

Normal cardiopulmonary responses during incremental exercise in 20- to 70-yr-old men

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ABSTRACT

INBAR, O., A. OREN, M. SCHEINOWITZ, A. ROTSTEIN, R. DLIN, and R. CASABURI. Normal cardiopulmonary responses during incremental exercise in 20- to 70-yr-old men. *Med. Sci. Sports Exerc.*, Vol. 26, No. 5, pp. 538–546, 1994. Healthy men ($N = 1424$, age 20–70 yr) underwent a progressive incremental treadmill exercise test to volitional maximum. Cardiopulmonary variables were measured breath-by-breath. The aerobic power ($\dot{V}O_{2\max}$) declined at an average yearly rate of $0.33 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, HRmax declined $0.685 \text{ beats}\cdot\text{min}^{-1}\cdot\text{yr}^{-1}$, and max O_2 pulse declined at an annual rate of $0.115 \text{ ml}\cdot\text{beat}^{-1}\cdot\text{kg}^{-1}\cdot 100$. Gas exchange threshold (GET) expressed as percentage of $\dot{V}O_{2\max}$ was 58% and 69% in the youngest (20–30 yr) and oldest (61–70 yr) decades, respectively. The average decline in \dot{V}_E , \dot{V}_I , f , and PETCO_2 over the entire age range was 29%, 10%, 21%, and 7%, respectively. There were increases in $\dot{V}_E/\dot{V}O_2$, and $\dot{V}_E/\dot{V}_E\text{CO}_2$, from age 20–70 yr of 13% and 14%, respectively, but no changes across 5 decades in PETO_2 . Physical (height and weight) as well as life-style characteristics (leisure time activity, place of residency, smoking), were found to be potent predictors in most of the cardiopulmonary values at maximal exercise and therefore should be incorporated in the predictive equations for such variables. Normal response patterns of most cardiopulmonary variables throughout the range of exercise intensities were shown to be age-affected and thus should be standardized for age decades.

CARDIOPULMONARY EXERCISE TESTING, MALE, NORMAL RESPONSES

Cardiopulmonary exercise testing (CPET) has become a common procedure to objectively assess the cardiac and respiratory responses of individuals to exercise. These responses can be compared to previously established “normal” values, and inferences regarding limitations of exercise due to cardiac, respiratory, metabolic, endocrine, neuromuscular, or other factors may be made.

The general pattern of cardiopulmonary responses during incremental exercise are known (1,21,25,38). How-

ever, the range of normal response patterns that may be expected to occur over the course of an incrementally increasing exercise task have been based on fairly small samples. Further, the influence of factors such as age, gender, physical characteristics, type of residency, occupation, smoking habits, and leisure-time physical activity, on the response patterns have not been thoroughly studied. This may limit the clinician’s ability to interpret CPET data.

The purpose of the present report is to establish a comprehensive set of reference values for the response of healthy men to submaximal and maximal incremental exercise challenges. In addition, this study may provide the basis for subsequent studies which seek to establish response patterns that separate healthy individuals from those with specific health disorders.

MATERIAL AND METHODS

Selection criteria. Subjects were selected from a population of 4500 Israeli men and women who, over the period of 1985–1991, underwent a periodic medical examination with CPET. Also included in the medical evaluation were: comprehensive medical history, physical examination (including skinfolds thickness measurements), resting 12-lead ECG, chest x-ray, urinalysis, complete blood count, blood chemistry panel (SMA-12), and resting pulmonary function (spirometry). Subjects who had abnormal ECG tracings, medical history, or physical or laboratory findings of cardiac, respiratory, metabolic, or neuromuscular diseases were excluded from the study. Although normal spirometric data (11) were required for entry into the study’s sample, subjects who had a history of current or past smoking were included. Information regarding previous health, leisure habits, occupation, and smoking history was obtained by questionnaire. Written informed consent was obtained from all subjects before the examination started.

All subjects completed a maximal incremental treadmill exercise test, as detailed subsequently. Subjects were excluded if the test was stopped by the supervising physician because of an arrhythmia, significant hypertension (BP > 230/95 mm Hg), or electrocardiographic signs of ischemia (ST depression > 1 mm). The CPET studies that were obtained in men between the age of 20–70 yr form the basis of this report.

Study population. The anthropometric data of the 1424 male subjects are shown in Table 1, grouped by decades. The mean (± 1 SD) age of our sample was 46.7 ± 10.2 yr, height was 1.73 ± 0.065 m, weight was 76.2 ± 9.1 kg, total body fat (calculated from four skinfolds measurements, 14) was $27.9 \pm 5.3\%$, and Quetelet index (weight \cdot height $^{-2}$) 25.6 ± 2.7 . Table 2 displays life-style characteristics of the study sample as a function of age. Twenty-five percent of the men were regular smokers (>10 cigarettes \cdot d $^{-1}$), more than 70% did not partake in more than 2 h \cdot wk $^{-1}$ leisure time physical activity, 80% held an office job, and about 90% were city dwellers. These characteristics are typical of most adult working populations in Western industrialized countries (2,4,7,8,11,17,23,24).

Exercise test protocol. Exercise tests were performed on a motor-driven treadmill (Quinton Q65) in an air conditioned room with the temperature and humidity levels at $23 \pm 2^\circ\text{C}$ and $55 \pm 5\%$, respectively. The test was performed at least 3 h after the last meal and after a minimum 12 h of limited exertion. The test protocol included 3 min of rest followed by walking at a fixed speed (between 4 and 6.5 km \cdot h $^{-1}$), which was individually assigned (based on age, height, and leisure-time activity level) in an attempt to bring about volitional exhaustion within 7–12 min (9). Mean (± 1 SD) test time was $8:25 \pm 1:19$ min. The treadmill slope was elevated by 2% every minute until the subject could no longer maintain the imposed walking speed despite verbal encouragement (modified Balke protocol, 3). Heart rate (HR) and ECG were continuously monitored by 12-lead electrocardiography (Elma Minograd-Siemens) and blood pressure was periodically measured by auscultation. Subjects breathed through a small dead-space (100 ml), low-resistance (0.7 cm H $_2$ O at air flow of 120 l \cdot min $^{-1}$) mouthpiece and turbine volume transducer (Alpha Technologies, CA). Respired gases were withdrawn from the mouthpiece (1 ml \cdot s $^{-1}$) for the determination of

oxygen (zirconium dioxide electrochemical cell, Sensor-Medics, CA) and carbon dioxide (Infrared analyzer, Andros Inc., CA) fractions in the expired air (Metabolic Cart, SensorMedics 4400, CA). Signals from these sensors underwent analog to digital conversion (at 100 Hz) by a computer (Data Acquisition, OMS Inc., CA) and were transferred on-line to another computer (Hewlett Packard model 200, CA) for breath-by-breath analysis of the following variables: oxygen uptake ($\dot{V}O_2$, STPD), carbon dioxide output ($\dot{V}CO_2$, STPD), minute ventilation (\dot{V}_E , BTPS), breathing frequency (f), tidal volume (Vt, BTPS), respiratory quotient (R), ventilatory equivalents for oxygen ($\dot{V}_E/\dot{V}O_2$), and for carbon dioxide ($\dot{V}_E/\dot{V}CO_2$), oxygen pulse (O $_2$ pulse = $\dot{V}O_2$ /HR), and end tidal PO $_2$ and PCO $_2$ (PETO $_2$ and PETCO $_2$, respectively).

The CO $_2$ and O $_2$ analyzers as well as the volume transducer were calibrated before each test using three precision gas mixtures and a 3-l volume calibrated syringe, respectively.

The exercise peak values for each variable were determined as the average of the two highest consecutive 30-s measurements during the last 2 min of the test. A test was considered maximal, and was included in the final analysis, only if it lasted between 6–12 min, and if final HR was within 15% of age predicted HRmax (8,13,18,26), and R was greater than 1.13. The gas exchange threshold (GET), the point at which $\dot{V}CO_2$ accelerates out of proportion to $\dot{V}O_2$, signifying the onset of bicarbonate buffering of lactic acid, was determined for each subject by two expert readers from plots of $\dot{V}CO_2$ vs $\dot{V}O_2$ (modified V-slope technique) (36). Due to a technical shortcomings the GET was determined for a subset (936 men) of the total sample.

Statistical treatment. Analysis of variance (ANOVA) was used to determine differences in peak exercise values among age groups. If a significant *F*-ratio was obtained, then *post-hoc* comparisons were completed using Neuman-Keuls tests. To obtain uniformity in analyzing individual tests whose duration and maximal power-load varied, it was necessary to equalize the number of observations per exercise test. The incremental portion of each test was divided into 18 equal parts (approx. 30-s intervals). The subject's $\dot{V}O_2$ value in each interval was then converted to the percent of maximal $\dot{V}O_2$ (% $\dot{V}O_{2\text{max}}$). The best fit response curves of the five age groups were compared using repeated measures

TABLE 1. Physical characteristics of population by age groups ($\bar{X} \pm$ SD).

Age Group (yr)	N	Weight (kg)	Height (cm)	Fat* (%)	QI**
20–30	98	76.6 \pm 9.6	176.5 \pm 6.2	26.8 \pm 5.5	24.7 \pm 2.6
31–40	603	77.3 \pm 8.8	174.9 \pm 6.1	26.9 \pm 5.0	25.1 \pm 2.5
41–50	492	76.9 \pm 8.6	173.1 \pm 6.3	27.8 \pm 4.3	25.7 \pm 2.6
51–60	188	76.2 \pm 9.6	170.7 \pm 7.2	29.4 \pm 4.0	26.3 \pm 2.6
61–70	43	74.5 \pm 10.3	167.9 \pm 6.3	28.6 \pm 6.2	26.3 \pm 3.1

* SkyndexTM U.S.A. (biceps, triceps, subscapula, iliac-crest), Durnin and Womersley, 1969 (14).

** Quetelet index = weight \cdot height $^{-2}$.

TABLE 2. Life habits of population by age groups (N and %).

Age Group (yr)	N	Habitual Activity		Current Smoking		Residency		Occupation	
		Active	Sedentary	Smokers	Nonsmokers	Urban	Rural	Office	Manual
20-30	98	36 (37)	62 (63)	26 (27)	72 (73)	85 (87)	13 (13)	75 (76)	23 (24)
31-40	603	236 (39)	367 (61)	149 (25)	454 (75)	529 (88)	74 (12)	468 (78)	135 (22)
41-50	492	203 (41)	289 (59)	98 (20)	394 (80)	416 (85)	76 (15)	394 (80)	98 (20)
51-60	188	57 (30)	131 (70)	36 (19)	152 (81)	159 (85)	29 (15)	150 (80)	38 (20)
61-70	43	10 (23)	33 (77)	4 (9)	39 (91)	37 (86)	6 (14)	37 (86)	6 (14)

ANOVA, where $\% \dot{V}O_{2\max}$ serves as an independent variable. Simple and stepwise multiple linear regression was done by the technique of least squares minimization with inclusion of between and within subject factors. The equality of regression equations was also examined using an SAS compatible BMDP statistical package. The probability of a Type I error was established at 0.05.

RESULTS

Effect of age on variables at maximal exercise. Figures 1-3 display the individual data points for each of the cardiopulmonary variables measured at peak exercise, as a function of age. Superimposed on each figure are the respective linear regression lines and the standard error of measurement (SEM). Age clearly influ-

enced maximal $\dot{V}O_2$, $\dot{V}CO_2$, HR, O_2 pulse, and \dot{V}_E . In contrast, R, Vt, $\dot{V}_E/\dot{V}O_2$, $\dot{V}_E/\dot{V}CO_2$, $PETO_2$, and $PETCO_2$ values at peak exercise are not appreciably influenced by age. Testing for normality in the distribution of the measured peak cardiopulmonary values showed that the normal distribution described the data well in all of the parameters in the sample as a whole, and within each age group. Normal distribution of the data justifies the use of parametric statistical procedures.

$\dot{V}O_{2\max}$ decreased from 2.88 ± 0.57 l·min⁻¹ in the 20-30 age group to 1.86 ± 0.37 l·min⁻¹ in the 61-70 age group (Fig. 1A). This is a decrement of 35% during the 50-yr age span studied, or an average decline of 25.5 ml·min⁻¹·yr⁻¹. When adjusted for body weight, $\dot{V}O_{2\max}$ (ml·kg⁻¹·min⁻¹) also declined in a linear fashion ($r = -0.47$) at a yearly rate of 0.33 ml·kg⁻¹·min⁻¹. A similar

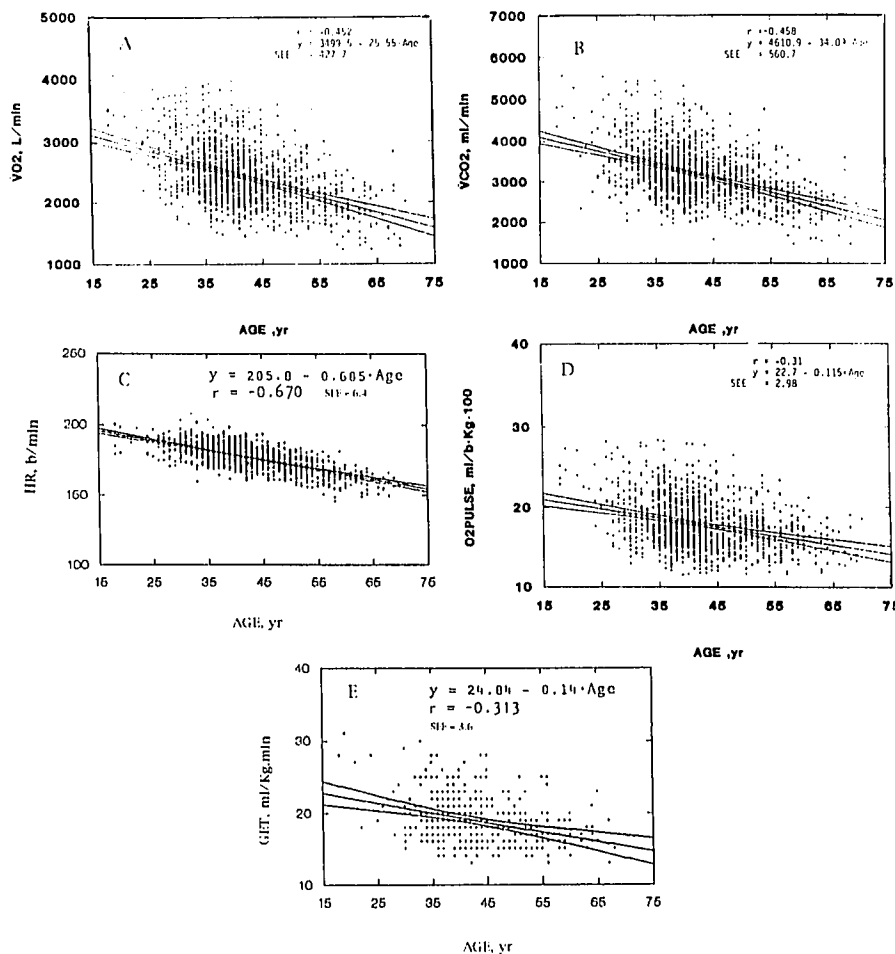


Figure 1—Relationship between age and cardiovascular variables at maximal exercise ($N = 1424$; missing data on GET yielded an actual N of 936 for GET). Lines in each panel represent the mean and standard error of measurement of the linear regression fit to the data. The correlation coefficient, linear regression equation, and standard error of measurement of the regression line is given in each panel.

trend was evident in $\dot{V}CO_{2max}$ (Fig. 1B). Peak R values did not change appreciably as a function of age and remained high (1.27 ± 0.08) at all ages. Maximal HR decreased with age ($r = -0.67$) by 13%, from 185 ± 6.5 $b \cdot min^{-1}$ to 161 ± 5.8 $b \cdot min^{-1}$, over the 50-yr age range studied (Fig. 1C). The O_2 pulse at peak exercise declined from 20.4 ± 3.5 to 15.6 ± 2.1 $ml \cdot b^{-1} \cdot kg^{-1} \cdot 100$, an overall decrease of 24% or an average yearly decline rate of 0.6% (Fig. 1D). The $\dot{V}_{E_{max}}$ decreased steadily with increasing age from a value of 108.7 ± 24.7 $l \cdot min^{-1}$ in the youngest group to a value of 77.3 ± 14.4 in the oldest (Fig. 2A); an average decline of 29% across the 50 yr age range and a yearly decline rate of 0.74 $l \cdot min^{-1}$. While maximal breathing frequency (f) decreased significantly with age (21%), Vt was only mildly affected by increasing age (10% decline across the 50 yr) (Fig. 2, B and C). Maximal $\dot{V}_E/\dot{V}O_2$ and $\dot{V}_E/\dot{V}CO_2$ showed a relatively mild increase with increasing age (13% and 14%, respectively) (Fig. 3, A and B). Aging had no apparent effect on $PETO_2$ at peak exercise and only a mild lowering effect on peak $PETCO_2$ (7%) (Fig. 3, C and D).

There was a decline in the $\dot{V}O_2$ at the gas exchange threshold (GET), from 21.95 ± 5.2 at ages 20–30 to 17.2 ± 2.45 $ml \cdot kg^{-1} \cdot min^{-1}$ at 61–70. This indicates a reduction of 22% in the GET over 50 yr with an average

annual decline rate of 0.14 $ml \cdot kg^{-1} \cdot min^{-1}$ (Fig. 1E). When assessed as a fraction of $\dot{V}O_{2max}$ (GET-% $\dot{V}O_{2max}$), there was a continuous rise in GET-% $\dot{V}O_{2max}$ with age from $58.2 \pm 4.5\%$ in the youngest, to $68.8 \pm 5.3\%$ in the oldest age groups.

Effects of demographic and life-style characteristics on variables at maximal exercise. To determine the relative contributions of selected demographic and life-style related factors to the total variance of the cardiopulmonary variables at maximal exercise, a step-wise multiple linear regression analysis was conducted. Furnished in Table 3 are the predictive equations for the cardiopulmonary variables at maximal exercise. This analysis revealed that most of the independent variables studied (demographic and life-style characteristics), contributed significantly ($P < 0.01$) to the prediction of maximal $\dot{V}O_2$, $\dot{V}CO_2$, O_2 pulse, \dot{V}_E , $\dot{V}_E/\dot{V}O_2$, $\dot{V}_E/\dot{V}CO_2$, Vt, f, and $PETCO_2$. There were a few CP variables, HR, $PETO_2$, and GET, which were significantly influenced by only one or two independent variables. Age, leisure-time physical activity (>2 $h \cdot wk^{-1}$), and height (in that order) were the most potent predictors for most of the cardiopulmonary values at maximal exercise. Smoking affected mainly gas-exchange variables, while place of residency

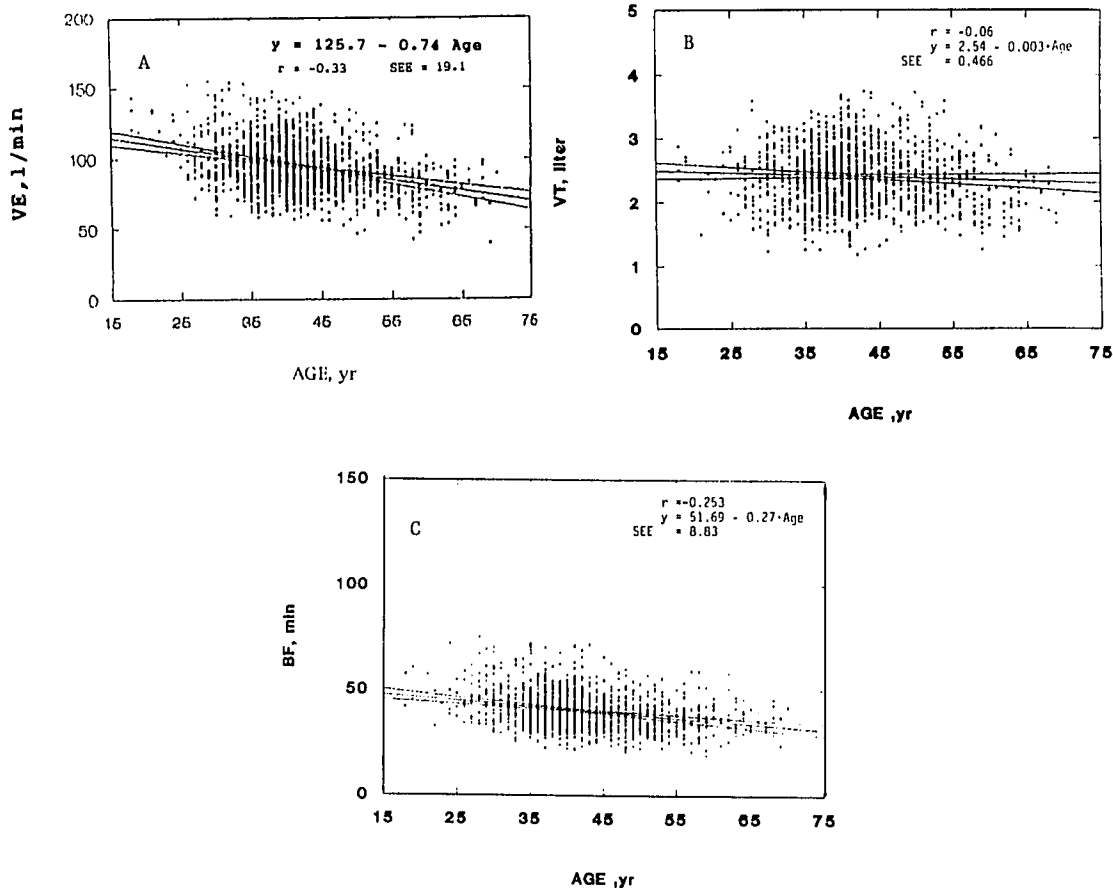


Figure 2—Relationship between age and ventilatory variables at maximal exercise (N = 1424). Lines and equations are as in Figure 1.

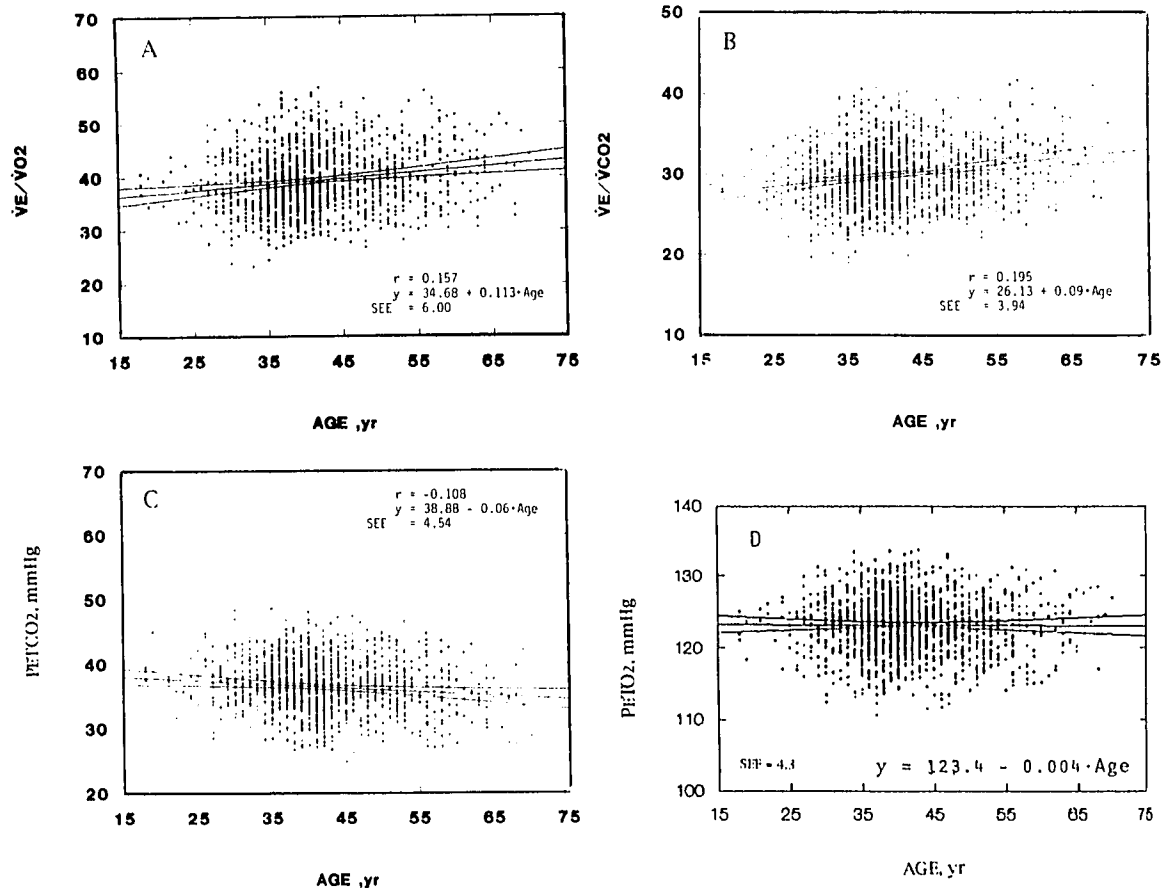


Figure 3—Relationship between age and gas-exchange variables at maximal exercise ($N = 1424$). Lines and equations are as in Figure 1.

TABLE 3. Predictive equations for selected cardiopulmonary values at maximal exercise ($N = 1421$).

Variable	Age (yr)	Ht (cm)	Wt (kg)	Active (>2 h·w ⁻¹)	Smoker (>10 Cigs·d ⁻¹)	Residence (urban)	Const.	SEE
$\dot{V}O_2$	-22.7	11.4	17.2	375		-251	182.8	343
$\dot{V}CO_2$	-30	15.8	22.9	405		-293	49.4	451
$\dot{V}O_2$ /kg	-0.33			4.6		-3.4	47.0	4.7
HR	-0.69						205.8	6.4
O ₂ pulse	-0.12			2.9		-1.9	23.7	2.7
GET	-0.14			2.1			24.1	3.3
\dot{V}_E	-0.72		0.78	7.6			71.5	16.2
$\dot{V}_E/\dot{V}O_2$	0.10	-0.07		-0.8	1.4	1.9	46.0	5.9
$\dot{V}_E/\dot{V}CO_2$	0.08	-0.07			0.9	1.1	37.8	3.9
Vt		0.02	0.01	0.1	-0.14		-1.63	0.4
f	-0.28	-0.24	0.12	1.4	2.8		82.1	7.9
PETO ₂							122.2	4.3
PETCO ₂	-0.06	0.03			-0.99	-0.6	34.0	4.4
R							1.27	0.08

Entries are regression coefficients for each variable obtained by multiple linear regression. For entering life habits categories into equations, active is coded 1, sedentary 0; smoking 1, nonsmoking 0; urban dwellers 1, rural 0. Blank spaces indicate insignificant effect for the variable in question ($P > 0.01$).

influenced both cardiovascular and pulmonary variables (Table 3).

Response patterns during incremental exercise.

The cardiopulmonary values at all exercise intensity levels were examined to discern the average response patterns for each age decade (Figs. 4 and 5). An increase in relative exercise intensity (% $\dot{V}O_{2max}$) was associated with a uniform increase in $\dot{V}O_2$ (both absolute and relative to body weight), $\dot{V}CO_2$, HR, O₂ pulse, \dot{V}_E , Vt, and f, up to an exercise intensity of about 50% of $\dot{V}O_{2max}$, which was

age independent. Above that exercise intensity level, the rate of increase in those variables was shown to be influenced by age. Significant differences among age groups in slopes were apparent at exercise intensities above 70% of $\dot{V}O_{2max}$ (Figs. 4 and 5). The response patterns of PETO₂ and $\dot{V}_E/\dot{V}O_2$ showed relatively small age differences at most submaximal levels, with significant inter age-group slope differences found only within the intensity range of 40–80% of $\dot{V}O_{2max}$ and only between the two extreme age groups (Fig. 5). R response

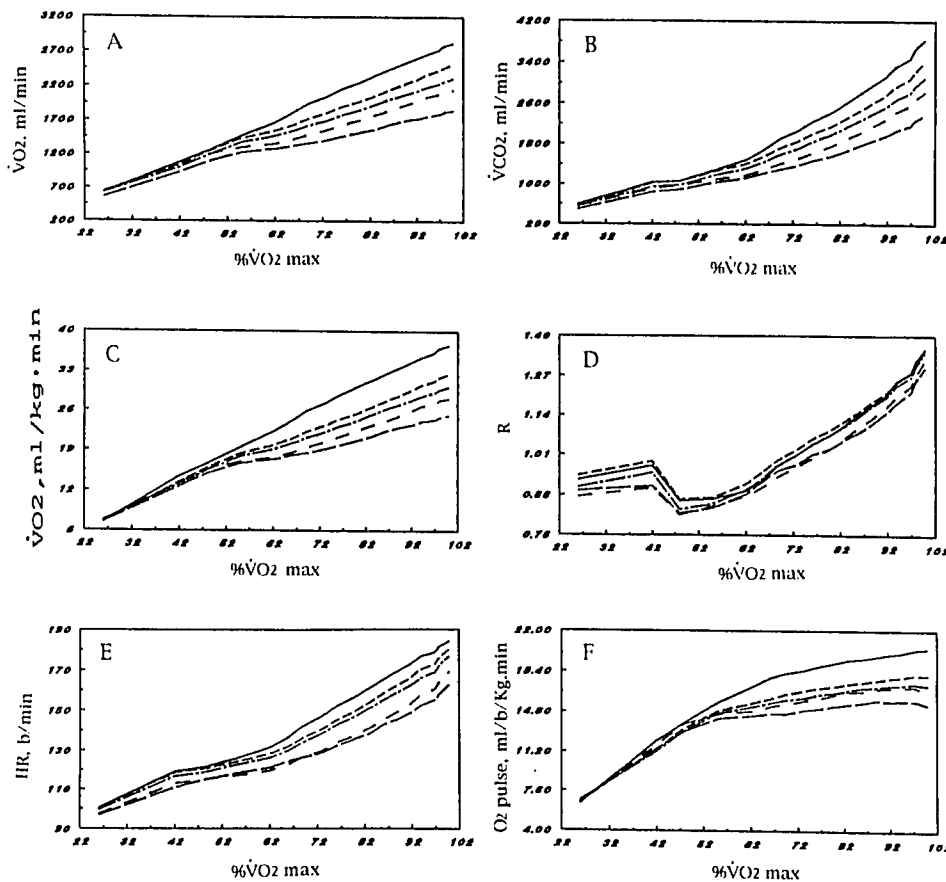


Figure 4—Cardiovascular variables in relation to % $\dot{V}O_{2max}$ during submaximal and maximal treadmill exercise by age groups. Solid line = age 20–30; short dash = age 31–41; dash with dots = age 41–50; medium dash = age 51–60; long dash = age 61–70.

patterns were very similar among all age groups (Fig. 4D).

Applying curve-fitting procedures to the average response curves indicated that only HR (besides $\dot{V}O_2$ itself) demonstrated linear increases with increasing relative physiologic load (% $\dot{V}O_{2max}$) (Fig. 4E). Three variables, $\dot{V}CO_2$, $\dot{V}E$, and V_t , showed an exponential response to increased exercise intensity (Figs. 4B and 5, A and B), while six other variables, R, f, $\dot{V}E/\dot{V}O_2$, $\dot{V}E/\dot{V}CO_2$, $PETO_2$, and $PETCO_2$, demonstrated polynomial function patterns with increasing relative exercise intensity. Only the response pattern of O_2 pulse to an incremental increase in exercise intensity showed a logarithmic-type function (Fig. 4F). The respective r values for all the response functions ranged between 0.978 and 0.999.

DISCUSSION

This study presents normative values for the interpretation of cardiopulmonary responses to standardized incremental exercise testing on a treadmill. Most previous reports of reference values for cardiopulmonary variables during exercise in healthy individuals have been based on small sample sizes (1,2,4,6,10,17–19,22,24,26,30,32,33,44). Statistics based on these studies, therefore, are less likely to provide a precise estimate of population parameters. In the

few studies using larger sample sizes for both submaximal and maximal exercise, a full range of response variables are not presented (3,7,8,13,15,29,37). The demographic and anthropometric features (Table 1), as well as the life-style characteristics (Table 2), of our population sample are within the reported normal ranges for Western populations, suggesting that the sample used in this study is presumably similar to normal and healthy populations in other Western industrialized countries (2,4,7,8,11,17,23,24,31).

Values at maximal exercise—cardiovascular variables. In several European (1,2,31) and North American (3,10,18,23,27,37) studies, $\dot{V}O_{2max}$ values were comparable to those reported here. However, $\dot{V}O_{2max}$ values in the present study are 5–12% lower throughout the age range studied, than those reported by Dehn and Bruce (13), Jones et al. (26), and others (1,2,7,22,38). The relatively low $\dot{V}O_{2max}$ values found in this sample of Israeli men may indicate lower than European and/or North American cardiovascular fitness levels, especially in the youngest age-group (20–30 yr), and may explain, at least partially, the relatively slow $\dot{V}O_{2max}$ age-related rate-of-decline of $0.33 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}\cdot\text{yr}^{-1}$, when compared with several American- and European-based studies ($0.45\text{--}0.50 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}\cdot\text{yr}^{-1}$) (1,2,7,13,22,26,38). However, one cannot exclude the possibility that some of the reported European and/or American studies used subjects

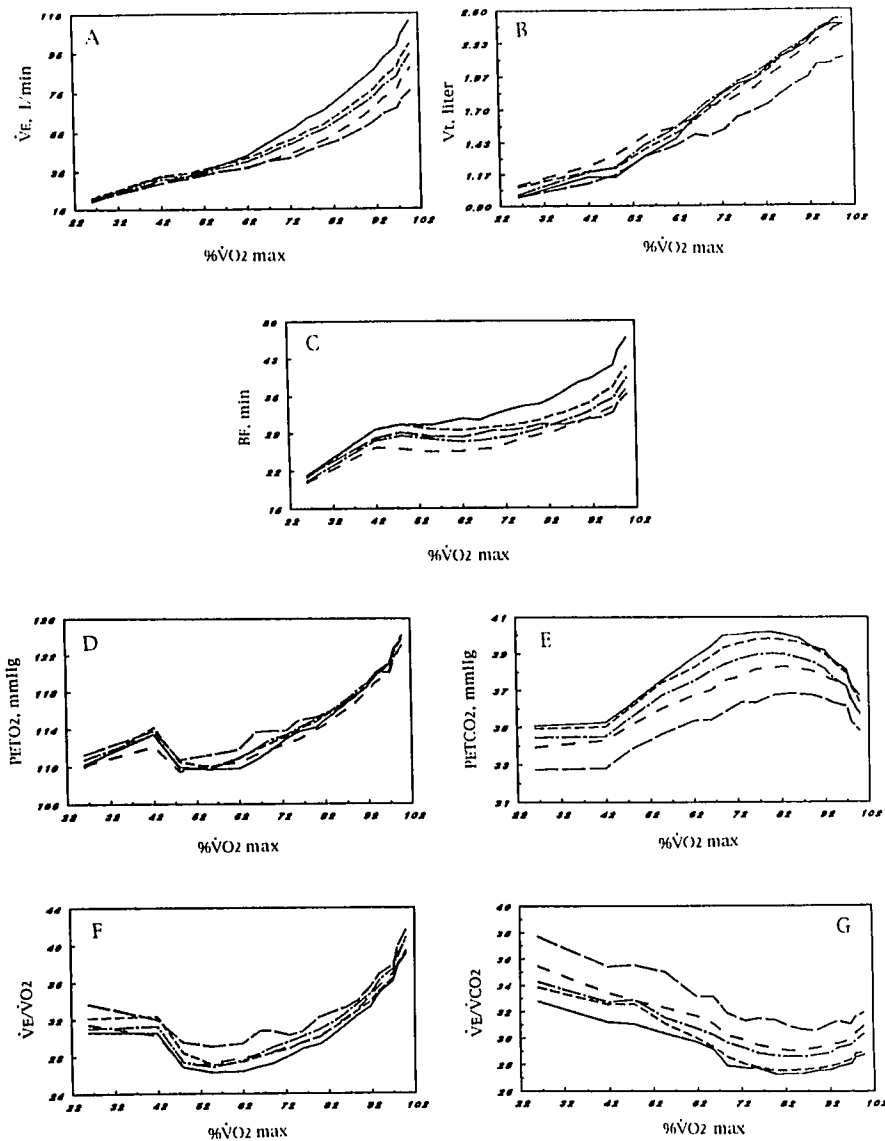


Figure 5—Respiratory and gas-exchange variables in relation to $\% \dot{V}O_{2\max}$ during submaximal and maximal treadmill exercise by age groups. Line symbols are as in Figure 4.

who did not truly represent their respective populations, favoring more active and fitter subjects.

The improvement in $\dot{V}O_{2\max}$ following a training program is well established. Thus, a major factor that may account for the variation in $\dot{V}O_{2\max}$ and related variables in subjects of any given age, sex, height, and weight is their level of recreational and/or occupational physical activity. A crude index of habitual leisure time physical activity ($>2 \text{ h}\cdot\text{wk}^{-1}$) and/or type of residency (rural vs urban), added significantly to the prediction of $\dot{V}O_{2\max}$ (Table 3). We therefore suggest to include the subject's leisure time activity, type of residency, age, weight, and height, in the calculation of predicted $\dot{V}O_{2\max}$.

Among other variables measured at maximal exercise, heart rate was shown to vary as a function of age only, the relationship (Fig. 1C) being quite similar to that obtained from several large population studies over the past 50 yr (3,7,8,13,15,29,37). The relationship between maximal heart rate and oxygen uptake (O_2 pulse) yields informa-

tion on the maximal cardiac stroke volume and oxygen-content difference between arterial and mixed venous blood. Thus, the O_2 pulse at maximal exercise ($\dot{V}O_{2\max}/HR_{\max}$) reflects the maximal stroke volume. Regression analysis suggests that values for maximal O_2 pulse may be best predicted from age together with leisure-time activity level and type of residency (Table 3). It should be noted that in previous studies, prediction of O_2 pulse was obtained as the quotient of predicted $\dot{V}O_{2\max}$ and predicted HR_{\max} . Provision of an independent prediction equation for max O_2 pulse, as well as for other calculated quotients (R , $\dot{V}_E/\dot{V}O_2$, $\dot{V}_E/\dot{V}CO_2$), enables a more accurate estimate of these variables.

Wasserman and McIlroy (39), and later Weber and Janicki (42), established the relevance and importance of the anaerobic threshold (GET) in identifying cardiovascular and metabolic abnormalities. In the present study, we used gas exchange criteria to identify the GET (36). Our data show a steady decline in GET through age 60.

Adding leisure time activity level to the predictive equation for GET significantly decreases the error of estimate from 3.60 to 3.28 ml·kg⁻¹·min⁻¹ and increases its residual variance from 10–17% (Table 3). These findings confirm previous reports which showed that anaerobic threshold increases with physical activity and/or fitness level (12,30,40,42). The overall decline in GET between the ages 20 and 70 yr averages 4.75 ml·kg⁻¹·min⁻¹. When calculated as percentage of $\dot{V}O_{2\max}$, an opposite trend emerges with the lowest values (58%) in the youngest age group and the highest (69%) in the oldest age group. Thus, as shown in previous studies, anaerobic threshold increases as a percentage of $\dot{V}O_{2\max}$ with increasing age (17,18,33,38,42), suggesting that the rate of work that can be performed anaerobically decreases less than maximal aerobic power.

Values at maximal exercise—ventilatory variables. $\dot{V}_{E\max}$ is closely related to $\dot{V}CO_{2\max}$ ($r = 0.47$; $P < 0.001$), with their relationship being independent of all anthropometric and demographic factors studied. As a function of % $\dot{V}O_{2\max}$, $\dot{V}_{E\max}$ also fell with age ($r = -0.33$; $P < 0.001$). Including body weight and level of leisure time physical activity in the predictive equation significantly improved its predictive power from $r = -0.33$ to $R = 0.53$ (Table 3). The overall decline in $\dot{V}_{E\max}$ from age 20 to age 70 (averaging 31 l·min⁻¹; ~30%) is consistent with previous reports (2,4,6,17,18,24,26,31,33,34) and is likely related to the lower work rates and lower levels of lactic acidosis tolerated by older subjects. One, however, cannot exclude the possibility that the observed reduced $\dot{V}_{E\max}$ with age results, at least partially, from the reduced MVV associated with aging. The observed decline in $\dot{V}_{E\max}$ with age was due predominantly to reductions in maximal breathing frequency (f) until the age of 50, and to reduced V_t from that age on.

Ventilation during exercise is primarily associated with metabolic needs. Hence, it is more closely related to $\dot{V}CO_2$ and $\dot{V}O_2$ than to any particular resting pulmonary function (5,20,25,34,35). This close correlation, both at submaximal and maximal exercise, supports the use of the ventilatory equivalents for CO_2 ($\dot{V}_E/\dot{V}CO_2$) and O_2 ($\dot{V}_E/\dot{V}O_2$) to assess the appropriateness of minute ventilation during exercise (4,20,24,27,34,40). The mean values from five previous studies were 31 ± 4.5 and 40 ± 5.2 for $\dot{V}_{E\max}/\dot{V}CO_{2\max}$ and $\dot{V}_{E\max}/\dot{V}O_{2\max}$, respectively (4,17,18,24,33). These are similar to those found in our sample. In both ventilatory equivalents we found a slight increase as a function of age (Fig. 3, A and B). Body stature and smoking habits (>10 cigarettes·d⁻¹) also influenced these ratios (Table 3). The inclusion of height and smoking status in the predictive equations improves the predictive power (residual variance) of the respective age-dependent equations by about 50% (Table 3). The observed increase in the common variance of both $\dot{V}_E/$

$\dot{V}CO_2$ and $\dot{V}_E/\dot{V}O_2$ by adding height and smoking habits is attributed to the known relationship between height (positive) and smoking (negative) on pulmonary function.

End-tidal PO_2 ($PETO_2$) at peak exercise was marginally affected by age. The range of $PETO_2$ values found in this study are somewhat higher than measured PaO_2 values normally observed at peak exercise (16,27,28,43). End-tidal PCO_2 ($PETCO_2$) at peak exercise showed a small decline with increasing age from 37.1 at 25 to 34.4 at 65, and is modestly higher than measured $PaCO_2$ values at maximal effort (16,27,28,43). Other demographic and life-style characteristics had no appreciable influence on the end-tidal values (Table 4).

Cardiopulmonary response patterns at submaximal exercise intensities. The response patterns of most cardiopulmonary variables to an incremental increase in exercise intensity are similar to those observed in previous studies, which generally used much smaller and selective samples (1,2,4,6,18,24,26,31–33). For most of the cardiopulmonary variables, aging is associated with reduced response at a given % $\dot{V}O_{2\max}$ at high exercise intensities. The influence of age is most apparent in the cardiovascular-related variables at exercise intensities higher than 70% of $\dot{V}O_{2\max}$ (Figs. 4 and 5). This response reduction may also be related to the lower level of lactic acidosis tolerated by older individuals. The variable-specific response patterns (functions), as identified in this study (Figs. 4 and 5), could be a useful addition in the assessment and interpretation of cardiopulmonary exercise (incremental) test results.

In summary, we have presented cardiopulmonary responses to incremental treadmill exercise tests in normal males representing wide range of ages, body sizes, fitness levels, and life-styles. The relatively wide range of response patterns indicates that normal responses vary widely. This must be considered when cardiopulmonary data from exercise tests are analyzed. The significant contribution of several demographic and life-style elements to the overall variance of many cardiopulmonary variables emphasizes the need to consider them when applying predictive equations for cardiopulmonary variables at maximal and submaximal exercise. Their inclusion in the prediction equations can lead to a more accurate definition of the “normal” response for a given subject.

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