

Maximal Oxygen Uptake Validation in Children With Expiratory Flow Limitation

Katherine E. Robben, David C. Poole, Craig A. Harms

Kansas State University

A two-test protocol (incremental/ramp (IWT) + supramaximal constant-load (CWR)) to affirm max and obviate reliance on secondary criteria has only been validated in highly fit children. In girls ($n = 15$) and boys ($n = 12$) with a wide range of VO_2max (17–47 ml/kg/min), we hypothesized that this procedure would evince a VO_2 -WR plateau and unambiguous VO_2max even in the presence of expiratory flow limitation (EFL). A plateau in the VO_2 -work rate relationship occurred in 75% of subjects irrespective of EFL. There was a range in RER at max exercise for girls (0.97–1.14; mean 1.06 ± 0.04) and boys (0.98–1.09; mean 1.03 ± 0.03) such that 3/15 girls and 2/12 boys did not achieve the criterion RER. Moreover, in girls with RER > 1.0 it would have been possible to achieve this criterion at 78% VO_2max . Boys achieved 92% VO_2max at RER = 1.0. This was true also for HRmax where 8/15 girls' and 6/12 boys' VO_2max would have been rejected based on HRmax being < 90% of age-predicted HRmax. In those who achieved the HRmax criterion, it represented a VO_2 of 86% (girls) and 87% (boys) VO_2max . We conclude that this two-test protocol confirms VO_2max in children across a threefold range of VO_2max irrespective of EFL and circumvents reliance on secondary criteria.

El protocolo que comprende dos test (incremental en rampa (TTI) + carga constante supramaximal) (CCS) aplicado para confirmar el consumo máximo de oxígeno y obviar la dependencia de los criterios secundarios ha sido solamente validado en niñas ($n=15$) y niños ($n=12$) bien entrenados, que poseían amplios rangos de VO_2max (17-47 ml/kg/min). Nosotros hipotizamos que este procedimiento podría evidenciar una meseta en la relación VO_2 -tasa de trabajo y por lo tanto indicar valores ambiguos de VO_2max incluso en niños que presentan limitaciones del flujo espiratorio (LFE). La meseta en la relación entre el VO_2 -tasa de trabajo ocurre en el 75% de los sujetos, independientemente de que presenten LFE. El rango de valores en la relación de intercambio respiratorio (RER) se extendió entre 0.97 a 1.14 en niñas ($M=1.06\pm 0.04$) y entre 0.98 a 1.09 en niños ($M=1.03\pm 0.03$). De esta forma, 3/15 niñas y 2/12 niños no alcanzaron el criterio de RER para estimar el VO_2max . Por otra parte, en las niñas que mostraron un RER>1.0 hubiera sido posible alcanzar este criterio con un valor del 78% VO_2max . Los niños alcanzaron el 92% del VO_2max con un RER=1.0. Esta respuesta, fue observada también

Robben, Poole, and Harms are with the Depts. of Kinesiology and Anatomy and Physiology, Kansas State University, Manhattan, KS.

para los valores de frecuencia cardiaca máxima (FCmax) en donde el VO₂ max de 8/15 niñas 6/12 niños podría haber sido rechazado basándose en el criterio de FCmax ya que <90% alcanzaron los valores de FCmax predichos a partir de la edad. De esta manera, el 86% de las niñas y el 87% de los niños alcanzaron el criterio de FCmax para estimar el VO₂max. Se concluye que el protocolo de dos test es útil para confirmar los valores de VO₂ max en niños a través de un triple rango de valores máximos independientemente de LFE y evita la dependencia de los criterios secundarios.

The most widely accepted criterion of fitness in humans and animals is the maximal capacity for oxygen uptake (VO₂max). Measured during 'whole body' or, at least, large muscle mass exercise, for example cycling or running, VO₂max represents the integrated capacity of the respiratory, cardiovascular and muscle systems to uptake, transport and use O₂ (e.g., ref 3, 45). Early in the 20th century Hill and Lupton (1923) demonstrated that there was a work rate (WR) or running speed above which VO₂ did not increase further (rev. ref 17). This observation defined the 'plateau concept' where the lack of increase of VO₂ as a function of WR or speed was deemed to provide unequivocal evidence of achievement of VO₂max (4).

Determination of VO₂max is one of the most common measurements made in clinical and experimental physiology and sports medicine. However, its quantification has become problematic, in part, because use of continuous (ramp or incremental (IWT)) testing protocols may preclude identification of a VO₂ plateau or leveling-off in a substantial proportion of individuals (32). Specifically, even when continued to unambiguous fatigue, in the majority of subjects (~two-thirds in children, refs. 6,36) the VO₂-WR relationship may be linear throughout the test or even curve upwards at high WR's without any tendency to plateau (14,17,32). Thus, although the continuous test is time-efficient and can resolve important parameters of aerobic function such as the gas exchange (and lactate) threshold as well as work efficiency (9,13,47), such that it is often *de rigueur* in exercise testing laboratories, it has not resolved ambiguity with respect to determination of VO₂max (14,25,32).

In the absence of a VO₂-WR plateau and in an attempt to validate that a true VO₂max has been achieved several 'secondary' criteria have been adopted. These criteria include reaching values for respiratory exchange ratio (RER ≥ 1.10 or 1.15 in adults, ref 32; ≥ 1.0 in children, ref 37), heart rate (HR ≤ 10 b/min of age-predicted maximum in adults, ref 32; ≥185 b/min or ≥90% of age-predicted maximum in children, ref 1,37) and/or blood lactate (8–10 mmol in adults, ref 32; ≥9 mmol in children, ref 7). However, because of the broad ranges of these variables at maximal exercise between, and sometimes even within, individuals including children (3,11,39,44,45) their scientific veracity for discriminating VO₂max in adults has been challenged (32) and there is emerging support for a two-test procedure that has the potential to yield a VO₂-WR plateau (or leveling off) in all subjects (6,14,26,32).

With respect to experimental and clinical exercise physiology, children present a particularly challenging population and yet determination of their VO₂max may yield crucial information regarding cardiopulmonary and muscular development and health (rev. 7,35,37). Unfortunately, the problem regarding use of secondary criteria such as RER and HR to validate VO₂max is especially acute in children and there is thus the pressing need to establish a uniform testing procedure or, at least, standard principles for identifying VO₂max rather than simply resorting to reporting the peak VO₂ in this population. To this end, Barker and colleagues (6) have demonstrated

recently that, in children of relatively high aerobic fitness (mean $\text{VO}_{2\text{max}}$ ~ 50 ml/kg/min), the two test (incremental/ramp + supramaximal constant-load (CWR)) can validate achievement of $\text{VO}_{2\text{max}}$ (see also refs. 2 and 34 for use of supramaximal tests to validate $\text{VO}_{2\text{max}}$). What has not been established in children is whether this procedure is effective across the spectrum of lower fitness levels as might be expected in a randomly recruited population, for example, in the United States. It is also pertinent that among this population of prepubescent children there may be a high prevalence of expiratory flow limitation (EFL, 28,29,40) and possibly exercise-induced arterial hypoxemia (EIAH, 27). Whether the two-test protocol can effectively determine $\text{VO}_{2\text{max}}$ across a broad spectrum of fitness levels and in the presence of EFL in children which, in and of itself may increase fatigability and modulate the respiratory response to exercise, has not been determined.

To address this issue in prepubertal girls and boys of widely disparate fitness levels we used a maximal incremental exercise protocol followed by a fatiguing CWR test at 105% of the highest WR achieved during the preceding incremental exercise. Whereas in adults all work rates in the severe exercise intensity domain may elicit $\text{VO}_{2\text{max}}$ when exercise is continued to fatigue (30–32), this may not be the case for children (5,6,48). However, we reasoned that this procedure would permit identification of $\text{VO}_{2\text{max}}$ thereby making the issue of secondary criteria redundant. The presence and severity of EFL was determined on the incremental test (40). The following hypotheses were tested: 1) Irrespective of the presence of EFL and absolute aerobic fitness, completion of the two-test protocol in children is feasible and evinces a VO_2 -WR plateau and unambiguous $\text{VO}_{2\text{max}}$ determination, and, 2) commonly accepted criteria adopted for $\text{VO}_{2\text{max}}$ validation in children (i.e., $\text{RER} \geq 1.0$, $\text{HR}_{\text{max}} \geq 90\%$ of age-predicted maximum) are erroneous and could feasibly result either in acceptance of invalid (i.e., submaximal) $\text{VO}_{2\text{S}}$ or, in some cases, mandate rejection of individuals who have actually achieved $\text{VO}_{2\text{max}}$.

Methods

Twenty seven healthy prepubescent children (15 girls, 12 boys) ages 7–11 years, of widely varying activity/sporting pursuits were recruited and volunteered as participants. All participants were free of asthma or airway disease determined by history and demonstrated by normal lung function measured with standard pulmonary function tests. Children were prepubescent and were in the first stage of maturation, as defined by Tanner stage 1 (41). Each child had a parent or guardian present to provide medical history information and informed consent. All research components were reviewed and approved by the Institutional Review Board of Human Subjects at Kansas State University, Manhattan, KS.

Experimental Design

A parent or guardian of the children was present during testing sessions. Height and weight were recorded using a calibrated eye-level physical scale with height rod (Detecto, Webb City, MO). Participants were then familiarized with the equipment and procedures. After several practice trials, standard pulmonary function measurements were performed using an automated pulmonary function testing system in accordance with recommended techniques. Participants then completed

a symptom-limited incremental cycle exercise test to determine maximal oxygen uptake (VO_2max). A second exercise test at constant work load (105% of that achieved at exhaustion in the incremental test) was performed following 15 min rest designed to verify VO_2max .

Pulmonary Function Tests

Total lung capacity (TLC) and maximal flow-volume loops (MFVL) were assessed before exercise testing (SensorMedics 229 Metabolic Cart, SensorMedics Corp, Yorba Linda, CA). TLC was determined using the nitrogen wash-out technique. All tests were performed in triplicate, with the average value used in analysis.

Maximal Oxygen Uptake (VO_2max)

An incremental exercise test to exhaustion was performed using a cycle ergometer (Ergometer 800S, Sensor Medics Corp., Yorba Linda, CA) to determine VO_2max . Subjects were given consistent and complete instructions explaining the protocol of the test to ensure maximal volitional effort. Before testing, a 3-L calibration syringe was used to calibrate the flow sensor. Known gas concentrations that spanned the range of expected measurements were used to calibrate gas analyzers. Resting metabolic measurements were taken for three minutes. Participants then began with a warm-up for approximately two minutes at a work rate of 20 W, pedaling between 50–60 rpm (rev/min). Children were instructed to maintain this pedaling speed while the work rate was increased by 10 W each minute. Participants remained seated throughout the test. Heart rate (HR) was monitored throughout the test via a four lead ECG interfaced to the metabolic software. The sensor from a pulse oximeter (Datex-Ohmeda, 3900P, Madison, WI) was secured to the left earlobe to estimate arterial oxygen saturation (SpO_2). The pulse oximeter was self calibrated before each test. The pulse oximeter supplied a visual pulse waveform to ensure adequate blood perfusion throughout the test. SpO_2 values were averaged over the last minute of each exercise stage. Participants continued to exercise until reaching volitional exhaustion. Verbal encouragement was provided throughout the test. The VO_2max test concluded when subjects could not maintain a pedal frequency of >50 rev/min for five consecutive revolutions despite firm but gentle encouragement. Metabolic and ventilatory data were assessed continuously through breath-by-breath analysis (SensorMedics 229 Metabolic Cart, SensorMedicsCorp., Yorba Linda, CA) and were averaged over the last 20 s for each minute of exercise.

Following the VO_2max test, participants rested for 15 min and then performed a constant load (105% VO_2max) exercise test until exhaustion to verify VO_2max (6,14,25,32). Verbal encouragement was provided throughout the test. Work rate for the test was determined from the final work rate (watts) during the incremental test. Participants were given a warm-up period of 90 s pedaling 50 rev/min at 20 W. Work rate was increased until reaching calculated work rate (~ 30 s) and subjects were instructed to maintain 50 rev/min until volitional fatigue. VO_2 was averaged over the final 20 s of this test after it was ensured that this period did not include breaths in which VO_2 was still increasing systematically.

VO_2max was identified as a reduced slope of the VO_2 –WR relationship as described in principal by Day et al. (14). Briefly, a linear regression was fit to the linear portion of the IWT-derived VO_2 –WR response (SigmaPlot, San Jose, CA) after

the first and last two minutes were excluded. Subsequently, the difference between the extrapolated linear fit and the measured response in the last 20 s before fatigue was calculated. $\dot{V}O_{2\max}$ was defined when $\dot{V}O_2$ increased $\leq 50\%$ that expected based on the $\dot{V}O_2$ -WR relationship for that subject. This procedure was also followed for the CWR test where the last 20 s $\dot{V}O_2$ was compared with that achieved on the IWT (see Figure 1). Where this procedure did not identify $\dot{V}O_{2\max}$ these data were not (and indeed could not) be used for the subsequent analyses of RER and HR relative to $\dot{V}O_{2\max}$.

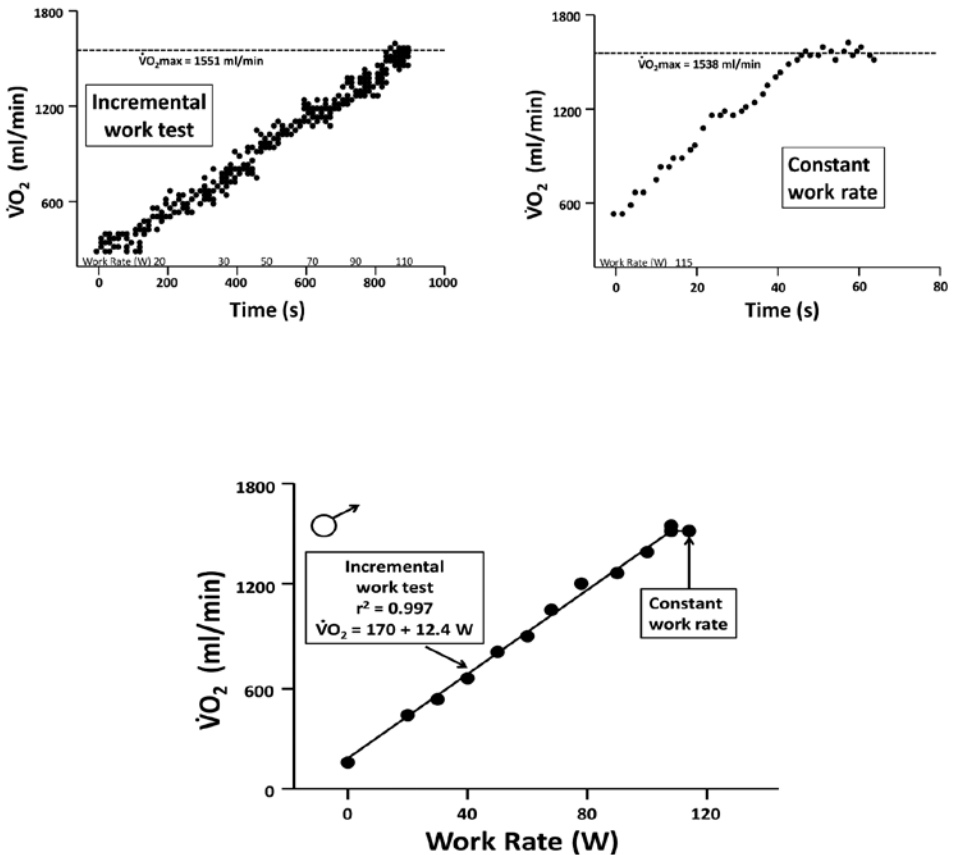


Figure 1 — Oxygen uptake ($\dot{V}O_2$) responses to exhausting incremental and constant-load exercise used to verify that $\dot{V}O_{2\max}$ has been achieved. Upper left panel presents breath-by-breath response to incremental exercise for 1 representative boy. Notice the absence of a plateau of $\dot{V}O_2$ against work load. Upper right panel shows the response to a work load above that achieved on the incremental test. Despite the higher work load $\dot{V}O_2$ achieves almost exactly the same value as the incremental test. Bottom panel conflates the two responses for $\dot{V}O_2$ (20 s averages) against work load and demonstrates a plateau for $\dot{V}O_2$ definitive for $\dot{V}O_{2\max}$.

Expiratory Flow Limitation. Tidal volume (V_T) loops were recorded during incremental exercise by means of a bidirectional flow sensor in line with the gas analysis system. Each subject received a detailed explanation and demonstration of the required technique and performed at least three maximal flow-volume loop maneuvers before and immediately following exercise. Quality control was ensured by the system software and the requirement for reproducibility within 5%. EFL was identified when the exercising VT loop intersected the maximal flow volume loop by $\geq 5\%$ (10,29,40).

Statistics

SigmaStat statistical software (Janel Scientific Software) was used for data analysis and Bland-Altman plots were used to determine the agreement between variables (mean bias, 95% confidence intervals) in subjects for whom VO_{2max} was validated. Data are expressed as mean \pm *SD*. Differences were determined using ANOVA. Significance was set at $p < .05$ for all analyses.

Results

The stated objective of achieving a broad range of VO_{2max} values (17–47 ml/kg/min) was achieved. Oxygen saturation (SpO_2) was maintained within 3% of resting values in all subjects throughout exercise and was not different ($p > .05$) between boys and girls. As shown in Table 1, despite no difference in age, weight or height between girls and boys, lung capacities (total lung capacity, TLC, forced vital capacity, FVC), volumes (residual volume, RV), and flows (peak expiratory flow, PEF, forced expiratory volume in 1 s, FEV_1 , forced expiratory flow at 50%

Table 1 Chronological, Physical and Pulmonary Function Characteristics of Subjects

	Boys (<i>n</i> = 12)	Girls (<i>n</i> = 15)
Age (yr)	9.6 \pm 0.8	9.7 \pm 0.9
Weight (kg)	33.9 \pm 8.1	33.0 \pm 9.4
Height (cm)	137.1 \pm 5.2	135.3 \pm 6.2
TLC (L)	2.7 \pm 0.5 *	2.1 \pm 0.5
FVC (L/sec)	2.3 \pm 0.3 *	1.9 \pm 0.4
RV (L)	0.4 \pm 0.3 *	0.2 \pm 0.1
PEF (L/sec)	3.6 \pm 0.6 *	3.0 \pm 0.5
FEV_1 (L/sec)	1.9 \pm 0.2 *	1.6 \pm 0.3
FEV_1/FVC (%)	85.2 \pm 6.2	83.4 \pm 5.9
$FEF_{50\%}$ (L/sec)	2.3 \pm 0.5 *	1.9 \pm 0.5

*Significantly higher in boys ($p < 0.05$).

FVC, forced vital capacity; PEF, peak expiratory flow; FEV_1 , forced expiratory volume in 1 sec; $FEF_{50\%}$, forced expiratory flow at 50%; TLC, total lung capacity; RV, residual volume.

total lung capacity, $FEF_{50\%}$) were all greater ($p < .05$) in boys than girls. However, the ratio FEV_1/FVC was not significantly different between sexes. EFL occurred in 14/15 girls and 11/12 boys and, where present, encompassed $47 \pm 6\%$ (range 15–80%) and $61 \pm 4\%$ (range 10–85%) of V_T for girls and boys, respectively. However, there was no evidence that EFL precluded the two-test procedure from validating that VO_{2max} had been achieved.

Girls

A decrease of the VO_2 -WR slope necessary to identify VO_{2max} from the IWT occurred in only 2/15 (14%) of instances. However, the group means ($n = 15$) for the IWT and CWR test VO_2 's were 1.03 ± 0.05 and 0.99 ± 0.05 l $O_2 \cdot min^{-1}$ ($p > .05$), respectively. These occurred at work rates of 84 ± 4 and 89 ± 4 W and thus broadly satisfied the VO_{2max} criterion that an increased work rate was accomplished with no further increase in VO_2 (see example for boys in Figure 1). It is pertinent that, within that data set, were two subjects for whom VO_2 either increased (1.29 – 1.38 l $O_2 \cdot min^{-1}$) or decreased (1.03 – 0.89 l $O_2 \cdot min^{-1}$) substantially from IWT to CWR thereby preventing the CWR test from verifying that VO_{2max} had been achieved. Without these subjects (i.e., $n = 13$) inspection of the mean (IWT 1.03 ± 0.05 , CWT 1.00 ± 0.06 l $O_2 \cdot min^{-1}$, $p > .05$) and individual (mean of individual deltas 0.05 ± 0.01 l $O_2 \cdot min^{-1}$) subject data revealed excellent correspondence between the IWT and CWR tests. The Bland-Altman plot in Figure 2 illustrates the individual correspondence between the highest VO_2 achieved on the IWT and CWR tests.

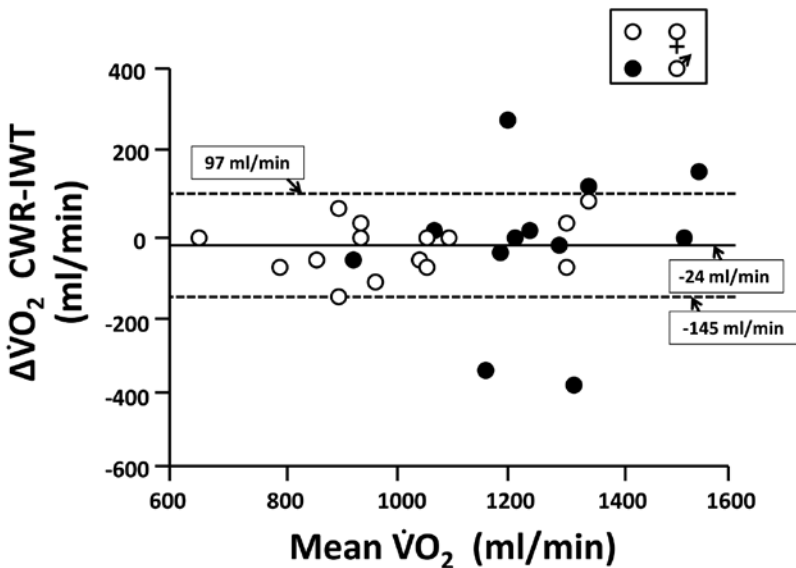


Figure 2 — Bland-Altman plot depicting oxygen uptake (VO_2) difference between the highest VO_2 achieved on the supramaximal constant work rate (CWR) and incremental work rate (IWR) tests for each subject. Mean bias is given by the solid line and 95% confidence intervals are dotted lines.

Use of 'Secondary' Criteria. RER. 3/15 subjects failed to achieve an $RER \geq 1.0$ and yet each of these demonstrated a plateau of the VO_2 -WR relationship. In addition, one subject whose VO_2 increased substantially (7%) from the IWT to the CWR elicited an RER of 1.14 on the IWT. For those subjects who achieved the criterion RER ($n = 12$) it was possible to do so at 78% VO_{2max} (Figure 3). The Bland-Altman plot (Figure 4) denotes the potential for underestimation of VO_{2max} possible using the $RER = 1.0$ criterion for all subjects in whom VO_{2max} was validated and RER reached 1.0 or higher. 2. HR. Eight subjects did not fulfill the HR criterion on the IWT and yet seven of these demonstrated a plateau of the VO_2 -WR relation. Moreover, the highest IWT HR recorded for any girl (205 b/min) was achieved on an IWT that did not evoke VO_{2max} (i.e., 1.29 (IWT) vs. 1.38 (CWR) l $O_2 \cdot min^{-1}$). In those seven subjects eliciting a VO_2 -WR plateau the criterion HR was attained at 86% VO_{2max} (Figure 5). The Bland-Altman plot (Figure 6) denotes the potential for underestimation of VO_{2max} possible using the $HR \geq 189$ b/min criterion for all subjects in whom VO_{2max} was validated and HR reached at least 189 b/min.

Boys

A decrease of the VO_2 -WR slope necessary to identify VO_{2max} from the IWT occurred in 3/12 (25%) of individuals. The group means ($n = 12$) for the IWT and CWR test VO_{2s} were 1.26 ± 0.19 and 1.21 ± 0.70 l $O_2 \cdot min^{-1}$ ($p > .05$), respectively, which occurred at work rates of 96 ± 4 and 101 ± 4 W. As for the girls, these satisfied the VO_{2max} criterion that an increased work rate was achieved without a matching VO_2 rise. Again, however, within this data set were multiple (i.e., 5) subjects for whom VO_2 either increased (up to 0.28 l $O_2 \cdot min^{-1}$) or decreased (up to 0.40 l $O_2 \cdot min^{-1}$) thereby disqualifying the CWR test from verifying that VO_{2max} was attained for these individuals. Without these subjects (i.e., $n = 7$) the remaining cohort elicited mean (IWT 1.25 ± 0.06 , CWT 1.23 ± 0.07 l $O_2 \cdot min^{-1}$, $p > .05$) and individual (mean of individual deltas 0.05 ± 0.01 l $O_2 \cdot min^{-1}$) subject data supporting achievement of VO_{2max} .

Use of "Secondary" Criteria. 1. RER. 2/12 subjects did not reach an $RER \geq 1.0$ although one of these elicited a VO_2 -WR plateau. Moreover, two subjects who did achieve an $RER > 1.0$ during the IWT did so at a clearly submaximal VO_2 as determined by comparison with the corresponding CWR VO_2 (i.e., 10–26% higher). For those 10 subjects who achieved their criterion RER it was possible to do so at 92% VO_{2max} (Figure 3). 2. HR. Six subjects did not reach their IWT HR criterion but, of these, four demonstrated a VO_2 -WR plateau when plotting both IWT and CWR results together (as exemplified in Figure 1). There was one individual who attained the HR (and RER) criterion on an IWT that clearly did not evoke VO_{2max} (i.e., 1.46 (IWT) vs. 1.61 (CWR) l $O_2 \cdot min^{-1}$). Those six subjects who reached their HR criterion did so at 87% VO_{2max} (Figure 5).

Discussion

There are many fascinating questions that remain unanswered regarding the physiology and pathophysiology of oxygen transport and utilization during growth and maturation. However, insofar as answering those questions is dependent upon

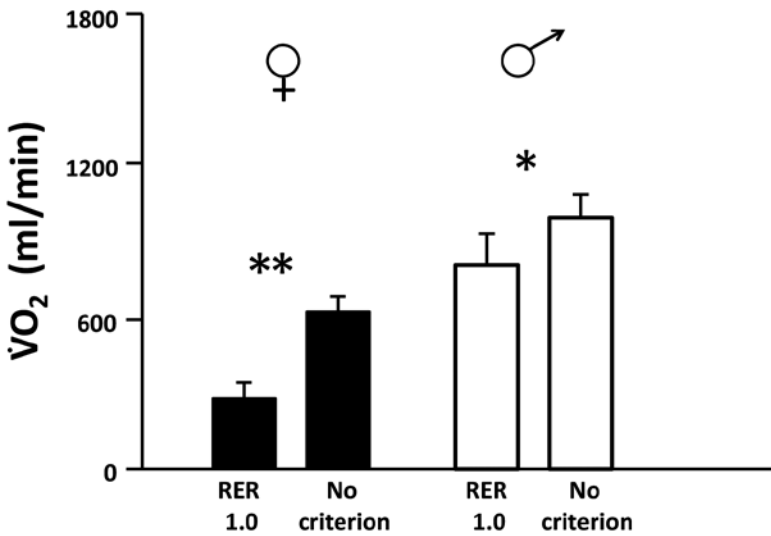
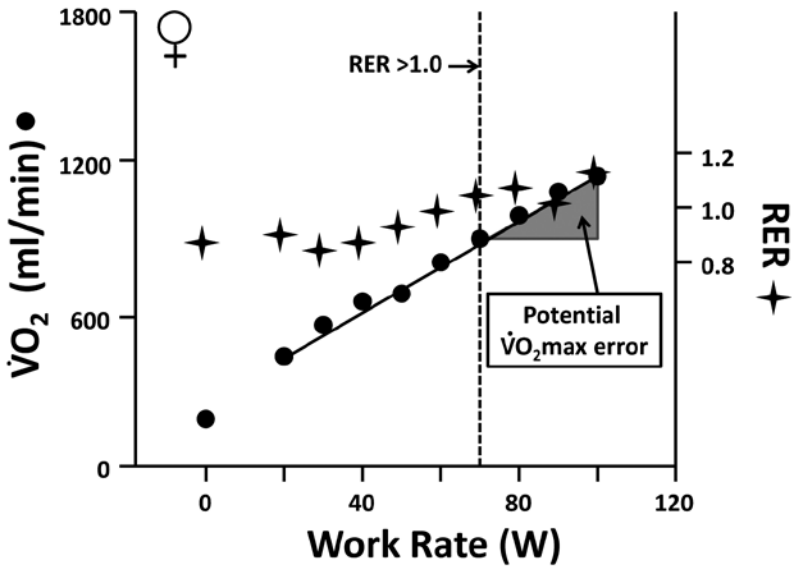


Figure 3 — Adoption of rigid respiratory exchange ratio criterion (RER = 1.0) can result in acceptance of submaximal $\dot{V}O_2$ and thus substantial errors in $\dot{V}O_2$ max measurement. Top panel demonstrates that RER can rise above 1.0 at ~70% $\dot{V}O_2$ max for this representative girl and the bottom panel gives the average maximum underestimation of $\dot{V}O_2$ max possible for girls (left, $n = 12$) and boys (right, $n = 10$) from utilizing this RER criterion. ** $p < .001$, * $p < .05$.

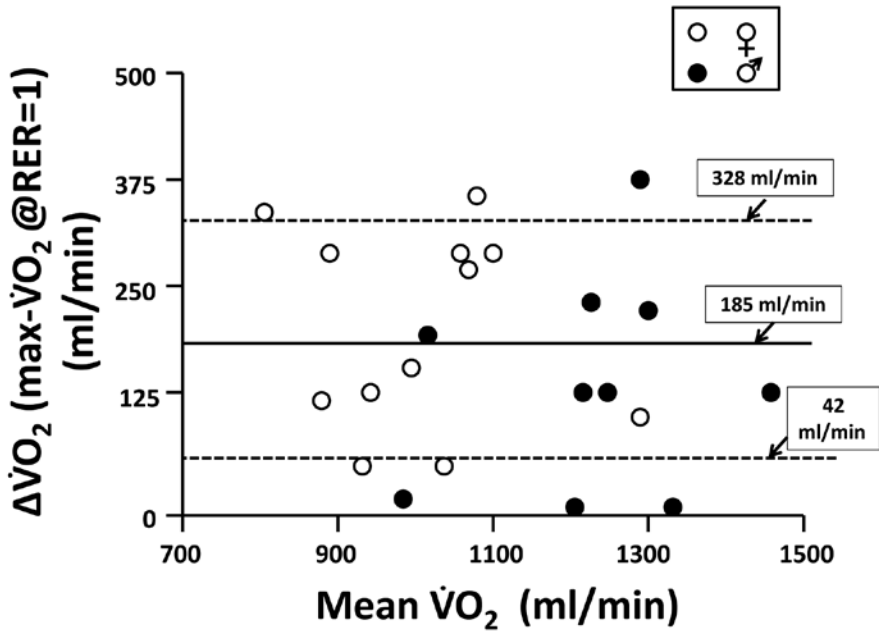


Figure 4 — Bland-Altman plot depicting oxygen uptake ($\dot{V}O_2$) difference between $\dot{V}O_{2max}$ (validated for these subjects using the two-test protocol) and $\dot{V}O_2$ at respiratory exchange ratio (RER) = 1.0. Mean bias is given by the solid line and 95% confidence intervals are dotted lines. Note subject numbers necessarily correspond to only those subjects in whom $\dot{V}O_{2max}$ was determined and RER reached at least 1.0.

accurate measurement of $\dot{V}O_{2max}$, children present a substantial challenge; not least of which is the high prevalence of EFL in this population (28,29,40). One approach has been to estimate $\dot{V}O_{2max}$ indirectly from submaximal tests whereas another has been to accept secondary criteria (e.g., HR, RER) to provide confidence that $\dot{V}O_{2max}$ has been achieved. Estimations are only as good as the assumptions made and the variability of HR_{max} in adults and children combined with the recent discrediting of secondary criteria for $\dot{V}O_{2max}$ validation in adults (25,32) and children (6) raises concerns over continuing to implement these practices. Pertinent to this issue, the principal original findings of the present investigation are that, across a broad range of aerobic fitness ($\dot{V}O_{2max}$, 17–47 ml/kg/min): 1. a two-test protocol (IWT and CWR) can yield a $\dot{V}O_2$ -WR plateau and thus unambiguous determination of $\dot{V}O_{2max}$ (achieved in 75% subjects herein) even concomitant with pronounced EFL. 2. RER and HR criterion cannot substantiate that $\dot{V}O_{2max}$ has been achieved. Rather, the high variability in peak or maximal values for RER and HR means that clearly submaximal $\dot{V}O_2$ values can be deemed acceptable for some individuals while mandating that data for others who may have reached $\dot{V}O_{2max}$ be discarded. Either eventuality is scientifically reprehensible, in part, because they erode objective discrimination and statistical power. What could not be addressed

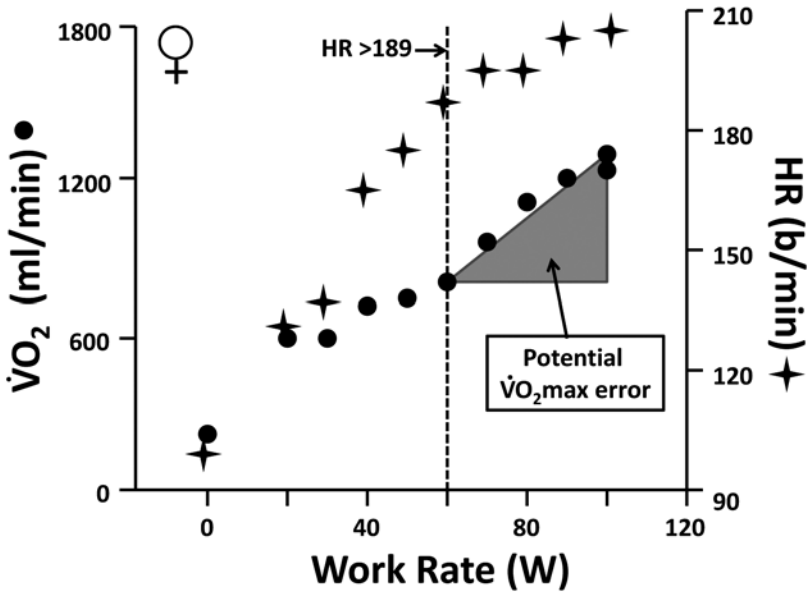


Figure 5 — Adoption of rigid heart rate criterion (90% of age-predicted maximum) can result in acceptance of submaximal $\dot{V}O_2$ and thus substantial errors in $\dot{V}O_2$ max measurement. Top panel demonstrates that HR can rise above 90% max at ~60% $\dot{V}O_2$ max for this representative girl and the bottom panel gives the average maximum underestimation of $\dot{V}O_2$ max possible for girls (left, $n = 7$) and boys (right, $n = 6$) from utilizing this HR criterion. ** $p < .01$, * $p < .05$.

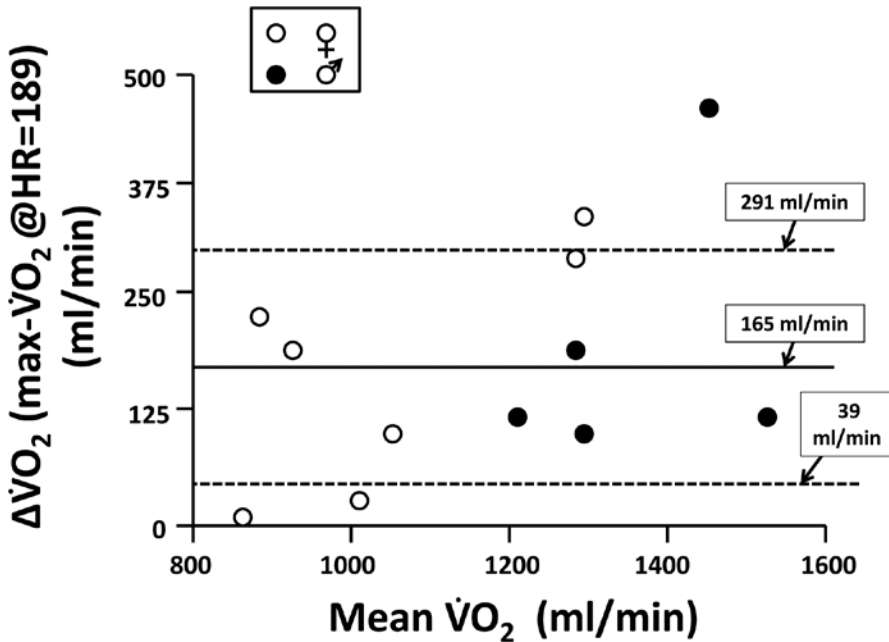


Figure 6 — Bland-Altman plot depicting oxygen uptake ($\dot{V}O_2$) difference between $\dot{V}O_{2\max}$ (validated for these subjects using the two-test protocol) and $\dot{V}O_2$ at heart rate (HR) = 189 b/min. Mean bias is given by the solid line and 95% confidence intervals are dotted lines. Note subject numbers necessarily correspond to only those subjects in whom $\dot{V}O_{2\max}$ was determined and HR reached at least 189 b/min.

herein is whether children who demonstrate EIAH (27) can perform the two-test protocol successfully. This was because all children maintained arterial oxygenation throughout the tests and thus, the possibility that EIAH might contribute to fatigue and preclude an individual from cycling for sufficient duration at 105% of the peak IWT power cannot be dismissed at this time.

Determinants of $\dot{V}O_{2\max}$

$\dot{V}O_{2\max}$ reflects the capacity of all (pulmonary, cardiovascular, muscle) systems in the O_2 transport pathway (8,33,38,42,43). Given the extraordinary growth and muscle metabolic changes that occur through puberty it may well be that the determinants of $\dot{V}O_{2\max}$ in prepubertal children differ from those in adults. However, until rigorous protocols are developed to determine $\dot{V}O_{2\max}$ unambiguously in prepubertal children this issue remains undetermined. This situation give rise to speculation, for example, that children are less able to demonstrate a $\dot{V}O_2$ plateau at $\dot{V}O_{2\max}$ because their inferior anaerobic capacity limits exercise tolerance (which is low compared with adults; 18) or that the $\dot{V}O_2$ plateau may not indicate “the limits of cardiovascular function” in this population (36). In contrast, the present

investigation demonstrates that, using a simple two-test protocol, a plateau of VO_2 against work rate can be achieved in 75% of instances across a broad range of aerobic capacities. Additional tests may improve this success rate and help resolve whether fatigue or lack of motivation prevented defining VO_2max in the remaining 25% of children herein. What is evident from the literature is that supra-critical power exercise (but below peak power achieved on the IWT) in children may not always achieve VO_2max (5,6,48) as it almost invariably does in adults (19,21,30–32). This being the case, and, consistent with the ‘gold standard’ definition of VO_2max , to validate VO_2max , investigators may be forced to resort to supra-IWT peak work rates which are sustainable for only a short period of time (66 ± 18 s herein). Fortunately, children evince fast kinetics that drive VO_2 rapidly to its maximum (within 50 s for the subject in Figure 1 (upper right panel)). It is not surprising therefore that the 90 s mean duration of the supramaximal CWR test employed by Barker et al. (6) was effective in substantiating attainment of VO_2max . In contrast, adult populations, particularly the aged and less aerobically fit, may require approximately twice the exercise duration necessary in children (i.e., at least 120 s or longer) to achieve VO_2max at supramaximal work rates (16).

Resolution of an unambiguous VO_2max in this prepubertal population is important in-and-of itself given the long-term cardiovascular health benefits conferred by, or associated with, exercise capacity and a high VO_2max (15,22). Moreover it offers the opportunity to address questions of significant physiological and pathophysiological interest regarding VO_2max determinants in these populations.

EFL in Children

Anatomically children have smaller airways in comparison with lung size than adults (24) which, combined with greater ventilations at any given metabolic rate, leads to a high prevalence of EFL irrespective of VO_2max per se (28,29,40). EFL leads to dynamic hyperinflation (40) thereby mechanically disadvantaging the inspiratory muscles and increasing the likelihood of respiratory muscle fatigue which has been documented in adults during high intensity exercise (20). However, as demonstrated in a more highly fit population of children (6) and across a broad range of lower metabolic capacities herein, any such effect did not preclude either girls or boys from validating VO_2max using the two-test protocol. This issue was of particular concern in girls who, even at low fitness levels, may exhibit increased susceptibility to the mechanical constraints of ventilation (40).

Indirect Criteria for Validating VO_2max

1. RER. In the healthy adult population RER during maximal exercise may range from 1.0 to 1.44 being higher in the more rapidly incremented testing protocols (9,32,39,45,46). Cut-offs of 1.0, 1.1 and 1.15 have been selected to demarcate subjects who have achieved a valid VO_2max from those who have not (rev. 32). The maximal RER for a given individual is a complex entity that will depend: A. On total CO_2 evolution (i.e., VCO_2 , numerator) which in itself is dependent upon pulmonary function (as it determines the maximal voluntary ventilation, MVV), the peripheral and (to a lesser degree) the net central chemoreceptor drive to breathe, the breathing pattern (as it determines dead space ventilation), multiple sources of CO_2

(i.e., metabolic, H^+ buffering (amount and rate which itself is dependent upon rate of work rate progression, 46), unloading of CO_2 stores). B. On the denominator VO_2 .

As prepubertal children have a lower capacity to generate lactic acid (e.g., 18), the rate of H^+ appearance in the blood and consequent buffering by HCO_3^- will be lower than in adults. This consideration provides a mechanistic basis for the lower RERs typically observed during maximal exercise in children and therefore the RER criterion of 1.0 (37) versus the more common 1.1 or 1.15 in adults (32). However, the data presented herein extend those of Barker et al. (6) providing the first objective demonstration, over a broad range of aerobic fitness and in the presence of documented EFL, that a plateau of VO_2 versus work rate can be achieved over a range of RERs from 0.97 to 1.10 for girls (though one subject at RER = 1.14 was clearly at a submaximal VO_2) and 0.99–1.07 for boys (and, again, there was one subject at a higher RER of 1.09 at a submaximal VO_2). Hence most of the children in the present investigation would either have been rejected for RER < 1.0 (3 girls, 3 boys) or, because their RER rose above 1.0, could have stopped exercising at a submaximal VO_2 which could not have been discriminated (and thus rejected) based upon the presumption that RER = 1.0 denotes VO_{2max} in children. The data presented herein thus present irrefutable evidence that the RER criterion of 1.0 (or, indeed, any unitary value for such) is erroneous as a criterion measurement for VO_{2max} (see also ref. 6).

2. HR. The problems with presuming a one-size-fits all (i.e., $\geq 90\%$ age predicted HRmax) are at least as great as those for RER when considering either adults or especially children. The standard deviation for the estimate of maximal HR (HRmax) in adults is ± 11 b/min (23) and this may explain, in part, why eight girls and seven boys did not satisfy the criterion HR for VO_{2max} herein: this despite the fact that seven of these girls and two of these boys demonstrated an unambiguous VO_2 plateau using the two-test procedure. As with RER, there was a substantial range of HRs at VO_{2max} for girls (i.e., 177–203 b/min) and one girl reached a HR of 205 b/min at a submaximal VO_2 . For boys the HR range at VO_{2max} was 176–204 b/min with two boys at 204 and 206 b/min at submaximal VO_2 s. Figures 5 and 6 demonstrate the inability of the prescribed HR criterion to validate achievement of VO_{2max} and the potential for error this procedure allows.

For children this problem is emphasized by contrasting the HRmax data for two geographically distinct populations of children. Specifically, Cooper et al. (12) reported that, in N. American children aged 8–18 years, HRmax averaged 187 b/min with a lower 95% confidence interval of 160 b/min. This data were markedly different from the 205 b/min HRmax reported for Scandinavian children by Astrand and Rodahl (3). These and other considerations in combination with the data of Barker et al. (6) underline the American College of Sports Medicine (1991) mandate that specific HRs not be employed as definitive end-point criteria for exercise test termination.

Experimental Considerations

The two test protocol used herein validated VO_{2max} in 75% of this female and male cohort of children of which less than 1/3 of these demonstrated an unambiguous leveling off of the VO_2 -WR relationship during the IWT. However, what remains a concern is the 25% in which VO_{2max} could not be validated among whom several

demonstrated a considerable (280 to ~400 ml/min) VO_2 difference between peak values achieved on the IWT versus the CWR test. An a priori approach in future investigations would incorporate specific focus on the testing paradigm that yielded the lower VO_2 value (i.e., IWT, CWR) and assess the reproducibility of the value obtained. Possibly IWTs with different rates of WR increase or CWR tests at a range of supramaximal work rates (e.g., 105, 110, 115%) could be performed to increase the opportunity to achieve a VO_2 -WR leveling off. What remains especially challenging in some subjects in this population is motivation combined potentially with a lower capacity to generate energy from nonoxidative sources (18). This situation may create a very small window of opportunity to achieve $\text{VO}_{2\text{max}}$ before fatigue particularly in those subjects with slower VO_2 kinetics.

Conclusions

The straightforward two-test protocol described herein is feasible for prepubertal children across a broad range of aerobic capacity ($\text{VO}_{2\text{max}}$) and irrespective of the presence of EFL and produces a discernible VO_2 -WR plateau or leveling-off thereby discriminating achievement of $\text{VO}_{2\text{max}}$ in 75% of the 27 children tested. This success rate is over twice that reported commonly in the pediatric literature (36) and likely results, in part, from the very rapid VO_2 kinetics in this population that enables $\text{VO}_{2\text{max}}$ to be achieved within one min during “supramaximal” exercise (Figure 1, upper right panel). With sufficiently motivated children, a second square-wave test performed in the residual 25% may increase this success rate further. As with adults and demonstrated recently for children (6), use of secondary criteria based upon RER or HR is problematic and lacks any ability to discriminate submaximal from maximal $\text{VO}_{2\text{s}}$. In addition, such arbitrary cut-offs may justify accepting invalid (i.e., submaximal) $\text{VO}_{2\text{s}}$ or, alternatively, force rejection of children who elicited $\text{VO}_{2\text{max}}$.

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