C$, respectively.

Figure 2 shows the mean values of eight subjects for oxygen uptake. There was

Fig. 1. Mean values for rectal temperature obtained at 10th minute (○), 1st hour (●), 2nd hour (■), and 3rd hour (■) of exercise in the ambient temperature of 20, 25, 30, 35 and 40°C.
no distinct trend for oxygen uptake to increase with time.

The results of cardiac output are shown in Fig. 3. Analysis of variance disclosed no significant effects of the exercise time factor on cardiac output. The factor of the ambient temperature showed no significant effects on cardiac output as a whole. However, application of t-tests indicated that cardiac output in the 40°C environment was significantly higher than in the 25°C (P<0.01), 30°C (P<0.02), or 35°C (P<0.05) at the 1st hour of exercise, and cardiac output in the 40°C was significantly higher than in the 20°C (P<0.02) or 25°C (P<0.05) at the 2nd hour of exercise. These results are basically similar to the data of NADEL and colleagues (1979), who found that cardiac output was significantly higher in the 36°C environment than in the 20°C or 26°C environments during 20 to 25 minutes of moderate exercise (40% \(\dot{V}_{O_2 \text{max}}\)). The work load they used as a moderate exercise corresponded to the load of the present study (approximately 30-40% \(\dot{V}_{O_2 \text{max}}\)). During heavy exercise (70% \(\dot{V}_{O_2 \text{max}}\), NADEL et al. (1979) did not find the increase in cardiac output above the normal responses in a hot environment. Similarly, MAC-

![Fig. 2. Mean values for oxygen uptake obtained at 10th minute (○), 1st hour (●), 2nd hour (●), and 3rd hour (■) of exercise in the ambient temperature of 20, 25, 30, 35 and 40°C.](image)
DOUGALL and associates (1974) failed to find the significant increase in cardiac output during heavy prolonged exercise (70% \( \dot{V}O_2\text{max} \)). ROWELL and coworkers (1966) found that cardiac output did not increase by high ambient temperature during 15 minutes of exercise required greater than 49% of maximal oxygen uptake, and they observed the significant decrease in cardiac output when the subjects performed heavy exercise (63 to 70% \( \dot{V}O_2\text{max} \)). Thus, the effects of high ambient temperature on cardiac output may be affected by the severity of the exercise. During mild exercise cardiac output may be augmented by heat stress, since demands for the heat dissipation may become a primary stimulus for regulating cardiac output in this condition (ROWELL et al., 1966).

The correlation coefficient between oxygen uptake and cardiac output was highly significant as a whole (\( r=0.760, P <0.005 \)). The regression equations of cardiac output on oxygen uptake calculated in each time of exercise, however the analysis of covariance showed no significant difference between them. This implies the relationship between oxygen uptake and cardiac output did not change.

**Fig. 3.** Mean values for cardiac output obtained at 10th minute (○), 1st hour (●), 2nd hour (□), and 3rd hour (■) of exercise in the ambient temperature of 20, 25, 30, 35 and 40°C.
during 3 hours of exercise. Therefore, the sum of squares of deviation from the regression at each time of exercise were pooled and a regression equation of cardiac output (Q, l/min) on oxygen uptake (\(\dot{V}O_2\), ml/min) through the exercise time was calculated, which gave
\[ Q = 0.705 + 0.00776 \dot{V}O_2. \]

The average responses of stroke volume are shown in Fig. 4. Analysis of variance indicated that stroke volume in all environments significantly (P<0.005) reduced with time. The most marked decrease in stroke volume occurred at 40°C. The decrease in stroke volume during prolonged exercise were reported in several works (SALTIN & STENBERG, 1964; GRIMBY et al., 1966; MACDOUGALL et al., 1974). After 1 hour of exercise, stroke volume was significantly (P<0.05 to P<0.001) lower in the 40°C environment than in the conditions below 35°C.

Regression equations of stroke volume on rectal temperature were calculated in each time of exercise. The analysis of covariance showed no significant difference between the slopes and the elevations of these regression equations. Regression equation of stroke volume (SV, ml/beat) on rectal temperature (Tr, °C)

![Fig. 4. Mean values for stroke volumes obtained at 10th minute (○), 1st hour (●), 2nd hour (■), and 3rd hour (□) of exercise in the ambient temperature of 20, 25, 30, 35 and 40°C.](image-url)
through the exercise time was calculated as,

\[ SV = 770.6 - 17.96 \times Tr, \]

correlation coefficient being \(-0.522\) (\(P < 0.005\)).

Figure 5 gives the average responses of heart rate. Analysis of variance showed that the factor of the exercise time produced a significant influence (\(P < 0.005\)) on heart rate, suggesting that heart rate was significantly elevated during exercise. The most marked increase in heart rate occurred at 40°C environment. This increase in heart rate may be related to the decrease in stroke volume. From our data it would appear that the decrease in stroke volume during prolonged exercise was compensated by the increase in heart rate, and cardiac output was able to be maintained.

It was remarkable that there was no significant rise in heart rate until the 1st hour of exercise in the environments below 30°C, while rectal temperature significantly elevated during this period of exercise. Similar reactions in heart rate and rectal temperature were also observed by SHIMIZU et al. (1976). They found the least increase in heart rate between two submaximal works of 50% \(\dot{V}O_2\)max per-

![Figure 5](image_url)

**Fig. 5.** Mean values for heart rate obtained at 10th minute (○), 1st hour (●), 2nd hour (●), and 3rd hour (■) of exercise in the ambient temperature of 20, 25, 30, 35 and 40°C.
formed before and after the 1 hour of work of 30% $\dot{V}_{O_2}\text{max}$ or 40% $\dot{V}_{O_2}\text{max}$, while rectal temperature increased significantly between these two submaximal works. In the present study, mean skin temperature significantly (P<0.05 to P<0.01) dropped during the first 1 hour in the environments below 30°C, and showed no significant changes after 1 hour of exercise (TAKASAKI et al., 1979). Therefore, it may be concluded that the invariability in heart rate during the first 1 hour of exercise in the environments below 30°C can be accounted for by the combined effects of the fall in mean skin temperature and the rise in rectal temperature.

From the first measurement, heart rate was significantly (P<0.05 to P<0.02) higher at 40°C than in the environments below 30°C, while rectal temperature showed same level in all environments. Mean skin temperature observed at the

![Fig.6. Regression lines of heart rate on rectal temperature obtained at 10th minute, 1st hour, 2nd hour and 3rd hour of exercise.](image)
beginning of exercise was significantly (P<0.02 to P<0.01) higher at 40°C than below 30°C. It may be suggested that skin temperature accounted for some part of the initial rise of heart rate.

Heart rate significantly (P<0.01 to P<0.001) increased during the last 1 hour of exercise in all environments, in spite of rectal temperature showed no significant elevation during this period in the environments below 30°C.

The regression equations of heart rate on rectal temperature in each time of exercise were calculated, and the regression
lines are shown in Fig. 6. The statistical significance of difference in the regression coefficients and the elevations among these equations were tested by the analysis of covariance, and the results are shown in Table 2 and Table 3. The significance of difference in the elevations were confirmed (P<0.005), that is to say, the regression line significantly (P<0.005) shifted toward the right during the first 1 hour of exercise and the line significantly (P<0.025) shifted upward during the last 1 hour. This alteration in the relationship between heart rate and rectal temperature, especially the alteration during the last 1 hour, is noticeable. The elevated heart rate during the prolonged exercise was found by a number of investigators (Dill et al., 1931; Saltin & Steenberg, 1964; MacDougall et al., 1974; Shimizu et al., 1976; Ohnaka et al., 1977). Commonly, the elevated heart rate at a given oxygen uptake during prolonged exercise might be accounted for by the elevated internal body temperature (Shimizu et al., 1976; Ohnaka et al., 1977). Although it might explain to a great extent the elevation in heart rate in the present study, it does not apply to the rise in heart rate in the environments below 30°C during the last 1 hour of exercise. The detailed mechanism which underlies this reaction remains to be determined.

Since there have been very few works concerning cardiovascular functions during more than 3 hours of exercise in the different ambient temperatures, it is clear that further studies on these problems are necessary.

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REFERENCES


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種々の気温における長時間運動時的心拍出量、
一回拍出量、および心拍数の変化について

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8名の健康な成人男子（年齢22〜28歳）を被検者とし、気温20℃、25℃、30℃、35℃、および40℃（相対湿度約50％）に設定した人工気象室内で3時間のトレッドミル歩行（毎時5.6km、勾配2.5％）を行った。その間、10分目、1時間目、2時間目、および3時間目に、心拍出量、一回拍出量、心拍数を、酸素摂取量、直腸温、平均皮膚温と共に求めた。心拍出量は CO₂再呼吸法により求めた。

心拍出量と酸素摂取量は3時間の運動中、すべての気温条件で有意な変化を示さなかった。心拍出量と酸素摂取量の関係が密接であることは両者の相関が高いことから推測される。心拍出量は高温条件で高い傾向が認められ、その傾向は運動の1時間目および2時間目では有意であった。一回拍出量は運動の時間経過と共に有意に減少し、その傾向は気温の高い程、著しいことが示された。一回拍出量と直腸温には有意な負の相関が認められた。測定時間毎に求めた一回拍出量と直腸温の回帰直線は有意に異なり、両者の関係は3時間の運動中、変わらないことが示された。心拍数は運動中、有意に増加し、また、この傾向は気温の高い程、著しいことが認められた。運動の1時間目までは、直腸温は著しい増加を示したが、30℃以下の気温で得られた心拍数は有意な変化を示さなかった。これにより、この期間に有意な低下を示した平均皮膚温と有意な上昇を示した直腸温の複合作用によるものと思われる。30℃以下の気温で得られた直腸温は運動の1時間目以降、有意な変化を示さず定常状態を呈したが、心拍数は運動の2時間目から3時間目に有意な増加を示した。直腸温に対する心拍数の回帰を測定時間毎に求めると、回帰式の高さが有意に異なることが認められ、両者の関係が運動の時間経過により変化することが示された。