Brief Report

Metabolic Rate Prediction in Young and Old Men by Heart Rate, Ambient Temperature, Weight and Body Fat Percentage

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Abstract: Metabolic Rate Prediction in Young and Old Men by Heart Rate, Ambient Temperature, Weight and Body Fat Percentage: Satoru UENO, et al. National Institute of Occupational Safety and Health—Objectives: An estimation of metabolic rate (MR) is needed to determine wet-bulb globe temperature (WBGT) reference values in order to reduce heat strain in physical workers. The aim of this study was to develop MR prediction equation for younger and older men in hot working environments. Methods: We measured the MR and heart rate (HR) of both younger and older men at ambient temperatures (T_a) of 25, 30 and 35°C while they cycled on a bicycle ergometer at a workload of 30, 45 and 60% of maximal oxygen uptake (VO_2max). Seven younger male university students aged 22.9 ± 0.7 (mean ± SD) years and seven older male workers aged 61.7 ± 2.2 (mean ± SD) years participated in this study. MR, HR and rectal temperature (T_r) were measured during the study. HR, ambient temperature (T_a), body weight (BW) and body fat percentage (BF) served as predictors of MR using multivariate analysis. To increase the MR prediction accuracy, the following three alternative predictors of HR were used: HR_rest, calculated as 100 × ([HR – resting HR] / [maximal HR – resting HR]); HR_wet, calculated as (HR – resting HR); and HR, calculated as (HR / resting HR). Results: The R^2 value indicated that the models with HR_wet or HR_rest were more accurate than those with HR or HR. T_a had a significantly positive correlation with MR in older men. BW had a significantly positive correlation with MR in both younger and older men, and BF had a significantly negative correlation with MR in both younger and older men. Conclusions: HR_rest or HR_wet enabled more accurate MR prediction than HR. BW and BF would increase the accuracy of MR prediction. (J Occup Health 2014; 56: 519–525)

Key words: Age, Ambient temperature, Heart rate, Metabolic rate, WBGT

The Ministry of Health, Labour and Welfare of Japan reported that 47 workers died from employment-related heat stroke in 2010 due to hot temperature; a sharp increase from the average of 20 workers per year over the previous ten years1). Heat stroke made up 3.9% of all employment-related deaths in 2010, and it has become a critical issue in industrial health in Japan. Risk factors for heat stroke in the workplace include high workload, clothing and high heat stress environments involving high ambient temperatures, high humidity, high radiation levels and low air velocity2). These factors increase heat storage in the body and consequently elevate the deep body temperature. Worker age is also considered to increase the occurrence of heat stroke.

ISO 72433) provides a simple standard for employees working under heat stress conditions using the wet-bulb globe temperature (WBGT) index. WBGT reference values are listed in ISO 72434) for acclimated and non-acclimatized workers, corresponding to metabolic rates (MR) during work. In addition to ISO 72435), ACGIH-TLVs6) on heat stress and heat strain also set a WBGT limit in work places according to the MR level, acclimatization and work-rest ratio. To apply these standards or guidelines to workplaces, information about both the WBGT of the working environment and the MR of the employee during work is needed. The method for estimating MR by job content outlined in ISO 72433) is ambiguous. Though WBGT can be measured by a natural wet bulb sensor, globe sensor and air temperature sensor, measuring metabolic rate is difficult.

ISO 89967) provides four levels for the determination of MR: screening, observation, analysis and expertise. Screening provides a range of metabolic rates for each type of work, as well as examples of types of work with resting, low, moderate, high and
very high MRs. However, the MR estimated by this screening method cannot be assumed to be correct. Observation provides time-averaged MRs for individual tasks. However, it is difficult to apply observation results to accurately calculate MRs. One reason for this is that it is time-consuming to record each task performed by workers. Moreover, the metabolic rate of each task would be different among workers due to different intensities of work during specific tasks. At the analysis level, HR is used to estimate MR as a function of the worker’s age, weight and sex, supposing a linear relationship between HR and MR. Some studies have demonstrated a linear relationship between HR and MR within a range of approximately 90–150 beats/min. In expertise, MR is determined by measuring oxygen consumption rate. However, direct measurement of oxygen consumption (VO2) in industry is rather cumbersome.

HR monitoring would be one of the most economical and convenient ways of estimating the MR of large groups of people. Much research has been carried out on the prediction of MR using HR in industry, sport, and daily life. The HR method has been found to be more reliable than self-report activity diary methods. Recent advances in handy type heart rate monitors have made it easier to record the interval between an R wave and the next R wave in an electrocardiogram (R-R interval) in the field. One shortcoming of the HR method is that the HR-MR relationship is influenced by weight, body composition, age and fitness level. Because of this, it is generally agreed that HR-MR calibration for each individual increases the accuracy of MR prediction using HR. However, measuring an HR-MR curve for every worker in the field is unfeasible. To decrease the errors in MR prediction by HR without calibration for each individual, some papers have used the generalized MR prediction equation for a large number of people, taking into account age, body weight (BW) and sex. Other papers have used percent of HR reserve (HRrec) or HR index (HRi) instead of HR to consider the subjects’ fitness level. However, there are few reports about MR prediction taking into account ambient temperature (T_a). In outdoor work in the summer, heat stress is so high that the effect of T_a on the HR-MR relationship should be considered.

To apply a standard, such as ISO 7243 or ACGIH-TLVs, with a view to decrease the effect of heat stress on workers, the MR of workers should be measured more accurately than simply using job content. In this study, to predict the MR of outdoor workers in the summer, we studied MR prediction equations for younger and older men using HR variables (HR, HRrec, HRr, and HR net (HRnet)), age, BW, body fat percentage (BF) and T_a.

**Methods**

**Subjects**

Subjects were qualified to participate in this study if they were free from heart disease, pulmonary diseases and hypertension and were able to complete the assigned tasks. Seven younger male university students and 7 older male workers participated in this study. The older male workers were recruited from an employment service center for older people. They were performing a job introduced by the employment service center after retiring from their former jobs at the age of 60. Female subjects were not included, as physical capacity is dependent on sex. The physical characteristics of the younger and older subjects (mean ± SD) were 22.9 ± 0.7 and 61.7 ± 2.2 years old, 64.1 ± 6.0 and 67.7 ± 18.0 kg in weight, 173.9 ± 5.3 and 168.1 ± 8.6 cm in height and 17.1 ± 4.3 and 20.9 ± 6.4% body fat, respectively. None of these parameters were significantly different by the Student’s t-test excluding age. The criteria for selection of the subjects followed the 8th Edition of the Guidelines for Exercise Testing and Prescription. Subjects’ health conditions were certified by a medical doctor based on a medical examination carried out within a year of the study. All subjects were informed of the procedure and schedule of this study, and signed a written informed consent form before participating. The subjects were paid after the experiments even if they had not completed the scheduled tasks. The study protocol was approved in advance by the local Institutional Ethics Committee in accordance with the recommendations of the Declaration of Helsinki.

**Protocol**

The subjects underwent the same experiment three times under different room conditions from mid-September to early October 2012 in Tokyo. The subjects reported to the laboratory on three days during the same week. On each day, the subjects cycled in a climate chamber with a T_a of 25.0 ± 0.5°C, 30.0 ± 0.5°C or 35.0 ± 0.5°C in the afternoon at the same time on each day. The tests were conducted in the afternoon and at least 2 hours after a light lunch. Four young subjects and one old subject had a smoking habit, but they were restricted from consuming caffeine or smoking for 12 hours before and during the tests. Water intake was not restricted before or during the tests. In the morning of the first day of the experiment, the BF of each subject was estimated before the experiment by measuring the skinfold thickness at three points (subscapular, triceps and abdominal sites). Body density was estimated from...
the sum of the skinfold thickness of the three points and the age of the subject using the prediction equations of Tahara\textsuperscript{(16)}. Using the body density, the BF was estimated using the equations of Brožek\textsuperscript{(17)}. Each subject performed a cycle ergometry ramp protocol at a maximum HR of \((180\text{-age})\) beats per minute (bpm). The measured workload of the cycle ergometry was used to determine the load used in a submaximal test for each subject.

Figure 1 shows the experimental protocol and measurement methods. The subjects first entered the pre-test chamber, which was controlled at a \(T_a\) of \(25\pm0.5^\circ\text{C}\) and a relative humidity (RH) of 40\%. Before testing, a thermistor was inserted into the rectum to a depth of 10 cm. The rectal temperature (\(T_{re}\)), was collected on a portable data logger (LT-8A, Gram, Japan). HR was recorded by R-R interval with an RS800CX heart rate monitor (Polar Electro, Kempele, Finland), with the transmitter fitted on a chest band. After attaching this measurement equipment, the weights of the subjects were measured (Sartorius, Göttingen, Germany) with the summer work clothing worn during the experiment. The summer work clothing consisted of trunks, T-shirts, outer work clothes with long sleeves and pants, socks, a helmet and safety boots. The thermal insulation of all the items worn by the subjects was about 1.0 clo. After attaching sensors to the body, the subjects rested in the pre-test chamber for 30 minutes. During the experiment, rectal temperature, HR and body weight loss were measured. Then, the subjects entered the test chamber set at a different \(T_a\) on each experimental day, \(25.0\pm0.5^\circ\text{C}, \ 30.0\pm0.5^\circ\text{C}\) or \(35.0\pm0.5^\circ\text{C}\), and a RH of \(40\pm3\%\). After resting for 40 minutes while sitting on a chair, the subjects performed three work-load exercises on a bicycle ergometer with successively heavier loads to reach approximately 30, 45 and 60\% of \(\dot{V}O_{\text{max}}\) based on the Karvonen Formula. This level of load conformed to the guidelines for exercise testing of the American College of Sports Medicine\textsuperscript{(18)}. The exercise lasted five minutes at a fixed load, and one more minute was used for cooling down by linearly decreasing the load. A pedal rate of 50 r/min was used during all of the cycle exercise tests. Between the exercises, the subjects took a rest of 10 minutes each. \textit{Ad libitum} drinking of water was encouraged during the rest periods between exercises. Each subject was tested at the same time of day to minimize the effects of circadian variation in HR and core temperature.

During the test, subjects wore a face mask connected to a Metamax\textsuperscript{®} Metabolic Test System (Cortex Biophysik GmbH, Leipzig, Germany). Before the test, the gas analyzer was calibrated with a 3-l syringe, a reference gas with 5\% \(\text{CO}_2\) + 15\% \(\text{O}_2\) + balance gas of \(\text{N}_2\) and fresh air. Metamax software was used to calculate breath-by-breath ventilation, oxygen consumption (\(\dot{V}O_2\)), rates of carbon dioxide production, and respiratory exchange using the ambient air pressure.

Since subjects over 55-years-old were included, we set mild termination criteria for these trials, including
\begin{enumerate}
\item \(T_{re}\) of 38.5\(^\circ\text{C}\),
\item HR sustained over 180-age bpm for three minutes,
\item participant wished to stop, and/or
\item experimenter judged that the subject was not able to continue the trials.
\end{enumerate}

![Fig. 1. Experiment protocol and measurement items.](image_url)

Metabolic rate, heart rate and rectal temperature were measured during the time shown in this figure. The workload exercises on a bicycle ergometer in exercises 1, 2 and 3 were performed at approximately 30, 45 and 60\% of \(\dot{V}O_{\text{max}}\) based on Karvonen Formula, respectively.
Data analysis

Metabolic rate (MR) was calculated from the measured O$_2$ consumption using the partial method described in ISO 8996$^5$. In our protocol, HR and MR recovered to the initial resting level in the rest period between exercises. We averaged the HR and MR from the first 4 to 5 minutes of the exercise. The resting HR was calculated as the average of the last 5 minutes of HR in the pre-test room. The measured MR was compared with the MR predicted by ISO 8996$^5$. Generalized linear models were used to calculate the MR prediction equation on a desktop computer using SAS 9.3 (SAS Institute Inc., Cary, NC, USA) for Windows. HR was the main predictor used in the models. The alternative predictors of HR were %HR reserve (HR$_{res}$), HR net (HR$_{net}$) and HR index (HR$_i$), whose equations are shown below.

\[
HR_{res} = \frac{(HR - \text{resting HR})}{\text{(maximal HR - resting HR)}} \times 100 \quad (1)
\]

\[
HR_{net} = HR - \text{resting HR} \quad (2)
\]

\[
HR_i = \frac{HR}{\text{resting HR}} \quad (3)
\]

The other predictors used in the models were BW, $T_a$ and BF. Age was not included in this model, because younger and older men were examined separately. $R^2$ values were calculated as an index to show the goodness of fit of each model.

Results

Heart rate and metabolic rate almost reached a steady state during the 5 minutes of exercise and recovered to the initial level during the rest period (Fig. 2). There were no subjects who exceeded the termination criteria of this study. The average $T_{rc}$ of the young men at start of study were 37.1−37.3°C, and those at the end (mean ± SD) were 37.5 ± 0.3 (max: 37.6°C), 37.1 ± 0.5 (max: 37.6°C) and 37.2 ± 0.4°C (max: 37.5°C) for $T_a$ of 25, 30 and 35°C, respectively. The HR of each exercise period is shown in Table 1.

A linear relationship between MR and HR variables (HR, HR$_{res}$, HR$_{net}$ and HR$_i$) was found. The coefficients of the MR prediction equation are listed in Table 2 for one of the HR variables (HR, HR$_{res}$, HR$_{net}$ and HR) and the other selected predictors ($T_a$, BW, BF). The $R^2$ of the generalized linear model using HR$_{res}$ or HR$_{net}$ was larger than those for the other models of HR or HR$_i$ in Table 2. For the models using HR$_{res}$ and HR$_{net}$, BW and BF were significant explanatory variables of MR. $T_a$ was a significant explanatory variable with HR$_{res}$ and HR$_{net}$ only for older men. The mean relative errors of the data compared with the prediction equation were 7−9% in the models using HR$_{res}$ or HR$_{net}$.

Discussion

We studied the MRs of older men and younger men during three levels of ergometric activity at 25, 30 and 35°C. Multiple regression analysis with the explanatory variables of $T_a$, BW, BF and HR variables (HR, HR$_{res}$, HR$_{net}$ and HR) showed that the $R^2$ value of the model constructed using HR$_{res}$ or HR$_{net}$ had a lower margin of error (Table 2). BW and BF were significant explanatory predictors of MR for both younger and older men. For older men, $T_a$ was a significant explanatory predictor of MR.

Through the well-known linear relationship$^{18}$ between HR and MR, MR can be estimated when HR is known. Previous studies have shown that the HR-MR relationship is affected by factors such as age, gender, weight, body composition and fitness level$^{12}$. Therefore, it is generally accepted that calibration for each individual is needed to correctly predict MR by HR monitoring. However, calibration...
for each individual is unfeasible for every outdoor worker during the summer. In this study, to decrease the error in MR prediction caused by different fitness levels, we introduced $HR_{res}$, $HR_i$ and $HR_{net}$ as variables, which negate the error caused by the difference in resting HR. To correct the linear HR-MR relation for different individuals, ISO 8996\(^5\) includes age, weight and gender as explanatory variables, and other studies have included gender and weight in their multiple regression analyses. In this study, we included temperature in addition to BW, BF and HR variables ($HR$, $HR_{res}$, $HR_i$ and $HR_{net}$). Table 2 shows that the model using $HR_{res}$ has the smallest error and that $HR_{net}$ is a better parameter than HR for both younger and older men. A previous study\(^{14}\) also showed that $HR_{net}$ and HR predicted MR more accurately than HR. Another study\(^{19}\) provided evidence that MR prediction using $HR_{res}$ and $HR_{net}$ is more accurate than HR. It is known that the resting HR of physically fit subjects is lower than that of unfit subjects. Since the difference in resting HR accounts for a large part of the MR prediction error, using an HR variable of $HR_{res}$ or $HR_{net}$, which includes the resting HR, for MR prediction could reduce the error from a physiological point of view.

One subjective problem is whether $T_a$ is an explanatory variable of MR. In this study, $T_a$ was a significant explanatory variable of MR for older workers. In acclimatized men, HR does not increase during rest or exercise in hot environments\(^{20}\), though it is generally known that HR increases in a high $T_a$ without an increase in energy expenditure in younger men\(^{21}\). The subjects in this study can be assumed to have acclimatized because the experiment was carried out during the summer.

### Table 1. Mean heart rate of each exercise

<table>
<thead>
<tr>
<th>Exercise</th>
<th>$T_a$ 25°C</th>
<th>$T_a$ 30°C</th>
<th>$T_a$ 35°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Younger men</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exercise 1</td>
<td>110.9 ± 8.1</td>
<td>105.2 ± 6.6</td>
<td>106.8 ± 7.5</td>
</tr>
<tr>
<td>Exercise 2</td>
<td>128.7 ± 8.3</td>
<td>126.8 ± 8.5</td>
<td>126.3 ± 5.1</td>
</tr>
<tr>
<td>Exercise 3</td>
<td>151.6 ± 6.1</td>
<td>148.9 ± 10.5</td>
<td>149.5 ± 6.8</td>
</tr>
<tr>
<td>Older men</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exercise 1</td>
<td>90.7 ± 4.7</td>
<td>87.7 ± 7.9</td>
<td>88.3 ± 6.7</td>
</tr>
<tr>
<td>Exercise 2</td>
<td>103.9 ± 4.6</td>
<td>100.7 ± 7.5</td>
<td>101.4 ± 6.8</td>
</tr>
<tr>
<td>Exercise 3</td>
<td>114.7 ± 3.5</td>
<td>108.5 ± 8.4</td>
<td>109.7 ± 6.7</td>
</tr>
</tbody>
</table>

The values of this table indicate mean heart rate and standard deviation (SD). The values in parentheses are maximum heart rate of the subjects.

### Table 2. The coefficients of the metabolic rate prediction equation for explanatory variables with coefficients of determination for each heart rate variable

<table>
<thead>
<tr>
<th>Variables</th>
<th>$T_a$ Temperature</th>
<th>Body weight</th>
<th>% Body fat</th>
<th>$HR$ variables</th>
<th>Intercept</th>
<th>$R^2$</th>
<th>MRE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Younger men</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$HR$</td>
<td>-0.29 (0.80)</td>
<td>1.53 (0.08)</td>
<td>-0.39 (0.68)</td>
<td>3.12** (&lt;.001)</td>
<td>-241.8* (.002)</td>
<td>0.74</td>
<td>13.5</td>
</tr>
<tr>
<td>$HR_{res}$</td>
<td>-0.32 (0.66)</td>
<td>2.43** (&lt;.001)</td>
<td>-1.49* (0.011)</td>
<td>4.03** (&lt;.001)</td>
<td>-44.9 (0.28)</td>
<td>0.90</td>
<td>7.2</td>
</tr>
<tr>
<td>$HR_{net}$</td>
<td>-0.71 (0.32)</td>
<td>2.94** (&lt;.001)</td>
<td>-2.43** (&lt;.001)</td>
<td>3.11** (&lt;.001)</td>
<td>-34.5 (0.40)</td>
<td>0.90</td>
<td>7.7</td>
</tr>
<tr>
<td>$HR_i$</td>
<td>-1.15 (0.26)</td>
<td>3.09** (&lt;.001)</td>
<td>-2.95** (&lt;.001)</td>
<td>184** (&lt;.001)</td>
<td>-172.0* (0.01)</td>
<td>0.79</td>
<td>11.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variables</th>
<th>$T_a$ Temperature</th>
<th>Body weight</th>
<th>% Body fat</th>
<th>$HR$ variables</th>
<th>Intercept</th>
<th>$R^2$</th>
<th>MRE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Older men</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$HR$</td>
<td>1.32 (0.80)</td>
<td>0.57 (&lt;.005)</td>
<td>-0.14 (0.79)</td>
<td>3.51** (&lt;.001)</td>
<td>-235.9** (&lt;.001)</td>
<td>0.74</td>
<td>10.0</td>
</tr>
<tr>
<td>$HR_{res}$</td>
<td>1.76** (&lt;.005)</td>
<td>0.54** (&lt;.001)</td>
<td>-0.99* (0.02)</td>
<td>3.30** (&lt;.001)</td>
<td>-10.2 (0.66)</td>
<td>0.84</td>
<td>7.7</td>
</tr>
<tr>
<td>$HR_{net}$</td>
<td>1.67* (0.02)</td>
<td>0.39* (0.02)</td>
<td>-1.41** (&lt;.005)</td>
<td>3.31** (&lt;.001)</td>
<td>-44.6 (0.09)</td>
<td>0.79</td>
<td>8.8</td>
</tr>
<tr>
<td>$HR_i$</td>
<td>1.38 (0.10)</td>
<td>0.21 (0.31)</td>
<td>-1.51** (0.01)</td>
<td>180** (&lt;.001)</td>
<td>-92.3* (0.02)</td>
<td>0.68</td>
<td>11.0</td>
</tr>
</tbody>
</table>

The $p$-value is shown next to the coefficient. MRE stands for mean relative error. * 0.01 ≤ $p$ < 0.05; ** $p$ < 0.01.
at around the end of the summer season. Therefore, $T_c$ could have an augmentary effect on MR without increasing HR in older men. A high $T_c$ would increase the risk of heat stroke in older men by increasing the MR.

Metabolic rate is composed of three components: resting energy expenditure, physical activity energy expenditure and the thermic effect of food. Many papers have suggested that the fat-free mass is a significant factor for resting energy expenditure. From a physiological point of view, the fat-free mass includes the organs that consume high amounts of energy, such as muscle. Then lower BF leads higher energy expenditure. For BW, physical activity energy expenditure is correlated with BW because all physical activities are weight bearing. Kleiber suggested that metabolic rate was proportional to 0.75 power of the body mass. The statistical results of this study, that the coefficients of BW were significantly positive and that those of BF were significantly negative (Table 2), coincided with the current physiological knowledge of MR.

Inclusion of smokers in the subjects of this study would not have any effects on the results of this study. A previous report showed that there was no chronic metabolic effect of smoking. Although it was reported that metabolic rate increased on the order of 2–3% after smoking, the effect disappeared within half an hour. Concerning the effect of smoking on HR, HR increased to the maximum value within 5 to 10 minutes and returned to the base level after 2 hours. In this study, subjects were restricted from smoking for 12 hours before the test. The effect of smoking on the results of this study is considered negligible.

In conclusion, this study showed that MR can be predicted more precisely when using $HR_{rest}$ or $HR_{sat}$ than HR, that BW and BF are significant explanatory variables of MR and that $T_c$ was also a significant factor for older men. By utilizing these variables, the accuracy of MR prediction would be raised in field studies.

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Conflict of interest: The authors have no potential conflicts of interest to disclose.

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