COMBINED INFLUENCES OF AMBIENT TEMPERATURE AND GRADED WORK ON CARDIOPULMONARY FUNCTIONS

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Several cardiopulmonary items were measured in eight adult females who had performed stationary ergometer cycling of 75–450 kgm/min in air temperature between 14°C and 35°C. The experiments were designed on the basis of the Latin square method and the results were analyzed by computing the analysis of variance and multiple regression equations for each item linked with work rate and air temperature. In view of the degree of affinity of the effect of work rate and that of air temperature, the items could be divided into three groups. The first group consisted of items of pulmonary functions closely related with work rate but independent of air temperature, such as pulmonary ventilation, oxygen intake, carbon dioxide production, respiratory exchange ratio, and ratio of oxygen removal. The second group characterized by linear dependency on air temperature included mean skin temperature and mean innermost air temperature. The third group consisting of heart rate, pulse sum during work, and work pulse sum was intermediate. In spite of the confusion in the literature about the attitude of oxygen intake or mean skin temperature during work in heat, the former was the most stable in relation to change in air temperature and the latter was independent of work intensity.

Many investigators have studied the effects of muscular work and air temperature on cardiopulmonary functions or body temperature, however, as is well known, inconsistency among such studies still exist. The oxygen intake in heat and the mean skin temperature during work are the most typical inconsistencies (Rowell, 1974; Sato and Katsuura, 1975). Progress in studies on combined influence on cardiopulmonary functions of work load and air temperature is dependent upon the investigation in numerical terms of the degree of the effect of both factors on some of the fundamental parameters of cardiopulmonary func-

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tions and determining which functions or items are influenced most by each of the two factors.

METHODS

The experiments were designed on the basis of the Latin square method using 4³. Eight young female subjects, age 19 to 20, all in good physical condition, were divided into four groups of two each. Each subject first sat relaxed on a bicycle ergometer and then performed stationary ergometer cycling at three different levels of work (75, 225, and 450 kgm/min) to make four work rate (WR) grades. The four groups of subjects, four grades of WR, and four different air temperature (Ta) conditions constituted the experimental design based on the Latin square method of 4³.

The experiments were performed in a climatic chamber. The wall, ceiling, and floor of the room were maintained at the same temperature as the Ta during all the experiments. The relative humidity was maintained at 50% throughout all the Ta conditions. The subjects wore the same type of ordinary clothing weighing a total of 465 g, and each rested for 30 min on a chair before performing the four grades of work at the same Ta as the experimental Ta condition in the climatic chamber. The duration of work was 6 min and all the measurements were performed during the last one minute of the work.

The skin temperature of the chest, upper arm, thigh, and lower leg were recorded by means of copper-constantan thermocouples, and the mean skin temperature (Tsk) was calculated according to Ramanathan’s formula (RAMANATHAN, 1964). The innermost temperature of the air between the skin and the clothing was also recorded by means of the thermocouples on the chest, upper arm, thigh, and lower leg, and the mean innermost air temperature (Ta) was obtained as an arithmetical mean of the innermost air temperature readings at the above four sites. Pulmonary ventilation (Ve) and oxygen intake (VO₂) were determined by analyzing collected samples of the expired air. The heart rate (HR) was recorded electrocardiographically using chest leads.

The following physiological items were investigated: Tsk (°C), Tna (°C), Ve (l/min, BTPS), VO₂ (ml/min, STPD), carbon dioxide production (VCO₂, ml/min, STPD), HR (beats/min), work pulse sum (WPS, beats), pulse sum during work (PSW, beats), oxygen pulse (O₂P, ml/beats/min, STPD), respiratory exchange ratio (R), ratio of oxygen removal (R–O₂R, ml·STPD/l·BTPS), and ratio of carbon dioxide annexing (R–CO₂A, ml·STPD/l·BTPS).

The measurement results were analyzed by calculating the analysis of variance. The sum of squares from the sample means for the Ta factor were divided into the linear, quadratic, and cubic components. The multiple regression equation of each of the above items on WR and Ta, correlation coefficients between each item and WR and/or Ta, and the relative strength of either or WR or Ta for
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prediction of the estimated value of each item from the multiple regression equations were also computed.

RESULTS

The influence of the WR factor, the linear, quadratic, and cubic components in the \(T_a\) factor, and the interaction between WR and each component in \(T_a\) on all the items were examined by the analysis of variance, and the significantly influenced items, their significance level, and their source of variation are shown in Table 1. None of the items investigated here were confirmed to be significantly influenced by the interaction factor.

Table 1. Significantly influenced items.

<table>
<thead>
<tr>
<th>Items</th>
<th>Significance level</th>
<th>Source of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\dot{V}_{O_2})</td>
<td>0.005</td>
<td>WR</td>
</tr>
<tr>
<td>(\dot{V}_e)</td>
<td>0.005</td>
<td>WR</td>
</tr>
<tr>
<td>(\dot{V}_{CO_2})</td>
<td>0.005</td>
<td>WR</td>
</tr>
<tr>
<td>R</td>
<td>0.005</td>
<td>WR</td>
</tr>
<tr>
<td>R-O(_2)R</td>
<td>0.005</td>
<td>WR</td>
</tr>
<tr>
<td>R-CO(_2)A</td>
<td>0.005</td>
<td>WR</td>
</tr>
<tr>
<td>O(_2)P</td>
<td>0.005</td>
<td>WR</td>
</tr>
<tr>
<td>HR</td>
<td>0.005</td>
<td>WR</td>
</tr>
<tr>
<td>PSW</td>
<td>0.005</td>
<td>WR</td>
</tr>
<tr>
<td>WPS</td>
<td>0.005</td>
<td>WR</td>
</tr>
<tr>
<td>(T_a)</td>
<td>0.005</td>
<td>linear component in (T_a)</td>
</tr>
<tr>
<td>(T_e)</td>
<td>0.005</td>
<td>linear component in (T_a)</td>
</tr>
<tr>
<td>R-CO(_2)A</td>
<td>0.025</td>
<td>linear component in (T_a)</td>
</tr>
<tr>
<td>O(_2)P</td>
<td>0.025</td>
<td>linear component in (T_a)</td>
</tr>
<tr>
<td>HR</td>
<td>0.025</td>
<td>linear component in (T_a)</td>
</tr>
<tr>
<td>PSW</td>
<td>0.05</td>
<td>linear component in (T_a)</td>
</tr>
<tr>
<td>PSW</td>
<td>0.05</td>
<td>quadratic component in (T_a)</td>
</tr>
<tr>
<td>WPS</td>
<td>0.05</td>
<td>quadratic component in (T_a)</td>
</tr>
</tbody>
</table>

The multiple regression equation for each of the items on WR and \(T_a\) was calculated and is shown in Table 2 with the multiple correlation coefficients between each item and two independent variables, the simple and partial correlation coefficients between the items and either of the two variables, and the relative strength of both variables for prediction of the value of each of the items from the multiple regression.

HR was confirmed to be significantly affected by the WR factor and the linear component in the \(T_a\) factor. The significant effect of WR on HR is expressed also by a large correlation coefficient between them. This is reflected directly in the close multiple correlation among HR, WR, and \(T_a\). Although the simple correlation between HR and \(T_a\) is not statistically significant, the partial correla-
Table 2. The relation between each item, $WR$, and $T_a$.

<table>
<thead>
<tr>
<th>Item</th>
<th>Regression equation</th>
<th>$R$</th>
<th>$r$ (with $WR$)</th>
<th>$r$ (with $T_a$)</th>
<th>Relative strength (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Simple</td>
<td>Partial</td>
<td>Simple</td>
</tr>
<tr>
<td>$V_{O_2}$</td>
<td>$\hat{Y} = 282 + 1.54WR - 0.570T_a$</td>
<td>0.733**</td>
<td>0.733**</td>
<td>0.733**</td>
<td>-0.012</td>
</tr>
<tr>
<td>$V_{CO_2}$</td>
<td>$\hat{Y} = 166 + 2.41WR - 1.49T_a$</td>
<td>0.973**</td>
<td>0.973**</td>
<td>0.973**</td>
<td>-0.027</td>
</tr>
<tr>
<td>$V_e$</td>
<td>$\hat{Y} = 6.14 + 0.730WR + 0.100T_a$</td>
<td>0.935**</td>
<td>0.935**</td>
<td>0.935**</td>
<td>0.058</td>
</tr>
<tr>
<td>R</td>
<td>$\hat{Y} = 0.948 + 0.000405WR - 0.000999T_a$</td>
<td>0.761**</td>
<td>0.757**</td>
<td>0.760**</td>
<td>-0.085</td>
</tr>
<tr>
<td>R–O₂R</td>
<td>$\hat{Y} = 25.0 + 0.0152WR - 0.151T_a$</td>
<td>0.612**</td>
<td>0.557**</td>
<td>0.576**</td>
<td>-0.252</td>
</tr>
<tr>
<td>R–CO₂A</td>
<td>$\hat{Y} = 23.5 + 0.0252WR - 0.170T_a$</td>
<td>0.806**</td>
<td>0.770**</td>
<td>0.793**</td>
<td>-0.237</td>
</tr>
<tr>
<td>O₂P</td>
<td>$\hat{Y} = 3.51 + 0.00988WR - 0.0365T_a$</td>
<td>0.919**</td>
<td>0.906**</td>
<td>0.917**</td>
<td>-0.153</td>
</tr>
<tr>
<td>HR</td>
<td>$\hat{Y} = 58.3 + 0.187WR + 0.841T_a$</td>
<td>0.958**</td>
<td>0.938**</td>
<td>0.956**</td>
<td>0.193</td>
</tr>
<tr>
<td>PSW</td>
<td>$\hat{Y} = 36.7 + 0.841WR - 1.79T_a$</td>
<td>0.973**</td>
<td>0.968**</td>
<td>0.972**</td>
<td>-0.094</td>
</tr>
<tr>
<td>WPS</td>
<td>$\hat{Y} = 22.8 + 1.10WR - 1.88T_a$</td>
<td>0.959**</td>
<td>0.956**</td>
<td>0.959**</td>
<td>-0.074</td>
</tr>
<tr>
<td>$T_a$</td>
<td>$\hat{Y} = 28.9 - 0.000487WR + 0.213T_a$</td>
<td>0.898**</td>
<td>-0.045</td>
<td>-0.102</td>
<td>0.897**</td>
</tr>
<tr>
<td>$T_e$</td>
<td>$\hat{Y} = 22.1 - 0.00122WR + 0.380T_a$</td>
<td>0.948**</td>
<td>-0.066</td>
<td>-0.206</td>
<td>0.946**</td>
</tr>
</tbody>
</table>

*, ** Show the significance level at 0.05 and 0.01, respectively.

*** The relative strength for prediction of the estimated value was calculated based on the linear function of $T_a$. 

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The combined influence of temperature and work, or the correlation without influence of the WR factor, is significant. This may be connected with the significant effect of the linear component in $T_a$ on HR. These differences between the two independent variables, WR and $T_a$, may well explain the difference between them in the relative strength for prediction of the estimated value of HR.

PSW was confirmed to be significantly affected by WR and to have a close correlation with it. Although the simple correlation between PSW and $T_a$ is not significant, the partial correlation proves significant, suggesting a clear relationship between them if the influence of WR is excluded. Not only the linear component in $T_a$ but also the quadratic one showed a significant effect on PSW. This means that the rate of decrease in PSW with increase in $T_a$ is not linear and that the regression is evidently curved, the parabolic relation being significant. Therefore, the multiple regression of PSW on WR and $T_a$ is corrected as follows ($R=0.976$):

$$PSW = -98.3 + 0.841\ WR + 10.5\ T_a - 0.0250\ T_a^2$$

As $T_a$ rises from 14°C to 35°C, PSW increases gradually and reaches the maximum value at 21°C and then decreases with accelerated rapidity. Similarly, the quadratic component in the $T_a$ factor showed a significant effect on WPS. The multiple regression is corrected as ($R=0.964$)

$$WPS = -0.184.0 + 1.10\ WR + 16.9\ T_a - 0.384\ T_a^2$$

where the maximal value is estimated to appear when $T_a$ is 22°C.

O$_2$P and R–CO$_2$A during exercise in heat showed a tendency similar to that of HR. That is, these two items were significantly influenced by the WR factor and the linear component in $T_a$. Furthermore, the correlation between either of the two items and WR was very remarkable, though that between the two items and $T_a$ was significant only in the cases without influence of the WR factor.

So far as the items of $\dot{V}_o_2$, $\dot{V}_{CO_2}$, R, and R–O$_2$R are concerned, not one of the components, linear, quadratic, and cubic, in the $T_a$ factor was confirmed to produce a significant effect on them, although the WR factor showed powerful influence on them. The ineffectiveness of $T_a$ on these items is also expressed by insignificant correlation, including the partial ones, between each of the items and $T_a$. The correlation coefficients between these items and WR are very large and near the values of the multiple correlation coefficients between these items, WR, and $T_a$. Therefore, the relative strength of $T_a$ for prediction of the estimated value of these items was extremely smaller than that of WR. Especially, in case of $\dot{V}_o_2$, the relative strength of $T_a$ for the prediction was calculated to be less than 2%.

On the other hand, the items of $T_e$ and $T_s$ were confirmed to be independent of WR by the analysis of variance and the estimation of correlation. These items seem to be linearly dependent upon the $T_a$ factor. The relative strength of prediction of these items was estimated to be only around 5% for the WR factor.
DISCUSSION

The physiological parameters investigated in the present study can be classified into three groups from the degree of affinity of the WR and $T_a$ factors. The first group consists of items concerning pulmonary or respiratory functions, such as $V_e$, $\dot{V}_{O_2}$, $\dot{V}_{CO_2}$, R, and $R\cdot O_2R$. These items were independent of $T_a$ at least within the range from 14°C to 35°C, although the relation to WR was very close. The second group is composed of $T_s$ and $T_e$ and is characterized by its stableness as to the effect of WR. The third group consists of such cardiac functions as HR, PSW, and WPS. They are intermediate between the first and the second groups. WR and $T_a$ factors have significant influence on them, although the WR effect is more intense than the $T_a$ effect within the ranges of the present experiments. $O_2P$ and $R\cdot CO_2A$ could be regarded as members of the third group.

As for the WR factor, the relative strength of prediction of the estimated value along the multiple regression is greater in the order of the first group, the third group, and the second group. As for the $T_a$ factor, the order in the relative strength of the prediction is reverse among these three groups.

In the present study, $\dot{V}_{O_2}$ was confirmed to be the most stable as to the $T_a$ effect even among the items of the first group. This result is in agreement with some of previous investigations (DILL et al., 1931; MALHOTRA et al., 1960; TS'AO et al., 1962; STRYNDOM et al., 1966; SALTIN et al., 1968; STOLWIJK et al., 1968; ROWELL et al., 1969; SATO et al., 1976), though this is in contrast with the results of other previous studies that during submaximal work in heat $\dot{V}_{O_2}$ increases (OHNISHI, 1925; KATSUKI, 1933; CHRISTENSEN, 1933; SUZUKI et al., 1957; FUHRMAN and FUHRMAN, 1959; CONSOLAZIO et al., 1961, 1963; PIWONKA et al., 1965; DURNIN and HAISMAN, 1966; WEINMAN et al., 1967) or decreases (ASMUSSEN, 1940; EICHNER et al., 1961, 1963; PIWONKA et al., 1965; DURNIN and HAISMAN, 1966; CONCIA et al., 1961) or decreases (ASMUSSEN, 1940; EICHNER et al., 1961, 1963; PIWONKA et al., 1965; DURNIN and HAISMAN, 1966; WEINMAN et al., 1967) or decreases (ASMUSSEN, 1940; EICHNER et al., 1961, 1963; PIWONKA et al., 1965; DURNIN and HAISMAN, 1966; WEINMAN et al., 1967).

The work duration in the present study was 6 min and the total exposure time was 36 min. It might that this exposure time was too short to make a change in $\dot{V}_{O_2}$. However, STRYNDOM et al. (1966) confirmed that $\dot{V}_{O_2}$ corresponding to the same work rate was independent of exposure time to heat. MOSTARDI et al. (1974) could detect no change in $\dot{V}_{O_2}$ during 70 min of treadmill work, though the rectal temperature rose significantly.

The results showing no effect of $T_a$ on $\dot{V}_{O_2}$ was obtained with unacclimatized subjects to heat. This is in contrast with the supposition that in case of unacclimatized persons the extra demand on cardiovascular system may increase $\dot{V}_{O_2}$ during exercise in heat, though this tendency is well explained by the estimation that maximal metabolic cost of sweating is relatively negligible (KUNO, 1956).

GOLD et al. (1969) measured seasonal difference in energy expenditure in heat and observed an increment of $\dot{V}_{O_2}$ with heat exposure in summer. However, the present experiments were performed in summer (from July to early September).
and could not detect any increase in $\dot{V}_{O_2}$ by heat exposure. No seasonal difference in $\dot{V}_{O_2}$ during exercise in heat was reported previously by Consolazio et al. (1963) and Malhotra et al. (1960).

As a possible reason for no increase of $\dot{V}_{O_2}$ during work in heat, Rowell et al. (1969) supposed that the mechanical efficiency of muscles increased when its temperature was elevated and this increment of efficiency reduced $\dot{V}_{O_2}$ by an amount equal to or greater than the increment which should result from the $Q_{10}$ effect. It is extremely difficult to explain consistently why $\dot{V}_{O_2}$ during work is independent of $T_a$. As pointed out by Strydom et al. (1966), it is not valid to conclude from average values without consideration for spread. Such inadequate treatment of experimental results may be one of the reasons for the confusion in the literature mentioned above. The present study compared $\dot{V}_{O_2}$ during four grades of submaximal work among four $T_a$ conditions from 14°C to 35°C, and disclosed through statistical analyses that $\dot{V}_{O_2}$ was the most stable item even among the items of the first group.

The reason why no hyperventilation was observed in heat may be explained by the fact that the highest $T_a$ condition was 35°C in this experiment. The critical $T_a$ for hyperventilation during submaximal work seems to underlie around 40°C where no change in $\dot{V}_e$ (Gold et al., 1969) as well as a certain increase in $\dot{V}_e$ (Toda et al., 1943; Miura, 1953; Ts'ao et al., 1962) were reported.

The present study showed no significant effect of $T_a$ on $\dot{V}_{CO_2}$. This may be comprehensible from absence of changes in $\dot{V}_{O_2}$ and $\dot{V}_e$ with changes in $T_a$. Similarly, the immutability of $\dot{V}_{O_2}$ and $\dot{V}_e$ in accordance with $T_a$ changes may be responsible for the result showing that $R$ and $R-O_2R$ were independent of $T_a$. According to Robinson (1972), an increment of the ventilation equivalent can be observed when the body temperature is above 38°C. This character of $R-O_2R$ might accompany the considerably large share of $T_a$ in relative strength of prediction, as compared with the other members of the first group.

The present study disclosed the invariability of $T_s$ and $T_e$ as to WR. However, previous investigations are almost equally divided with respect to whether $T_s$ rises (Burton, 1934; Ooura, 1955; Shoji, 1966), falls (Winslow and Herrington, 1949; Weinman et al., 1967; Lund and Gisolfi, 1974), or remains at control values (Nielsen and Nielsen, 1965; Saltin et al., 1968; Nishida and Nakashima, 1975; Kikutsugi and Iwamoto, 1975) during muscular work. Judging from the $T_s$ condition, clothing worn by subjects, kinds of muscular exercise, methods of measurement, and statistical considerations of the results of the previous investigations, the immutability of $T_s$ as to WR observed here could be considered valid at least within the experimental conditions used. The fact that $T_s$ was not affected by produced heat in working muscles could be explained as follows. First, the blood flow to the skin may be reduced when the work begins, because the skeletal muscles may receive an increased share of the cardiac output. Christensen and Nielsen (1942) observed such kind of reduction of blood flow by a plethysmo-
graphic method. Secondly, additional air movement produced by movement during the work may increase the heat loss from the skin. This supposition could be supported by the fact that $T_s$ decreases rapidly in case of ergometer work without load (Burton, 1934) and $T_s$ increases in case of sustained contraction without any movement (Kataoka, 1972). Thirdly, the heat loss by way of evaporation may be accelerated when the deep body temperature rises and blood flow to the skin begins to increase. Winslow and Herrington (1949) suggested that the main reason for falls in $T_s$ was the heat loss by evaporation, because the falls in $T_s$ was observed at all parts of the body surface.

In this study, $T_s$ was calculated after Ramanathan's method. The validity and limitation of this method have been discussed elsewhere (Sato and Katsuura, 1975).

The invariability of $T_c$ as to WR may be explained by a close relationship between $T_s$ and $T_c$ (Kikutugi and Iwamoto, 1975).

As for the third group of parameters, the interaction between WR and $T_a$ showed no effect on HR, and the multiple regression of HR on WR and $T_a$ was expressed as a linear function of the variables. However, it should be stressed that these results were obtained under the present conditions such as a $T_a$ range between 14 and 35°C and WR below 450 kgm/min. The maximal HR has been observed to be almost identical for normal and high $T_a$ conditions (Williams et al., 1962; Parnay et al., 1970; Sakate, 1974). Therefore, the degree of increment of HR by work can be different between both $T_a$ conditions.

WPS and PSW have long been known to be useful for the evaluation of physiological strain (Müller, 1939). Both these items were confirmed by this study to change as a quadratic function of $T_a$. When physiological strain is evaluated in different $T_a$ conditions, this phenomenon naturally claims first consideration.

REFERENCES


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