Gas Exchange Response to Exercise in Children[1,2]

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SUMMARY We measured the gas exchange response to exercise in 109 normal children (51 girls and 58 boys, ranging in age from 6 to 17 yr old) using noninvasive breath-by-breath techniques. The protocol consisted of cycle ergometry in which the work rate increased in a linear manner (ramp forcing function) until the limit of the subject's tolerance was reached. We measured the maximal oxygen uptake ($\dot{V}O_2$max) and the $\dot{V}O_2$ at the anaerobic threshold (AT). We found that both of these parameters were highly correlated with increasing height, and that for both the AT and $\dot{V}O_2$max, the values for boys were significantly higher than girls. We compared our results of $\dot{V}O_2$max to those obtained by Åstrand over 30 years ago using different techniques. When boys and girls were considered together, there were no significant differences between our study and Åstrand's; however, girls in our study had significantly lower values for $\dot{V}O_2$max than did girls in Åstrand's study. These data provide normal values for both $\dot{V}O_2$max and AT and can be used to evaluate the exercise impairment resulting from disease in children.

Introduction

The focus of exercise studies in children has historically been on the child's capacity to participate in sports and on the identification of potential athletes (1, 2, 3). More recently, there has been interest in exercise as a means of evaluating children with asthma, cystic fibrosis, and congenital heart disease (4, 5, 6). With the development of noninvasive techniques to analyze gas exchange during exercise breath-by-breath (7, 8) and, therefore, the tools to gain insight to the kinetics of the exercise response, the potential usefulness of exercise testing in the clinical setting is even greater. In this report, we present our evaluation of exercise testing using breath-by-breath techniques in a large population of children. We measured two parameters of the aerobic response to exercise. The first is the traditional "maximum oxygen uptake." We compared our results to the classic study of Åstrand done 30 years ago, in which oxygen uptake was measured by the Douglas bag method (1). The second is the noninvasive measurement of the anaerobic threshold. We used height as an index of body size because this has previously proved to be accurate in developing predictive equations in pulmonary function testing in children (9, 10).

Methods

Population

We tested 109 children, 51 girls and 58 boys, ranging in age from 6 to 17 yr. Both the boys and girls were equally distributed over this age range. Mean values of height, weight, and age are given in table 1. Children were all volunteers from our community. No attempt was made to select children who were involved in rigorous sports or training programs. Obese children, children with a history of chronic disease of any organ system, or children who, for whatever reason, were not allowed to participate in physical education programs at school were excluded from the study. Eighty-six percent of the children were Causasian; the remainder were oriental, Hispanic, and black. The children were predominantly of the middle socioeconomic class. This study was approved by the Human Subjects Committee of the Harbor-UCLA Medical Center, and informed consent was obtained from the children and their guardians.

Protocol

We used cycle ergometry and a continuously increasing work rate—ramp forcing function—developed in this laboratory (11). The children pedaled at 0 watts (W), unloaded cycling, for a warm-up period of 3 to 4 min; then the work rate increased until the limit of the subject's tolerance was reached. Each child maintained a constant pedaling rate of 50 to 70 rpm for the whole test period. The children were actively encouraged to "get to the top of the hill." The average test period was only 12 min.

Measurement of Gas Exchange

Breath-by-breath measurements of gas exchange were made using rapid gas analyzers (mass spectrometer) and pneumotachygraphs for flow and volume measurements (10). On-line display of ventilation ($\dot{V}E$), oxygen uptake ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$), end-tidal Po_2 and Pco_2 (PET_{O_2}, PET_{CO_2}), ventilatory equivalents of O_2 and CO_2 ($\dot{V}E/\dot{V}O_2$, $\dot{V}E/\dot{V}CO_2$), and the gas exchange ratio (R) allowed us to measure the anaerobic threshold. This was taken as the point where hyperventilation with respect to $\dot{V}O_2$ occurred without hyperventilation with respect to $\dot{V}CO_2$. Thus, the AT was measured as the VO_2 where there was an abrupt increase in PET_{O_2}, $\dot{V}E/\dot{V}O_2$, and R with little or no change in PET_{CO_2} and $\dot{V}E/\dot{V}CO_2$ (12). The maximal $\dot{V}O_2$ ($\dot{V}O_2$max) was taken as the largest $\dot{V}O_2$ achieved by the child during the exercise test.

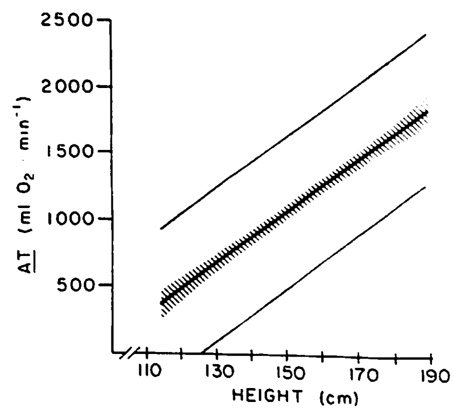

Fig. 1. The anaerobic threshold (AT) as a function of height in normal girls and boys. Hatched area represents the 95% confidence bands for the mean of our population. The outlying lines represent the 95% confidence bands for estimating AT from our population. *See* text and table 2 for linear regression equation, confidence band formulas, and correlation coefficient.

Results

In figures 1–4 we show the values of AT and $\dot{V}O_2$max as a function of height. For both the $\dot{V}O_2$max and the AT, girls had significantly lower values than the boys. The shaded areas in the figures represent the 95% confidence bands of the mean of the study population, and the outlying lines represent the 95% confidence bands for the predicted AT or $\dot{V}O_2$max based on height. The linear regression equations, standard error estimate (Sy.x), Σx^2, and correlation coeffi-

TABLE 1

MEAN HEIGHT, WEIGHT, AND AGE OF THE STUDY POPULATION

	N	Height (cm) Mean + 1 SD	Weight (cm) Mean + 1 SD	Age (yr) Mean + 1 SD
Girls	51	148 ± 19	43 ± 14	12 ± 3
Boys	58	152 ± 23	45 ± 18	12 ± 4
All children	109	150 ± 20	44 ± 16	12 ± 3

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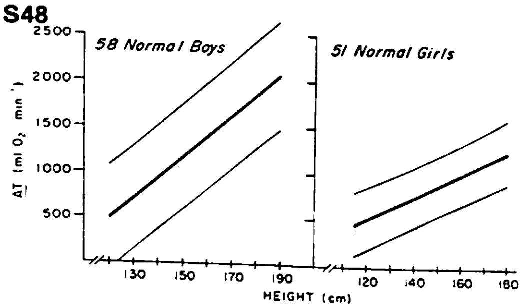

Fig. 2. *Left Panel:* The anaerobic threshold (AT) as a function of height in normal boys, and (*right panel*) in normal girls. Hatched areas represent the 95% confidence bands for the mean of our population. The outlying lines represent the 95% confidence bands for estimating AT from our population. *See* text and table 2 for linear regression equations, confidence band formulas, and correlation coefficients.

cients are given in tables 2 and 3. For any *y* (AT or $\dot{V}O_2max$) calculated from *x* (height) by the linear regression equation, the confidence bands are obtained from the following equations (13):

1. 95% confidence bands for the mean:

$$y \pm (t_{.05}) \times (Sy.x) \times [1/N + (x-\overline{X})^2/\Sigma x^2]^{1/2}$$

2. 95% confidence bands for y:

$$y \pm (t_{.05}) \times (Sy.x) \times [1 + 1/N + (x-\overline{X})^2/\Sigma x^2]^{1/2}.$$

Discussion

We reanalyzed the data of Åstrand obtained by cycle ergometry in 124 children (63 boys, 61 girls) in the same age range as our study population (1). Our regression equation for $\dot{V}O_2max$ of the boys and girls together (table 3) was not significantly different from Åstrand's (Y = 40.4 X - 3846.0). The regression equation of the Scandinavian boys (Y = 46.4 X - 4610.6) was virtually identical to ours, but the regression slope of the Scandinavian girls (Y = 32.6 X - 2820.3) was significantly higher than the slope obtained for girls in our study (table 3, $p < .05$ by *t* test). The similarity between the two populations is remarkable, but the marked difference between the girls of our study and those of Åstrand (from 30 years ago) may, perhaps, reflect cultural attitudes in our society toward physical fitness, which lead to generally lower levels of fitness among girls.

The AT indicates the point at which oxygen supply to the working muscles is inadequate in meeting all of their energy requirements; thus, anaerobic metabolism and excess lactic acid production ensue (14, 15). The onset of anaerobic metabolism has been shown to be affected by such factors as anemia (16) and the presence of peripheral vascular disease (17). Recent work on the AT in adults with congestive heart failure has shown its usefulness as an indicator of clinical severity in these patients (18). The ramp protocol and breath-by-breath analysis of gas exchange allow for the measurement of the AT and $\dot{V}O_2max$ in a single exercise test. This is especially suitable for children, first, because the test is noninvasive, and second, because the protocol is both brief and stimulating to the young child whose sense of competition is high, but whose attention span is low. This study provides normal values that can be used to evaluate the exercise impairment resulting from disease in children.

TABLE 2

REGRESSION EQUATIONS FOR AT (ML $O_2 \cdot MIN^{-1}$) AS A FUNCTION OF HEIGHT (CM)*

	M	b	r	Sy·x	Σx²
All children	19.6	− 1881.7	0.80	281.1	40036
Girls	12.5†	− 967.5	0.79	163.4	13951
Boys	22.6	− 2219.6	0.87	280.4	25862

* Y = Mx + b

† Significantly less than slope of boys ($p < 0.001$).

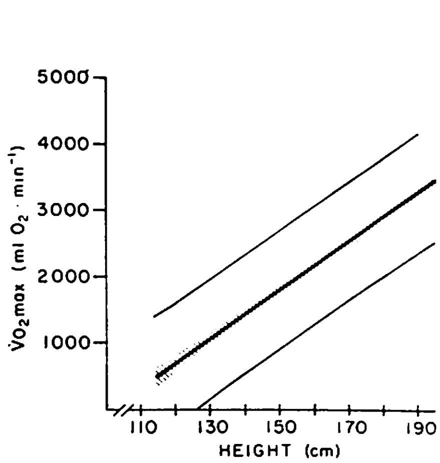

Fig. 3. The maximal oxygen uptake ($\dot{V}O_2max$) as a function of height in normal girls and boys. Hatched area represents the 95% confidence bands for the mean of our population. The outlying lines represent the 95% confidence bands for estimating $\dot{V}O_2max$ from our population. *See* text and table 3 for linear regression equation, confidence band formulas, and correlation coefficient.

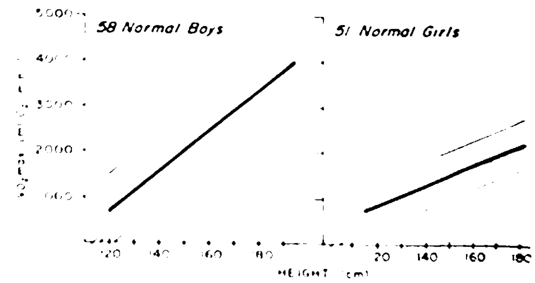

Fig. 4. *Left Panel:* The maximal oxygen uptake ($\dot{V}O_2max$) as a function of height in normal boys, and (*right panel*) in normal girls. Hatched areas represent the 95% confidence bands for the mean of our population. The outlying lines represent the 95% confidence bands for estimating $\dot{V}O_2max$ from our population. *See* text and table 3 for linear regression equations, confidence band formulas, and correlation coefficients.

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TABLE 3

REGRESSION EQUATIONS FOR $\dot{V}O_2max$ (ML $O_2 \cdot MIN^{-1}$) AS A FUNCTION OF HEIGHT (CM)*

	M	b	r	Sy·x	Σx²
All children	37.1	− 3770.6	0.85	447.0	40027
Girls	22.5†	− 1837.8	0.83	253.2	13951
Boys	43.6	− 4547.1	0.85	394.3	25857

* Y = Mx + b

† Significantly less than slope of boys ($p < 0.001$)