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Aerobic parameters of exercise as a function of body size during growth in children

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COOPER, DAN M., DANIEL WEILER-RAVELL, BRIAN J. WHIPP, AND KARLMAN WASSERMAN. *Aerobic parameters of exercise as a function of body size during growth in children.* J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 56(3): 628–634, 1984.—To examine the relationship between body weight in children and aerobic parameters of exercise, we determined the anaerobic threshold (AT), maximum O_2 uptake ($\dot{V}O_{2\,max}$), work efficiency, and response time for O_2 uptake (RT-$\dot{V}O_2$) in 109 healthy children (51 girls and 58 boys, range 6–17 yr old) using a cross-sectional study design. Gas exchange during exercise was measured breath by breath. The protocol consisted of cycle ergometry and a linearly increasing work rate (ramp) to the limit of the subject's tolerance. Both AT and $\dot{V}O_{2\,max}$ increased systematically with body weight, whereas work efficiency and RT-$\dot{V}O_2$ were virtually independent of body size. The ratio of AT to $\dot{V}O_{2\,max}$ decreased slightly with age, and its mean value was 60%. AT scaled to body weight to the power of 0.92, not significantly different from the power of 1.01 for $\dot{V}O_{2\,max}$. Thus both the AT and the $\dot{V}O_{2\,max}$ increase in a highly ordered manner with increasing size, and as judged by AT/$\dot{V}O_{2\,max}$, the onset of anaerobic metabolism during exercise occurred at a relatively constant proportion of the overall limit of the gas transport system. We conclude that in children cardiorespiratory responses to exercise are regulated at optimized values despite overall change in body size during growth.

anaerobic threshold; work efficiency; response time for oxygen uptake; maximum oxygen uptake; scaling; ramp exercise protocol

THE PURPOSE of this study was to examine metabolic rates during exercise as a function of the changes in body weight accompanying growth in children. We measured four aerobic parameters of exercise in a cross-sectional study of normal children. One parameter, the maximum uptake ($\dot{V}O_{2\,max}$), often has been used to assess the aerobic response to exercise in children (1, 6, 7, 10). However, $\dot{V}O_{2\,max}$ indicates only one aerobic factor: the limit of the organism's ability to utilize atmospheric O_2 for cellular energetics.

Three other important aerobic factors are the anaerobic threshold (AT), the highest metabolic rate for which the energy requirements may be obtained solely from O_2 uptake, and, hence, without concomitant anaerobiosis (28–31); the work efficiency, the organism's proportional aerobic cost of mechanical work; and the response time of O_2 uptake at the onset of exercise (RT-$\dot{V}O_2$), the temporal coupling between the metabolic demand of exercise and the response dynamics of the gas transport system (i.e., the sum of the response time constant and any inherent system delays). These four aerobic parameters can be obtained noninvasively from a single brief exercise protocol developed in this laboratory (32). Neither the AT nor the RT-$\dot{V}O_2$ have been measured in large numbers of normal children.

METHODS

Population. All subjects were volunteers obtained through local schools, community organizations, and children of the hospital staff. We excluded obese children, children with a history of chronic disease of any organ system, or children who were not allowed to participate in normal physical education programs at school. No attempt was made to select subjects who were particularly active; i.e., we did not recruit through physical education or sports programs.

One hundred nine children (58 boys and 51 girls, range 6–17 yr old) comprised the study population. One hundred fourteen children were originally tested; however, five were excluded because the AT could not be determined by gas exchange techniques. Pubertal ratings were not done on the children, but for certain of our analyses, the subjects were divided into the four following age groups, which corresponded to the onset of puberty based on recent studies in boys and girls (19): *1*) girls 6–11 yr old (younger girls); *2*) girls 12–17 (older girls); *3*) boys 6–13 (younger boys); and *4*) boys 14–17 (older boys). Age, weight, and height profiles of our study population are provided in Table 1. All children were within the normal range for height and weight by reference tables of the National Center for Health Statistics. The children were predominantly of the middle socioeconomic class. Eighty-six percent of the subjects were Caucasian; the remainder consisted of Oriental, Hispanic, and black children. This project was approved by the Human Subjects Committee of Harbor-UCLA Medical Center. Informed consent was obtained from each child and guardian before participation.

Exercise protocol. Height and weight were measured before testing. The subjects were told that they would be doing one hard exercise test on a special bicycle, and that they would feel like they were riding up a steep hill.

The protocol consisted of a ramp forcing function (32) utilizing an electronically braked cycle ergometer (Godart). Subjects began by cycling at 0 W (unloaded) work rate with a minimum of 3 min of a warm-up phase. For children 8 yr old and above, the warm-up period was 4 min. Work rate was then continuously incremented in a linear ramp pattern. An example of a ramp protocol is shown in Fig. 1.

TABLE 1. *Anthropometric profile of study population*

	Girls <12 yr (*n* = 24)	Girls, >11 yr (*n* = 27)	All Girls (*n* = 51)	Boys, <14 yr (*n* = 37)	Boys, >13 yr (*n* = 21)	All Boys (*n* = 58)	Total (*n* = 109)
Age, yr	9	15	12	10	16	12	12
	±2	±2	±3	±2	±1	±4	±3
Wt, kg	33	52	43	34	65	45	44
	±10	±11	±14	±9	±11	±18	±16
Ht, cm	135	160	148	138	176	152	150
	±14	±13	±19	±14	±11	±23	±21

Values are means ± SD.

The slope of the ramp (the increase in work rate per minute) was determined so that the ramp would be greater than 5- and less than 12-min duration. For each child, a suitable slope was chosen based on our own initial studies. In general, for children from 6 to 9 yr of age, the ramp was 10 W/min; from 10–13, 15 W/min; and from 14–17, 20 W/min. For certain adolescents who were deemed to be quite fit by history, ramp slopes as high as 40 W/min were chosen. The mean time for the ramp (not counting the warm up) was 9 min. The children were instructed to raise their hand when they could not continue, and on this signal, the work rate was reduced to 0 W. The children were actively encouraged periodically throughout the test.

The children were instructed to maintain as constant a pedaling rate as possible between 50 and 70 rpm. A pedaling rate meter was in full view of each subject, and

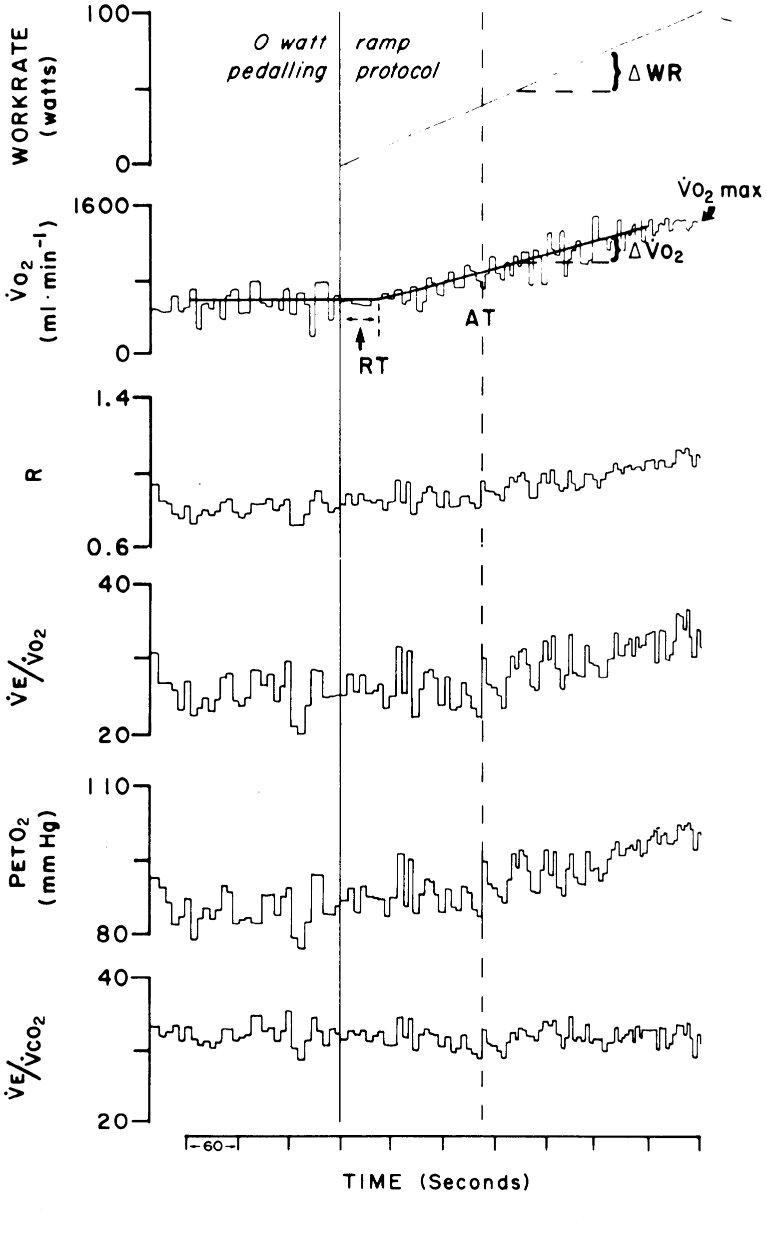

FIG. 1. Breath-by-breath response of gas exchange to ramp exercise protocol in 7-yr-old boy. After a period of 0-W pedaling, work rate increases (Δ WR) in linear manner. Note lag in response of O_2 uptake after WR has started (RT-$\dot{V}O_2$), linear increase of $\dot{V}O_2$ as WR increases, and plateau of $\dot{V}O_2$ despite an increasing WR ($\dot{V}O_{2max}$). Anaerobic threshold (AT) is determined by identifying $\dot{V}O_2$ where respiratory exchange ratio (R), ventilatory equivalent for O_2 ($\dot{V}E/\dot{V}O_2$), and end-tidal O_2 (PET_{O_2}) abruptly increase while ventilatory equivalent for CO_2 ($\dot{V}E/\dot{V}CO_2$) and end-tidal CO_2 (PET_{CO_2}) (not shown) remain unchanged or decrease. Work efficiency is determined from ratio of Δ WR to $\Delta\dot{V}O_2$.

a metronome could be activated at the discretion of the investigator present. A servomechanism in the electronic braking system of the ergometer maintained the input work to an accuracy of 1% within a range of pedaling rates of 50–90 rpm.

For the smaller children, the three following modifications were made in the ergometer itself: *1*) an adjustable seat designed to sit lower than the normal seat was used; *2*) the handlebars were lowered; and *3*) special attachments were used to effectively shorten the pedal cranks by 25%. We could, therefore, "fit" the ergometer to the size of the subject so that he or she was comfortable.

Measurement of gas exchange. The subjects breathed through low-resistance valves (Hans-Rudolph). For children less than 12 yr old, a 40-ml dead-space valve was used; for those 12 and above, a 90-ml dead-space valve was used. Inspiratory and expiratory airflow were measured by two pneumotachographs (Fleisch no. 3) attached to the inspiratory and expiratory ports of the breathing valves and by two variable-reluctance manometers (Validyne, MP45). The expiratory pneumotachograph was maintained at a constant temperature of 37°C by a thermal feedback device. This system was calibrated before each session by inputting known volumes of room air at various mean flows and flow profiles. Respired P_{O_2} and P_{CO_2} were determined by mass spectrometry (Perkins-Elmer MGA 1100) from a sample drawn continuously from the mouthpiece at 1 ml/s. Precision-analyzed gas mixtures were used for calibration of the mass spectrometer. The system was found to be stable throughout the period of the study (3, 22).

The electrical signals from these devices underwent analog-to-digital computation (Hewlett-Packard model 1050) for the on-line breath-to-breath determination of O_2 uptake ($\dot{V}O_2$, STPD), CO_2 output ($\dot{V}CO_2$, STPD), expired ventilation ($\dot{V}E$, BTPS), respiratory exchange ratio, ventilatory equivalent for O_2 and for CO_2, respectively, ($\dot{V}E/\dot{V}O_2$, $\dot{V}E/\dot{V}CO_2$), and end-tidal partial pressures of O_2 and CO_2, respectively, ($P_{ET_{O_2}}$, $P_{ET_{CO_2}}$). The data from each test were displayed on line (Beckman R711 dynagraph) and stored on digital tape for subsequent analysis. The breath-by-breath data of each subject were interpolated at 1-s intervals, and moving averages could be obtained for smoothing of studies with a great deal of breath-to-breath variation.

Analysis of Gas Exchange Data

Maximal O_2 uptake. We took the $\dot{V}O_{2\,max}$ as the largest $\dot{V}O_2$ achieved by the subject. We distinguished between these values and the "true" $\dot{V}O_{2\,max}$, defined as an interval of at least 20 s in which $\dot{V}O_2$ remained constant or decreased, despite an increasing work rate.

Anaerobic threshold. AT was determined from gas exchange data by finding the $\dot{V}O_2$ at which $\dot{V}E$ increased out of proportion to the increase in $\dot{V}O_2$. This is done most accurately by finding where $\dot{V}E/\dot{V}O_2$ and $P_{ET_{O_2}}$ increase (hyperventilation with respect to O_2) without an increase in $\dot{V}E/\dot{V}CO_2$ or a decrease in $P_{ET_{CO_2}}$. Hyperventilation with respect to O_2 without concomitant hyperventilation for CO_2 only occurs during buffering of a metabolic acid by HCO_3^-. Other forms of hyperventilation should cause $P_{ET_{O_2}}$ to increase and $P_{ET_{CO_2}}$ to decrease while $\dot{V}E/\dot{V}O_2$ and $\dot{V}E/\dot{V}CO_2$ increase together (23, 32). In five subjects of our original sample, the AT could not be found because $\dot{V}E/\dot{V}CO_2$ increased at the same time as $\dot{V}E/\dot{V}O_2$.

Response time for O_2 uptake. In a ramp work rate protocol, RT-$\dot{V}O_2$ is the lag in the response of $\dot{V}O_2$ following the increase in work rate (32). This lag is determined by the method of least squares in the following way. A best-fit line is drawn through the steady-state $\dot{V}O_2$ response during 0-W pedaling, and another line through the linear phase of $\dot{V}O_2$ response during the ramp. The RT-$\dot{V}O_2$ is the time interval between the onset of work and the intersection of these two lines.

Work efficiency. In the ramp test, $\dot{V}O_2$ increases linearly as work rate increases (32). Work efficiency is calculated from the ratio of the change in $\dot{V}O_2$ to the change in work rate (33). The values of work rate and $\dot{V}O_2$ are converted into equivalent energy units, and work efficiency is given by the following equation

$$\text{work efficiency (\%)} = \frac{\Delta \text{ work rate (W)} \times 0.0144 \text{ kcal}\cdot\text{w}^{-1}\cdot\text{min}^{-1} \times 100\%}{\Delta\ \dot{V}O_2\ (\text{l}\cdot\text{min}^{-1}) \times 4.9 \text{ kcal}\cdot\text{l}^{-1}}$$

Since the calculated work efficiency is virtually unaffected by values of respiratory quotient in the physiological range, respiratory quotient is assumed to be 0.9, which gives the value 4.9 kcal/l O_2.

To estimate differences in metabolic rates at the cellular level, comparative physiologists use allometric equations in which metabolic function is specifically scaled to body mass (weight) (15, 17, 21, 23, 25). This was used in part to analyze the data.

Allometric equations have the form

$$Y \propto M^b$$

where Y is a metabolic function (e.g., $\dot{V}O_{2\,max}$), M is an index of body size, usually measured as body weight, and b is the scaling factor. The scaling factor is found by using a log-log transform resulting in

$$\log Y \propto b \times \log M$$

where b is then solved by using least-squares technique to find the slope of the best-fit line.

In the boys of our sample population, the height scaled to weight was to the power of 0.35, with a 95% confidence interval of 0.33–0.38, $r = 0.95$. In girls, this same value was 0.33, with a 95% confidence interval of 0.30–0.36, $r = 0.95$. For the population as a whole, the scaling factor was 0.34, with a 95% confidence interval of 0.32–0.37, $r = 0.95$.

Statistical analysis. Standard techniques of linear regression were used. For significance testing of regression slopes and comparison of slopes of different regression equations, we used the two-tailed *t* test (12). Comparison of multiple means was done by analysis of variance and modified *t* test was done by the method of Bonferroni (27). Statistical significance was taken at the $P < 0.05$ level. Results are presented as means ± SD.

RESULTS

Anaerobic threshold. The AT was highly correlated to body weight in children (Fig. 2). The scaling factor for the group as a whole was 0.92 (Table 2). Slopes of the regression equations and the scaling factors were significantly higher in boys than in girls (Fig. 2, Table 2). Although the scaling factors differed in the children when grouped by age and gender (young boys 0.95; young girls 0.76; older boys 1.12; and older girls 1.02), these differences were not significant by analysis of variance. When the AT was normalized for body weight, there was no significant correlation with age ($r = 0.13$); however, the group of older girls had a significantly lower mean value (19 ± 3 $\text{ml} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$) than did the older boys (27 ± 6 $\text{ml} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$) or the younger children (boys 26 ± 5 and girls 23 ± 4 $\text{ml} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$).

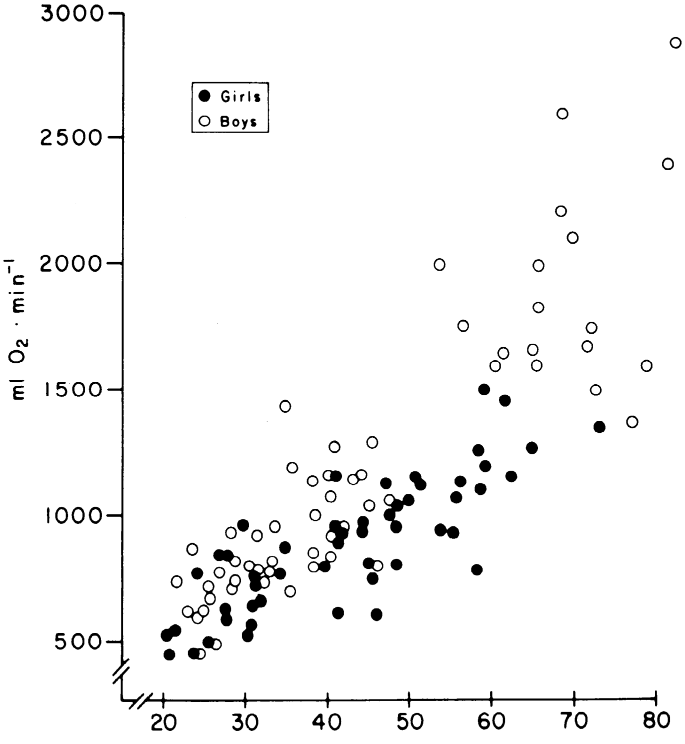

FIG. 2. Anaerobic threshold (AT) as function of weight in 109 normal children. AT increased systematically with increasing weight. Linear regression equations for AT (ml/min) as function of body weight (kg) were for boys, $Y = 27.3 \cdot X - 23.2$, $r = 0.78$; for girls, $Y = 16.1 \cdot X + 195.0$, $r = 0.82$; and for group as whole, $Y = 23.9 \cdot X - 4.3$, $r = 0.79$. Difference in slope between boys and girls was significant.

TABLE 2. *Scaling factors for AT and $\dot{V}O_{2\max}$ as a function of body weight in girls, boys, and all subjects*

Y	Group	b	95% Conference Interval		r
			Lower	Upper	
AT	All subjects	0.92	0.80	1.03	0.83
	Girls	0.77*	0.62	0.92	0.82
	Boys	0.99	0.87	1.13	0.90
$\dot{V}O_{2\max}$	All subjects	1.01	0.90	1.11	0.88
	Girls	0.83*	0.69	0.97	0.87
	Boys	1.09	0.97	1.20	0.93

AT, anaerobic threshold; $\dot{V}O_{2\max}$, maximum O_2 uptake. Regression equation: $Y \alpha$ weight^b. * Different from boys, $P < 0.001$.

Maximum O_2 uptake. $\dot{V}O_{2\max}$ also increased systematically with body weight (Fig. 3). The scaling factor for the group as a whole was 1.01 (Table 2). Slopes of the regression equations and the scaling factors were significantly higher in boys than in girls (Fig. 4, Table 2). Although the scaling factors differed in the children when grouped by age and gender (young boys, 1.01; young girls, 0.79; older boys, 1.02; and older girls, 0.91), these differences were not significant by analysis of variance. When $\dot{V}O_{2\max}$ was normalized for body weight, there was no significant correlation with age ($r = 0.17$). However, the group of older boys had a significantly greater mean value (50 ± 8 $\text{ml} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$) than did the three other groups (older girls, 34 ± 4; younger boys, 42 ± 6; and younger girls, 38 ± 7 $\text{ml} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$). In addition, the mean of the older girls was significantly lower than the younger boys.

In 31 subjects (28%) (15 girls and 16 boys) a "true" $\dot{V}O_{2\max}$ was observed.The regression equations and scaling factors of this group for both $\dot{V}O_{2\max}$ and AT were virtually indistinguishable from those obtained in the remaining 78 subjects.

In addition to the linear regression and log-log transforms done on the values for $\dot{V}O_{2\max}$ and AT, an analysis of quadratic regression equations ($\dot{V}O_{2\max}$ and AT as a function of weight) was done. Goodness-of-fit testing demonstrated no significant improvement in model fitting using the second degree equations for either of these parameters in the boys or the girls.

Relationship between anaerobic threshold and maximum O_2 uptake. The regression slope of AT vs. body weight was significantly lower than that of $\dot{V}O_{2\max}$ (Figs. 2 and 3). The scaling factor of AT was lower than that of $\dot{V}O_{2\max}$, but the difference was not significant (Table 2). The ratio of AT to $\dot{V}O_{2\max}$ decreased slightly as weight increased ($r = -0.28$, $P < 0.05$, Fig. 4). The mean ratio for the study population was 60 ± 9%. In the older boys, the ratio was 55 ± 10%; younger boys, 64 ± 6%; older girls, 58 ± 8%; and younger girls, 61 ± 7%. This ratio in the younger boys differed significantly from the older girls and older boys. The AT was highly correlated to the $\dot{V}O_{2\max}$. For the group as a whole, the correlation coefficient was 0.92; for boys 0.91; and for girls 0.89.

Response time for O_2 uptake. The RT-$\dot{V}O_2$ was independent of body weight in children and adolescents. There were no differences in mean values for this parameter among the younger and older boys and girls (F ratio from analysis of variance was 0.66). For the study population as a whole, the RT-$\dot{V}O_2$ was 43 ± 15 s.

Work efficiency. The work efficiency increased slightly with increasing body weight in children and adolescents (slope of regression equation = 0.07%/kg, $r = 0.22$). The slope of the regression was higher in girls (0.15%/kg, $r = 0.46$) than in boys (0.03%/kg, $r = 0.13$). The slope of the boys did not differ significantly from 0. Only the mean value of the older girls (33 ± 3%) differed significantly ($P < 0.05$) from the other groups (younger girls, 29 ± 5%; younger boys, 28 ± 5%; and older boys, 29 ± 4%).

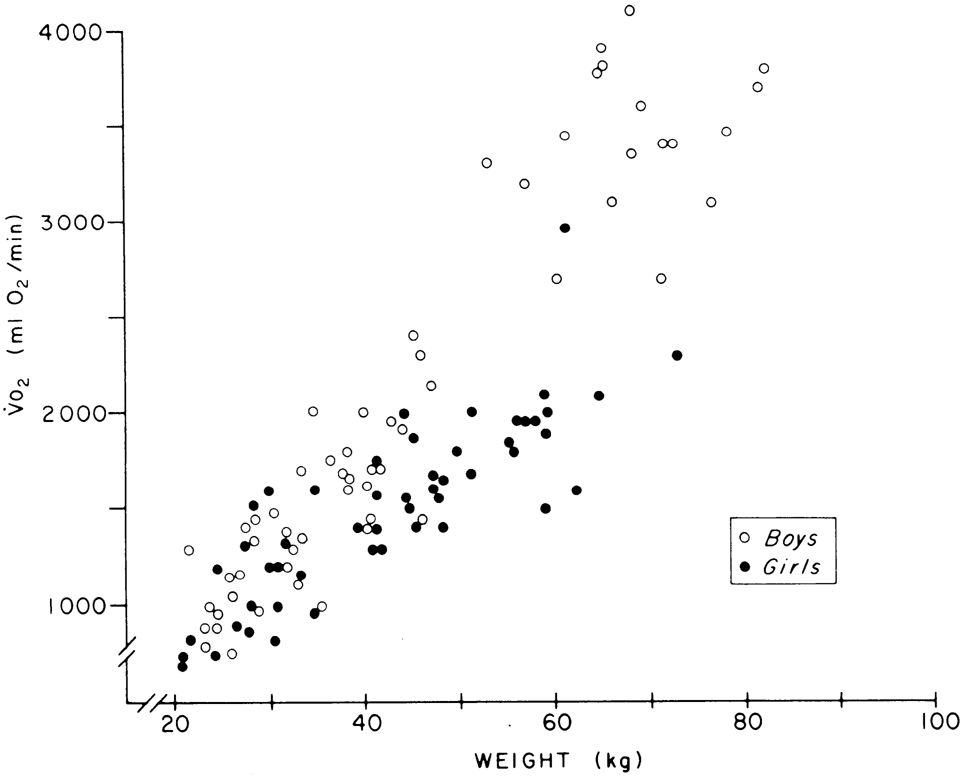

FIG. 3. Maximum O_2 uptake ($\dot{V}O_{2\max}$) as function of weight in 109 normal children. $\dot{V}O_{2\max}$ increased systematically with increasing body weight. Linear regression equations for $\dot{V}O_{2\max}$ (ml/min) as function of body weight (kg) were for boys, $Y = 52.8 \cdot X - 303.4$, $r = 0.94$; for girls, $Y = 28.5 \cdot X + 288.2$, $r = 0.84$; and for group as a whole, $Y = 45.6 \cdot X - 197.9$, $r = 0.86$. Difference in slope between boys and girls was significant.

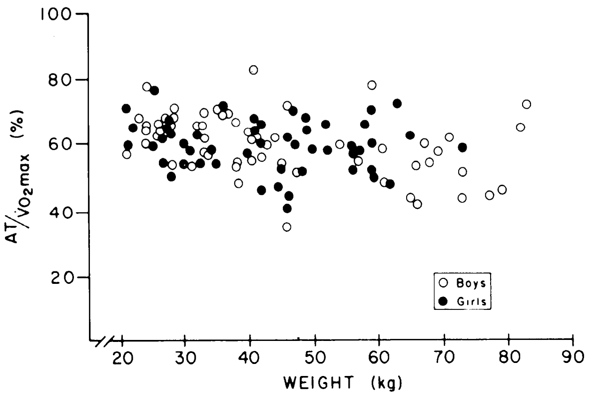

FIG. 4. Ratio of anaerobic threshold to maximal O_2 uptake (AT/$\dot{V}O_{2\max}$) (%) as function of weight in 109 normal children. Ratio decreased slightly with increasing body size. Regression equation $Y = -0.16 \cdot X + 67$.

DISCUSSION

We measured four aerobic parameters of exercise using a noninvasive brief exercise protocol in a large group of children. Both the $\dot{V}O_{2\max}$ and the AT bear a systematic relationship to body weight, whereas the work efficiency and the RT-$\dot{V}O_2$ are virtually independent of body mass. For the study population as a whole, the scaling factors of both the AT and the $\dot{V}O_{2\max}$ are not statistically different from the power of 1.0.

No previous studies of exercise in children have utilized the high density breath-by-breath measurement of gas exchange, which makes possible the measurement of aerobic function with the highest possible temporal resolution. To validate the use of our $\dot{V}O_{2\max}$ results as a true limit of the gas transport system, the subjects with true $\dot{V}O_{2\max}$ were compared with those who did not achieve plateaus. The subjects with true $\dot{V}O_{2\max}$ were indistinguishable from the others, suggesting that normal children, if sufficiently encouraged, usually approach true limits of $\dot{V}O_2$, even without reaching a plateau in $\dot{V}O_2$. These results were also similar to those of previous investigators using traditional methods of gas collection and exercise protocols (1, 6, 7). In addition, we reanalyzed the values of $\dot{V}O_{2\max}$ obtained by Åstrand et al. (1) in 63 boys and 63 girls (6–17 yr old) and found a scaling factor of 0.95 (95% confidence interval of 0.89–1.01), essentially the same as ours.

The relationship between AT and body weight (Fig. 2) implies that muscle mass is a major determinant of the anaerobic threshold during growth. Like the $\dot{V}O_{2\max}$, the AT indicates a physiological limit, the point at which O_2 transport alone is apparently insufficient to meet the energy requirements of muscular work. There is evidence that the determinants of the AT include such factors as levels of hemoglobin (34), cardiac function (29), the density of capillaries and mitochondria in muscle tissue, and levels of oxidative enzymes (4, 24).

The ratio of AT to the $\dot{V}O_{2\max}$ changed only slightly during growth (Fig. 4). The higher ratios found in the younger boys in particular may be related to such factors as the level of physical fitness, which is known in adults to increase the AT after periods of training (11). The mean ratio in adults tested in our laboratory was 56% (14), close to the mean of 60% that we found in children. It appears that regional O_2 transport becomes limited during exercise at a work rate that is demarcated by the onset of anaerobic metabolism and which defines a range of cellular energy production. Our data show that this range comprises a relatively constant proportion of the maximal $\dot{V}O_2$ response throughout the growth period.

The RT-$\dot{V}O_2$ was found to be highly variable, but the variability was the same in both large and small subjects. The RT-$\dot{V}O_2$ is likely to be determined by intracellular enzymatic constraints and also by factors such as muscular stores of "high-energy bond" phosphogens; intracellular stores of O_2 bound to myoglobin, stores of O_2 bound to hemoglobin, and anaerobic metabolism. Our finding that the RT-$\dot{V}O_2$ is independent of body size suggests that the growth of each of the components of the cardiorespiratory response to exercise (muscles, vessels, heart, and lungs) is integrated so that the temporal coupling among them is preserved at an optimized value despite the overall change in body size.

The virtual independence of work efficiency on body size implies that cellular mechanisms of energy utilization are mature early in childhood. In fact, even in preparations of fetal mitochondria, there is very little difference in pathways of oxidative phosphorylation compared with mature systems (13). Our mean value for the work efficiency (29%) was not different from values obtained in adults previously tested in this laboratory (33) but was higher than values in children and adults obtained in other laboratories (1, 26). Most likely, these previous investigators overestimated the $\dot{V}O_2$ for the work done. In their calculation of work efficiency, resting $\dot{V}O_2$ was subtracted from the $\dot{V}O_2$ at a particular work rate, and they neglected the $\dot{V}O_2$ cost of moving the legs of unloaded cycling. Thus the denominator of the equation was falsely high and the work efficiency artifactually low. This problem is avoided when measuring the difference in $\dot{V}O_2$ between two levels of work or when using the rate of change of $\dot{V}O_2$ and work rate, as is done in the ramp protocol (32) (Fig. 1).

It is unlikely that the small but statistically significant increases in work efficiency that we found in the older girls represent true differences in substrate and O_2 metabolism at the cellular level. Rather, these values may have been caused by the low AT observed in these subjects. As a result, the $\Delta\dot{V}O_2$ may not have represented all of the ATP produced for the Δ work rate (viz., some ATP came from anaerobic sources); the denominator would be falsely low, and the work efficiency would be artifactually high.

There were differences between boys and girls in the AT and the $\dot{V}O_{2\,max}$ (Figs. 2 and 3, Table 2). This resulted in large part from the low values in the older girls. Work from other laboratories has also shown that teenage girls have relatively lower $\dot{V}O_{2\,max}$ compared with boys (1, 10) and tend to have higher levels of blood lactate during exercise (18). There are several possible reasons for these observations. First, adolescent girls are prone to develop iron deficiency anemia (5), which could impede O_2 transport. Second, the increased percentage of body fat that occurs with adolescence in girls (19) may lead to lower values of $\dot{V}O_{2\,max}$ and AT relative to weight. In fact, several investigators have shown that when estimates of lean body mass are used as an index of body size rather than body weight, the differences in $\dot{V}O_{2\,max}$ between boys and girls is less marked (10). Additionally, social and cultural pressures may inhibit teenage girls' participation in vigorous activity and result in comparatively poorer fitness levels.

A. V. Hill (16) predicted that as animals increased in size, body height would scale to body mass to the one-third power and $\dot{V}O_{2\,max}$ would scale to body mass to the two-thirds power. Although the relationship between height and weight in the children was consistent with Hill's prediction, the scaling factor for $\dot{V}O_{2\,max}$ and the AT was significantly higher (Table 2). This discrepancy has been observed by others as well (2, 8, 9). To resolve this discrepancy, it has been proposed that the peak force generated per unit cross-sectional area of muscle (considered independent of body size by Hill) could increase with increasing body mass and result in a larger scaling factor for $\dot{V}O_{2\,max}$ than that predicted by Hill (20). This hypothesis is consistent with our findings.

Our results describe the relationship between growth and exercise as one in which certain aspects appear to be "optimized" relatively early in life. Both the work efficiency and the mean response time for $\dot{V}O_2$ are independent of age and size in our population despite their wide ranges. Both the AT and the $\dot{V}O_{2\,max}$ increased in a highly ordered manner with increasing size, and, as judged by the ratio of AT to $\dot{V}O_{2\,max}$ (Fig. 4), the onset of anaerobic metabolism during exercise occurred at a relatively constant proportion of the overall limit of the gas transport system.

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