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Maximum Oxygen Consumption Determined by the Bruce and Inclined Treadmill Protocols

Kyu Hwa Kim, Hyeong Jin Kim and Kyoung Soon Kim

Department of Physiology, School of Medicine, Kyungpook National University
Taegu 700-422, Korea

= ABSTRACT =

The aim of the present study was to derive regression equations for $\dot{V}O_{2max}$ vs. $\dot{V}O_{2peak}$, and $\dot{V}O_2$ vs. heart rate, exercise time, and other variables from maximal exercise tests on a treadmill using the the Bruce and inclined protocols.

Twelve male and 10 female Korean college students aged between 19 and 23 years volunteered for this study. After the resting measurements, the subjects performed a maximal exercise on a treadmill according to the Bruce protocol. When the resting conditions were restored, the subjects performed another maximal exercise according to an inclined protocol, where the speed was fixed at 8.05 $km \cdot h^{-1}$ and the grade was incremented starting from 0% by 2.5% for every 2 min.

Peak $\dot{V}O_2$ oberved during the Bruce exercise ($\dot{V}O_{2peak}$) was 37.7 ± 2.4 and 31.7 ± 1.8 $ml \cdot kg^{-1} \cdot min^{-1}$ in the male and female groups, respectively. Peak $\dot{V}O_2$ observed during the inclined exercise was higher than $\dot{V}O_{2peak}$ during the Bruce exercise. Maximum $\dot{V}O_2$ value observed during the two exercises ($\dot{V}O_{2max}$) was 43.0 ± 2.8 and 36.2 ± 1.4 $ml \cdot kg^{-1} \cdot min^{-1}$ in the male and female groups, respectively. Thus, $\dot{V}O_{2peak}$ by the Bruce protocol was about 12% (male) or 13% (female) lower than $\dot{V}O_{2max}$, and a linear relationship was found between $\dot{V}O_{2peak}$ and $\dot{V}O_{2max}$.

The peak values of $\%\dot{V}O_{max}$ with the Bruce protocol were 89.2 ± 3.3 and $87.5 \pm 3.6\%$, and those with the inclined protocol 97.7 ± 1.8 and $96.9 \pm 2.0\%$ in the male and female groups, respectively. In the female group, $\%\dot{V}O_{2max}$ at a given workload was higher than in the male group, while $\dot{V}O_2$ per kg body weight was the same.

Maximum HR observed during the two exercises was 204 ± 2 and 195 ± 3 $beat \cdot min^{-1}$ in the male and female groups, respectively. Linear relationships were found, excluding the last points, between 1) $\dot{V}O_2$ and exercise time, 2) $\dot{V}O_2$ and HR, and 3) $\%\dot{V}O_{2max}$ and $\%HR_{max}$.

Key Words: Oxygen consumption, Heart rate, Ventilation, Exercise time, Female.

INTRODUCTION

Graded exercise tests involving progressively increased workload are widely used to assess the cardiorespiratory fitness or to disclose dormant cardiac dysfunctions. The primary index for assessment of the cardiorespiratory fitness is the maximum oxygen consumption ($\dot{V}O_{2max}$).

$\dot{V}O_{2max}$ can be determined by measuring the oxygen consumption ($\dot{V}O_2$) during maximal exercise. In many instances, however, either the achievement of maximal exercise or direct measurement of $\dot{V}O_2$ is not possible due to laboratory conditions or subjects. Such circumstances often necessitate estimation of $\dot{V}O_{2max}$ from other measured variables.

A regression equation describing the relationship between heart rate and $\dot{V}O_2$ can be used to estimated $\dot{V}O_{2max}$ from a submaximal exercise test by extrapolation (Pollock et al, 1978). For

several treadmill protocols, regression equations are available to estimate $\dot{V}O_2$ from exercise time (Pollock et al, 1976). The latter equations, however, have been known to differ considerably in age, cardiorespiratory fitness, the presence or absence of cardiac diseases (Alexander et al, 1984; Foster et al, 1984) and possibly on race (Bae et al, 1990).

Recently, Weltman et al (1990) reported that the $\dot{V}O_{2peak}$ obtained by a Bruce-like treadmill protocol was lower than the $\dot{V}O_{2max}$ obtained by an inclined protocol, and proposed a linear regression equation to predict the latter from the former.

The aim of the present study was, therefore, to derive regression equations for $\dot{V}O_{2max}$ vs. $\dot{V}O_{2peak}$, and $\dot{V}O_2$ vs. heart rate, exercise time, and other variables from maximal exercise tests on a treadmill using the Bruce and inclined protocols.

METHODS

Twelve male and 10 female Korean college students aged between 19 and 23 years volunteered for this study. The physical characteristics of subjects are presented in Table 1. None of the subjects had an experience of regular exercise training. The subjects were informed of the purpose and nature of the study and of any risks or discomforts associated with the experiment. The subjects had refrained from strenuous exercise for 24 hours, and from smoking and ingestion of food or alcohol for 3 hours prior to the experiment. The room temperature and the relative humidity in the laboratory ranged from 12 to 22℃ and 43 to 69%, respectively, throughout the experiment.

Exercise protocols

After the resting measurements had been taken, the subjects performed a maximal exercise on a treadmill (model 28-49B, Quinton) according to the Bruce protocol (Bruce et al, 1973). When the resting conditions were restored, the subjects performed another maximal exercise according to an inclined protocol, where the speed was fixed at 8.05 $km \cdot h^{-1}$ and the grade was incremented starting from 0% by 2.5% for every 2 min.

Table 1. Physical characteristics of subjects and maximum exercise values obtained using the Bruce and the inclined protocols in the male and female groups

	Male (n=12)	Female (n=10)
Age (yr)	21.8±0.2	21.4±0.4
Height (cm)	174.2±1.3	162.3±1.1#
Body weight (kg)	67.1±2.0	48.3±0.5#
Body surface area (m^2)	1.81±0.03	1.49±0.01#
Exercise time (min)		
Bruce	12.35±0.22	9.97±0.27#
Inclined	10.47±0.48	6.83±0.35#
$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	37.7±2.4	31.7±1.8
$\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	43.0±2.8	36.2±1.4
HR_{max} ($beat \cdot min^{-1}$)		
Predicted	198.2±0.2	198.6±0.4
Observed	204.0±1.7	195.0±2.7#

Values are mean±S.E.

$\dot{V}O_{2peak}$: peak oxygen consumption observed during the Bruce exercise

$\dot{V}O_{2max}$: maximum oxygen consumption observed during the Bruce and the inclined exercises

HR_{max}: maximum heart rate

#Significantly different from the male group ($P<0.05$).

Measurements

Heart rate was obained from a lead CM5 electrocardiogram recorded on a physiograph (MK-IV-P, Narco Biosystems) and monitored with an oscilloscope (Narcotrace, Narco Biosystems) during the exercises. Oxygen consumption was measured by a conventional open-circuit spirometry every 3 or 4 min depending on the protocol employed. Expiratory gas was collected into a 200-liter Douglas bag for 45 s during exercise and for the last 30 s of each exercise. The volume (V, l) and temperature (T,

℃) of the collected gas was measured with a wet gas meter (W-75, American) and a telethermometer (model 44TA, YSI), respectively. Gas samples of 20 ml in duplicate were analyzed for P_{ECO2} (torr) and P_{EO2} (torr) in BTPS using a gas analyzer (model 175, Corning). From these parameters and the barometric pressure (P_B, torr), the minute ventilation ($\dot{V}_{E,BTPS}$, $l \cdot min^{-1}$) and O_2 consumption ($\dot{V}O_{2,STPD}$, $l \cdot min^{-1}$) were calculated as follows (t=45 or 30 s).

$$F_{EO2}=\frac{P_{EO2}}{P_B-47} \qquad F_{ECO2}=\frac{P_{ECO2}}{P_B-47}$$

$$\dot{V}_{E,BTPS}=V\cdot\frac{60}{t}\cdot\frac{273+37}{273+T}\cdot\frac{P_B-P_{H2O,T}}{P_B-47}$$

$$\dot{V}_{E,STPD}=V\cdot\frac{60}{t}\cdot\frac{273}{273+T}\cdot\frac{P_B-P_{H2O,T}}{760}$$

$$\dot{V}O_{2,STPD}=\dot{V}_{E,STPD}\cdot\left\{\frac{0.2115}{0.7850}\cdot(1-F_{EO2}-F_{ECO2})-F_{EO2}\right\}$$

Statistics

All data were expressed as mean±S.E. Significance of changes over time was tested by unweighted analysis of variance. Differences between groups were tested by an unpaired t-test. Linear regression analysis was performed between oxygen consumption, heart rate and exercise time.

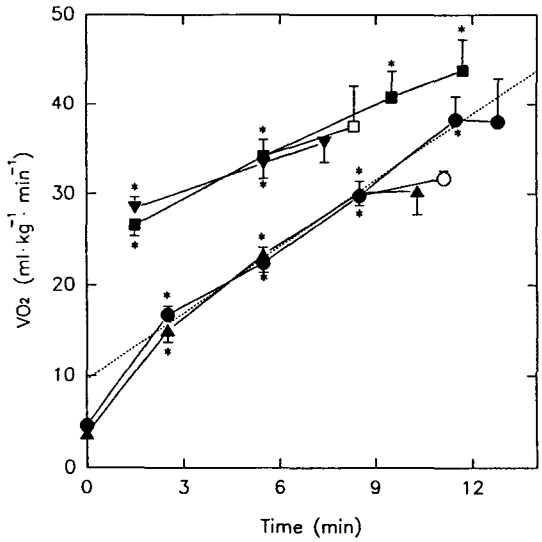

*Fig. 1. Oxygen consumption plotted against exercise time on the Bruce (● males, ▲ females) and the inclined (■ males, ▼ females) protocols. Two of the male subjects who terminated the exercise at earlier stages than others are plotted separately with open symbols (○, □). Vertical bars indicate standard errors. The dashed line indicates the regression line obtained from the pooled male and female groups for the Bruce exercise excluding the terminal points. * Significantly different from the respective previous points (P<0.05).*

RESULTS

The length of exercise time on the Bruce protocol was 12.35±0.22 and 9.97±0.27 min in the male and female groups, respectively (Table 1). All but two of the male subjects completed stage IV (12 min), while all of the female subjects completed stage III (9 min). With the inclined protocol, the exercise time was 10.47±0.48 and 6.83±0.35 min in the male and female groups, respectively. All of the male subjects, except two of them, completed 5 stages (10 min), and all of the female subjects completed 3 stages (6 min).

The oxygen consumption ($\dot{V}O_2$) per kg body weight are plotted against exercise time in Fig. 1. The two male subjects who terminated earlier than others are plotted as separate lines. Resting $\dot{V}O_2$ was 4.53±0.41 and 3.63±0.36 ml $\cdot kg^{-1} \cdot min^{-1}$ in the male and female groups, respectively. The $\dot{V}O_2$ increased linearly with time during both exercises, while the inclined protocol resulted in a higher increase. All the $\dot{V}O_2$ values measured during exercise, except the last points, were significantly higher than the respective previous points. The male and female groups followed almost identical paths of increase in $\dot{V}O_2$. Peak $\dot{V}O_2$ observed during the Bruce exercise ($\dot{V}O_{2peak}$) was 37.7±2.4 and 31.7±1.8 ml $\cdot kg^{-1} \cdot min^{-1}$ in the male and female groups, respectivley (Table 1). Peak $\dot{V}O_2$ observed during inclined exercise was higher than $\dot{V}O_{2peak}$ during the Bruce exercise. The maximum $\dot{V}O_2$ value observed during the two exer-

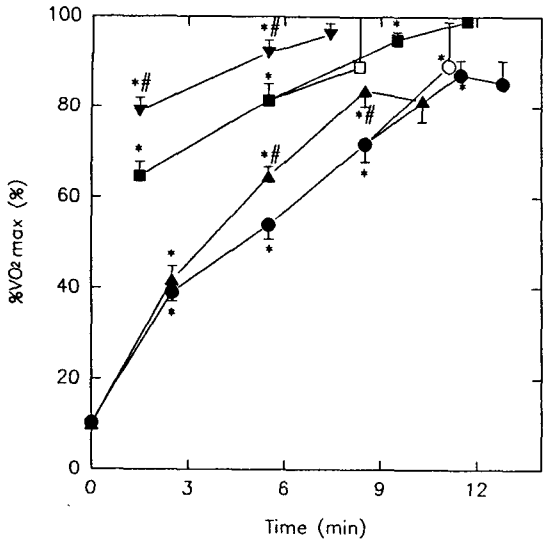

*Fig. 2. %$\dot{V}o_{2max}$ plotted against exercise time on the Bruce (● males, ▲ females) and the inclined (■ mlaes, ▼ females) protocols. For open symbols (○, □), see legend under Fig. 1. Vertical bars indicate standard errors. *Significantly different from the respective previous points ($P<0.05$). #Significantly different from the male group ($P<0.05$).*

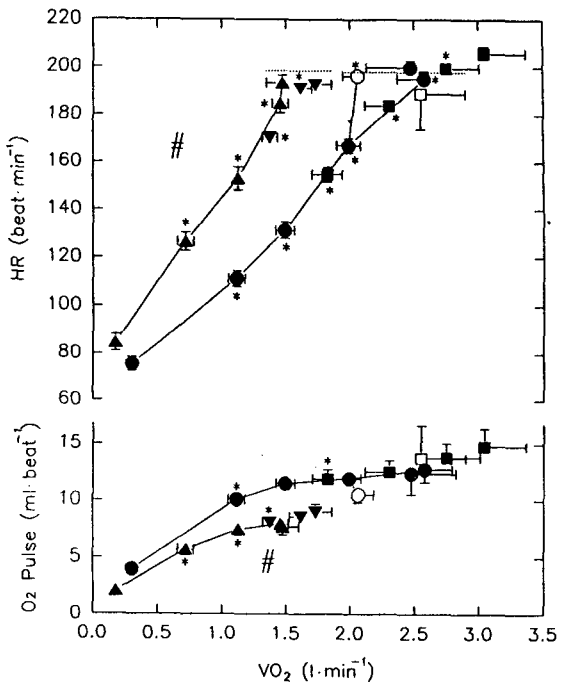

*Fig. 3. Heart rate and the oxygen pulse plotted against oxygen consumption during the Bruce (● males, ▲ females) and the inclined (■ mlaes, ▼ females) exercises. For open symbols (○, □), see legend under Fig. 1. Vertical and horizontal bars indicate standard errors. Dashed lines indicate the HR_{max} values predicted from age. *Significantly different from the respective previous points ($P<0.05$). #All data points, except for the resting heart rate, or the female group are significantly different from the corresponding points of the male group ($P<005$).*

cises ($\dot{V}o_{2max}$) was 43.0±2.8 and 36.2±1.4 ml·kg^{-1}·min^{-1}, or 2.91±0.23 and 1.75±0.08 l·min^{-1} in the male and female groups, respectively.

The $\dot{V}o_2$ values are expressed as per cent of $\dot{V}o_{2max}$ in Fig. 2. The %$\dot{V}o_{2max}$ values in the female group, except for lower workloads, were significantly higher than those in the male group. The peak values of %$\dot{V}o_{2max}$ with the Bruce protocol were 89.2±3.3 and 87.5±3.6% in the male and female groups, respectively. With the inclined protocol, the peak values were 97.7±1.8 and 96.9±2.0% in the male and female groups, respectively.

Heart rate (HR) during the Bruce and inclined exercises is plotted against $\dot{V}o_2$ in the upper plate of Fig. 3. Resting HR was 75.5±2.9 and 84.6±3.5 beat·min^{-1} in the male and female groups, respectively. HR increased linearly with $\dot{V}o_2$ where the female group showed a steeper increase than the male group. Maximum HR observed during the two exercises was 204.0±1.7 and 195.0±2.7 beat·min^{-1} in the male and female groups, respectively. In the lower plate of Fig. 3, the oxygen pulse is plotted against $\dot{V}o_2$. The resting values of oxygen pulse were 3.9±0.3 and 2.1±0.2 ml·beat^{-1} in the male and female groups, respectively. The oxygen pulse increased with $\dot{V}o_2$ to reach plateaus at about 1.5 l·min^{-1} of $\dot{V}o_2$ in both groups.

The HR values are expressed as per cent of maximum HR (%HR_{max}) and plotted against %

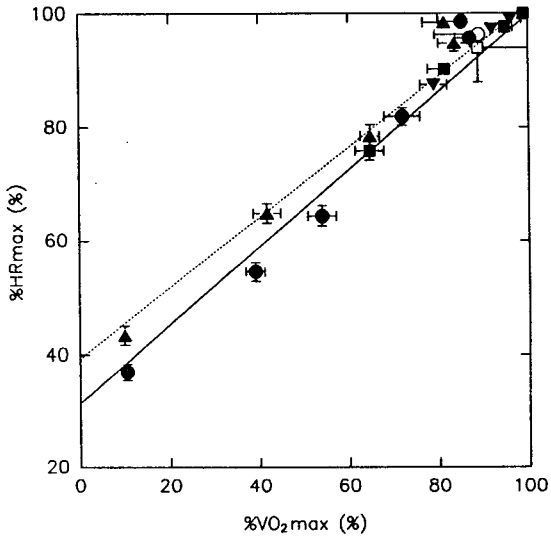

Fig. 4. $\%HR_{max}$ plotted against $\%\dot{V}O_{2max}$ during the Bruce (● males, ▲ females) and the inclined (■ males, ▼ females) exercises. For open symbols (○, □), see legend under Fig. 1. Vertical and horizontal bars indicate standard errors. The solid and dashed lines indicate the regression lines obtained from all the data points excluding the terminal points of exercise in the male and female groups, respectively.

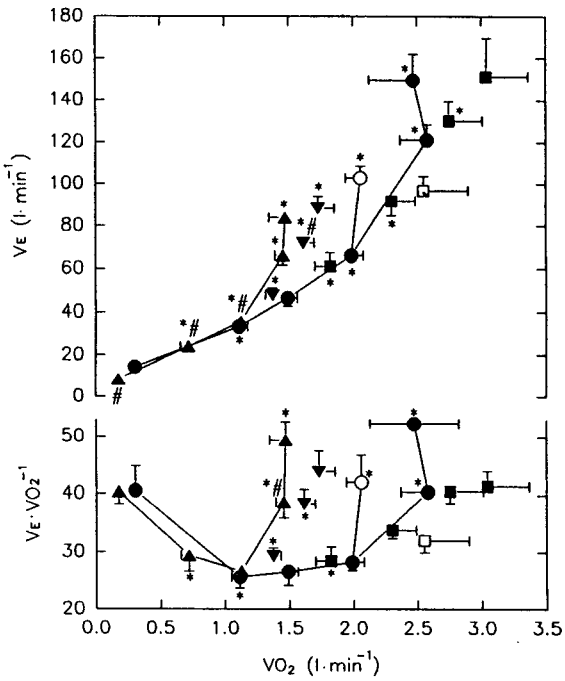

*Fig. 5. The minute ventilation and $\dot{V}_E \cdot \dot{V}_{O2}^{-1}$ plotted against oxygen consumption during the Bruce (● males, ▲ females) and the inclined (■ males, ▼ females) exercises. For open symbols (○, □), see legend under Fig. 1. Vertical and horizontal bars indicate standard errors. *Significantly different from the respective previous points ($P<0.05$). #Significantly different from the corresponding points of the male group ($P<0.05$).*

$\dot{V}O_{2max}$ in Fig. 4. The two parameters showed a linear relationship.

The minute ventilation is plotted against $\dot{V}O_2$ in the upper plate of Fig. 5. The ventilation increased linearly with $\dot{V}O_2$ until about 2.0 $l \cdot min^{-1}$ of $\dot{V}O_2$ in the male group and about 1.1 $l \cdot min^{-1}$ in the female. After this it deviated from the linear relationship and showed sharp rises. The $\dot{V}_E \cdot \dot{V}O_2^{-1}$ ratio is plotted against $\dot{V}O_2$ in the lower plate of Fig. 5. The ratio also showed sharp rises at the same levels of $\dot{V}O_2$ as described above.

Results of regression analysis on some measured variables are presented in Table 2. The exercise $\dot{V}O_2$ showed a linear relationship with time on the Bruce protocol except for the last points ($r=0.864$ in the male, and $r=0.875$ in the female group). The regression line for the pooled male and female groups is shown in Fig. 1. The exercise HR showed a linear relationship with $\dot{V}O_2$ except for the last points ($r=0.846$ and 0.902 in the respective groups). The correlation coefficents were even higher between $\%HR_{max}$ and $\%\dot{V}O_{2max}$ ($r=0.924$ and 0.950 in the respective groups). The regression lines for the latter relationship are shown in Fig. 4. Peak values of $\dot{V}O_2$ during the Bruce exercise ($\dot{V}O_{2peak}$) had a positive correlation with $\dot{V}O_{2max}$ ($r=0.871$ and 0.676 in the respective groups). HR_{peak} and HR_{max} also showed a similar correlation ($r=0.759$ and 0.892 in the respective groups).

Table 2. Linear regression analysis among measured variables in the male and female groups

Group	Regression equation	r*
Male	$\dot{V}O_2$ (ml·kg^{-1}·min^{-1})=10.017+2.391·t (min)	0.864
Female	$\dot{V}O_2$ (ml·kg^{-1}·min^{-1})=8.948+2.522·t (min)	0.875
Male	HR (beat·min^{-1})=82.44+39.16·$\dot{V}O_2$ (l·min^{-1})	0.846
Female	HR (beat·min^{-1})=83.18+63.49·$\dot{V}O_2$ (l·min^{-1})	0.902
Male	$\%HR_{max}$(%)=31.55+0.684·$\%\dot{V}O_{2max}$(%)	0.924
Female	$\%HR_{max}$(%)=39.30+0.621·$\%\dot{V}O_{2max}$(%)	0.950
Male	$\dot{V}O_{2max}$ (l·min^{-1})=−0.013+1.146·$\dot{V}O_{2peak}$ (l·min^{-1})	0.871
Female	$\dot{V}O_{2max}$ (l·min^{-1})=0.834+0.601·$\dot{V}O_{2peak}$ (l·min^{-1})	0.676
Male	HR_{max} (beat·min^{-1})=76.80+0.640·HR_{peak} (beat·min^{-1})	0.759
Female	HR_{max} (beat·min^{-1})=37.91+0.818·HR_{peak} (beat·min^{-1})	0.892

t: exercise time on the Bruce protocol
$\dot{V}O_2$: oxygen consumption
HR: heart rate
$_{peak}$: peak values observed during the Bruce exercise
$_{max}$: maximum values observed during the Bruce and the inclined exercises
*All of the correlation coefficients are significantly positive ($P<0.05$).

DISCUSSION

In the present study, all the subjects terminated the Bruce exercise with their $\dot{V}O_2$ reaching a plateau (Fig. 1) signifying a maximal exercise. The heart rate also reached the predicted maximal level at the end of the Bruce exercise (Fig. 3). However, the $\dot{V}O_{2peak}$ obtained from the Bruce exercise was only about 88 or 87% of the $\dot{V}O_{2max}$ in the male and female groups, respectively (Fig. 2). This result indicates that the measurement of $\dot{V}O_{2max}$ based solely on the Bruce protocol would involve a significant underestimation.

Weltman et al (1990) proved the reliability and validity of a continuous treadmill exercise protocol similar to the Bruce protocol by comparing discontinuous and inclined protocols. They also found that the $\dot{V}O_{2peak}$ obtained from a Bruce-like exercise was about 5% lower than the $\dot{V}O_{2max}$ obtained by an inclined protocol, but nevertheless could be used as a predictor of the latter by coupling with a linear regression equation. In the present study, the $\dot{V}O_{2peak}$ obtained from the Bruce exercise was about 12% or 13% lower than $\dot{V}O_{2max}$ and a linear relationship eristed between the two.

Alexander et al (1984) compared the Bruce equation (McDonough et al, 1970) and the Liang equation (Liang et al, 1982) to predict $\dot{V}O_2$ (ml·kg^{-1}·min^{-1}) from exercise time (t, min) on the treadmill in young males and found that using the Bruce equation ($\dot{V}O_2$ = 3.26t+6.14) resulted in a significant underprediction while using the Liang equation ($\dot{V}O_2$ = 3.62t+3.91) did not. Bae et al (1990) provided a regression equation ($\dot{V}O_2$=2.263t+2.41) for Korean male adolescents. We have presented, in this study, still other regression equations ($\dot{V}O_2$=2.391t+10.017 and $\dot{V}O_2$=2.522t+8.948) for Korean young males and females, respectively. It can be noted that the regression coefficients (slopes) for Korean subjects tend to be lower than those for Americans, which might be attributable to a racial difference.

Kang et al (1988) derived linear regression

equations on $\dot{V}O_2$ vs. HR and $\%\dot{V}O_{2max}$ vs. $\%HR_{max}$ from young Korean long-distance runners through a maximal treadmill exercise on the Balke protocol. Kang et al (1990) obtained linear regression equations between cardiac output, HR and $\dot{V}O_2$ from young Korean marathoners and nonathletes through a maximal treadmill exercise on the Bruce protocol. We have presented in this study similar regression equations on these parameters, which might be utilized in predicting $\dot{V}O_2$ from measured HR. It should be noted, however, that the last points in the $\dot{V}O_2$-HR and $\%\dot{V}O_{2max}$-$\%HR_{max}$ plots tend to deviate from the linear relationship. With near-maximal workloads, the heart rate may increase without concomitant increase of $\dot{V}O_2$ to make it unreasonable to extrapolate the prediction equations.

In summary, $\dot{V}O_{2peak}$ by the Bruce protocol was about 12% (male) or 13% (female) lower than $\dot{V}O_{2max}$, and a linear relationship was observed between $\dot{V}O_{2peak}$ and $\dot{V}O_{2max}$. Linear relationships were also observed, excluding the last points, between 1) $\dot{V}O_2$ and exercise time, 2) $\dot{V}O_2$ and HR, and 3) $\%\dot{V}O_{2max}$ and $\%HR_{max}$.

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