Critical Velocity and Anaerobic Distance Capacity in Prepubertal Children

Serge Berthoin¹, Georges Baquet¹, Gregory Dupont¹, Nicolas Blondel¹,², and Patrick Mucci²

Catalogue Data

Key words: aerobic power, anaerobic capacity, comparison, model, performance
Mots-clés: puissance aérobie, capacité anaérobie, comparaison, modélisation, performance

Abstract/Résumé
This study was designed to calculate the critical velocity (v_{crit}) and anaerobic distance capacity (ADC) of prepubescent children for running events. Thirty-four prepubertal children underwent a graded field test to exhaustion in order to determine peak oxygen uptake (peak VO₂) and maximal aerobic velocity (MAV). Then, in random order, they performed five runs to exhaustion (t_{lim}) at relative velocities corresponding to 90, 95, 100, 105, and 110% of MAV. The linear relationships between distance limit (d_{lim}) and t_{lim} were calculated in order to determine v_{crit} (slope of the relationship) and ADC (intercept). Very high individual coefficients of determination were found between d_{lim} and t_{lim} (0.98 < r^2 < 0.99; p < 0.001). The v_{crit} was significantly correlated with peak VO₂ (r = 0.73; p < 0.001). However, no relationship was found between ADC and the maximal accumulated oxygen deficit. In conclusion, our results indicated that, for children, the relationship between d_{lim} and t_{lim} could be calculated with t_{lim} ranging from 2 to 10 min, and that v_{crit} is a good indicator of the aerobic fitness of children. Nevertheless, further studies will have to be conducted to validate the use of ADC as an indicator of children’s anaerobic capacity.

Le but de cette étude était de calculer la vitesse (v_{crit}) et la capacité de distance anaérobie (CDA) d’enfants prépubères pour des exercices de course. Trente-quatre enfants on effectué

¹Laboratoire d’Études de la Motricité Humaine, Faculté des Sciences du Sport et de l’Éducation Physique, Université de Lille 2, 9 rue de l’Université, F-59790 Ronchin, France;
²Laboratoire d’Analyse Multidisciplinaire des Pratiques Sportives, UFR STAPS de Liévin, Université de d’Artois, Chemin des Marquages, F-62800 Liévin, France.
un test de terrain progressif et maximal afin de mesurer leur pic de consommation d’oxygène (pic VO₂) et de déterminer leur vitesse maximale aérobie (VMA). Ils ont ensuite effectué, dans un ordre aléatoire, cinq courses continues jusqu’à épuisement (tlim) à des allures relatives représentantes 90, 95, 100, 105, et 110% de VMA. Les relations linéaires entre les distances limites (dlim) et les tlim ont alors été calculées pour déterminer v₉₅ (pente de la relation) et CDA (ordonnée à l’origine). De très forts coefficients de détermination ont été calculés entre dlim et tlim (0.98 < r² < 0.99; p < 0.001). La v₉₅ était significativement corrélée au pic VO₂ (r = 0.73; p < 0.001). Cependant, aucune relation n’a été trouvée entre la CDA et le déficit maximal accumulé en oxygène. En conclusion, nos résultats indiquent que la relation entre dlim et tlim peut être calculée à partir de tlim dont les durées sont comprises entre 2 et 10 min, et que la v₉₅ est un bon indicateur de l’aptitude aérobie de enfants. Cependant, d’autres études sont nécessaires pour valider l’utilisation de la CDA comme indicateur de la capacité anaérobie des enfants.

**Introduction**

Since the initial paper by Scherrer et al. (1954), much has been published concerning the application of the critical power concept to general exercises (see Hill, 1993; Vandewalle et al., 1997, for review). Ettema (1966) was the first author to have applied this concept to running events. He proposed calculating the relationship between the distance limit (dlim) and time to exhaustion (tlim) as: dlim = (v₉₅ tlim) + ADC, where v₉₅ (critical velocity) and ADC (anaerobic distance capacity) were, respectively, the slope and intercept of this relationship (Figure 1: dlim = f(tlim)). In adults, research has demonstrated that the v₉₅ did not differ significantly from the velocity corresponding to a 4 mmol·L⁻¹ blood lactate concentration (Lechevalier et al., 1989) or the velocity at a maximal lactate steady

![Figure 1](image_url). An example of the dlim vs. tlim relationship.
Anaerobic Capacity in Prepubertal Children • 563

state (Sid-Ali et al., 1991). The ADC parameter was assumed to represent the distance that could be covered with the energy equivalent of maximal oxygen deficit. It was found to be correlated with maximal lactate concentration after exercise ([La]max) and maximal accumulated oxygen deficit (Hill et al., 1998).

Thus the \( d_{\text{lim}} = f(t_{\text{lim}}) \) relationship, and its parameters, are assumed to provide an indication of performance over a wide range of times (or distances), and to provide an indication of both aerobic power (i.e., \( v_{\text{crit}} \)) and anaerobic capacity (i.e., ADC). In addition, \( v_{\text{crit}} \) could be considered as a velocity criterion to determine a running pace for training, as are other physiological thresholds. This is of practical interest to coaches and physical educators, who cannot perform invasive measurements but yet need accessible methods to evaluate the metabolic characteristics of their athletes. For adults, many studies on the \( d_{\text{lim}} = f(t_{\text{lim}}) \) relationship have been conducted, as reviewed by Hill (1993) and Vandewalle et al. (1997). In children who have specific cardiorespiratory and metabolic exercise responses, only three studies have been conducted on the \( d_{\text{lim}} = f(t_{\text{lim}}) \) relationship, but these were based on swimming exercise (Denadai et al., 2000; Hill et al., 1995) or on cycling exercise (Fawkner and Armstrong, 2002). The results of these studies demonstrated that: critical swimming velocity increased with age (Hill et al., 1995) and was significantly correlated with either swimming performance (Denadai et al., 2000; Hill et al., 1995) or to a swimming velocity corresponding to a 4 mmol·L\(^{-1}\) blood lactate concentration (Hill et al., 1995). For cycling exercise, significant correlations were found between critical power and peak oxygen uptake (peak VO\(_2\)) and ventilatory threshold (Fawkner and Armstrong, 2002). These findings are of particular interest as they support the use of the \( d_{\text{lim}} = f(t_{\text{lim}}) \) parameters for assessing aerobic power in children. However, except for the study by Fawkner and Armstrong (2002), the assessment of \( v_{\text{crit}} \) and ADC were not validated with comparison to physiologically determined parameters, nor for running.

The aims of this study were to calculate the \( d_{\text{lim}} = f(t_{\text{lim}}) \) relationship in prepubertal children for running events and to assess the validity of the calculated parameters (\( v_{\text{crit}} \) and ADC) in comparison with the physiologically determined parameters of peak VO\(_2\) and maximal accumulated oxygen deficit.

Materials and Methods

SUBJECTS

Twenty-two girls 9.5 ± 0.7 years of age (range = 8–10) and 12 boys 9.5 ± 0.8 years of age (range = 9–11), attending a rural school, volunteered to enter the study. The children were not involved in any systematic training. They were fully informed of the goals and protocol of the study beforehand. Each child and his/her parents signed a consent form. This study received approval from the Comité Consultatif de Protection des Personnes dans la Recherche Biomédicale de Lille.

Height and body mass were measured with a wall stadiometer (Vivioz medical) and a calibrated scale (Tanita TBF 543). Sexual maturity was evaluated from pubertal stages (Tanner, 1962): breast and pubic hair stages were assessed for girls and pubic hair and genital development stages were assessed for boys. Subjects were classified as prepubertal when the combined stage assessment was \( \leq 3 \). The same physician made all the observations visually.
PROTOCOL

Before entering the study, the children were familiarized with the testing modalities and the gas analyzer. They then underwent six maximal field tests over a 3-week period: one graded test and five continuous tests. The first test measured maximal aerobic velocity (MAV) and peak oxygen consumption (peak VO₂). Then the children performed five exercises until exhaustion, or time limit (tlim), in a random order, at velocities equal to 90%, 95%, 100%, 105%, and 110% of MAV (tlim90 to tlim110). During the exercises the velocities were monitored via a pre-recorded soundtrack (graded test) or with a computer (continuous tests). All tests were performed in a covered area on a 150-m track marked with cones every 25 m. The soundtrack (or computer) emitted a brief sound to let the children know precisely when they had to pass near a cone to maintain a constant speed. During all tests the children were verbally encouraged to run until exhausted. To avoid any problem linked to a child’s inability to maintain a constant speed, an adult ran with the children. In all cases the tests ended when the children were exhausted or could no longer maintain the required running velocity.

Cardiorespiratory Parameters. During the graded and continuous tests, heart rate (HR) was continuously monitored with a heart rate monitor (Accurex+, Polar Electro, Kempele, Finland). In both the graded test and the tlim110 test, respiratory parameters were measured breath by breath with a portable analyzer (Cosmed K4b², Rome) in order to determine the values for oxygen consumption (VO₂), carbon dioxide production (VCO₂), respiratory exchange ratio (RER), and ventilation (VE). The measured values were averaged over 15-s periods. Before each test, the gas analyzers for O₂ and CO₂ were calibrated with a gas of known concentrations. The turbinflow meter was calibrated with a 3-l syringe (Quinton Instruments, Seattle).

Graded Test. The Université de Montréal Track Test (Léger and Boucher, 1980) was used to determine peak VO₂ and MAV. Immediately after a 4-min warm-up at 7 km·h⁻¹, the test began at 8 km·h⁻¹. The velocity was then increased by 1 km·h⁻¹ every 2 minutes. The velocity at the last completed stage, increased by 0.5 km·h⁻¹ if the child was able to run a half stage, was assumed to represent MAV. Peak VO₂ was accepted as a maximal index when, in addition to subjective indication of maximal effort, HR reached a value above 195 bpm or RER was >1 (Tolfrey et al., 1998). All subjects satisfied these criteria. The highest level of VO₂ measured (15 s) during the test was assumed to represent peak VO₂.

Continuous Test. In random order, five tlim were performed until exhaustion at velocities of 90%, 95%, 100%, 105%, and 110% of MAV. There was at least 24 hrs of recovery between two consecutive tests. The tlim were preceded by a standardized warm-up consisting of a 4-min run at 7 km·h⁻¹ followed by a 2-min rest period. For each test, running time was measured to the nearest second. The maximal value for HR reached at each tlim was retained as peak heart rate (peak HR).

In the tlim110 trial, the ventilatory parameters were measured with the portable analyzer as described previously. Prior to the warm-up, subjects had to remain seated for 30 min. During the last 10 min of the rest period, ventilatory parameters were measured in order to determine resting VO₂ (VO₂r: i.e., the lowest value for VO₂ averaged over four consecutive 15-s periods).
Calculation of Maximal Accumulated Oxygen Deficit. Maximal accumulated oxygen deficit (MAOD) was calculated from $\dot{V}O_2$ values collected during the tlim110. It was assumed this relative exercise velocity would allow children to reach exhaustion over a sufficient duration for MAOD to be calculated (Carlson and Naughton, 1998). The MAOD was calculated as the $O_2$ theoretically consumed to run at 110% of MAV minus the $O_2$ effectively consumed. The $\dot{V}O_2$ theoretically needed to run at 110% of MAV was calculated from $\dot{V}O_2r$ and energy cost of running (Cr). The Cr was calculated from $\dot{V}O_2$ values measured at 7 km·h$^{-1}$ or 116.6 m·min$^{-1}$ ($\dot{V}O_2 -7$) as: \[ Cr = (\dot{V}O_2 7 - \dot{V}O_2r) / 116.6. \] As the relationship between $\dot{V}O_2$ and velocity is: \[ \dot{V}O_2 = Cr \times velocity + \dot{V}O_2r, \] it is possible to estimate the $\dot{V}O_2$ required to run at 110% of MAV by replacing the known velocity (MAV*1.1) in the equation. The $O_2$ required to run the tlim110 was calculated as the product of the theoretical $\dot{V}O_2$ at 110% of MAV with time to exhaustion for the tlim110. The $O_2$ effectively consumed during this run was subtracted from this value to calculate MAOD. In addition to MAOD, the distance that can be covered with this $O_2$ anaerobic equivalent was calculated as the quotient of MAOD and Cr.

Calculation of the $dlim = f(tlim)$ Relationship. The $dlim = f(tlim)$ relationship was calculated from five tlims. If one measurement was not consistent with the others (i.e., tlim90 < tlim95 < tlim100 < tlim105 < tlim110), the children had to undergo an additional test. For example, if a tlim105 was shorter than a tlim110, the children had to perform an additional tlim105. If the tlim105 remained lower than the tlim110, the relationship was calculated with four experimental values (tlim105 was removed). To provide a more accessible estimation of this relationship, we also used all the combinations of two points to calculate the $dlim = f(tlim)$ relationship.

Statistics

Data were analyzed with StatView software (StatView + Graphic, Abacus Concepts). The experimental values were presented as mean ± SD. Mean cardiorespiratory values have been compared with a Student $t$-test for paired (graded test vs. tlim100) or unpaired series (boys vs. girls). The times and HR values measured during the five continuous tlim tests have been compared with a two-way ANOVA (repeated measures by gender). For both variables there was no effect that could be attributed to a gender-by-time interaction, nor to a gender difference. Therefore, data for boys and girls were pooled and analyzed through a one-way ANOVA with repeated measures. Where necessary, a post-hoc Scheffé test was used to compare experimental means. Linear regressions were calculated between the different parameters and for determination of the $dlim = f(tlim)$ relationships.

To analyze the validity of the simplified methods for the $dlim = f(tlim)$ determination, with only two tlim, the technique suggested by Bland and Altman (1986) was applied. The difference in estimated parameters ($v_{crit}$ or ADC) was plotted against means for $v_{crit}$ or ADC. The mean difference (Bias) and the limits of agreement (Bias + and − 2 SD) were graphically indicated. Bland and Altman suggested that if the values are within the average difference ± 2 standard variations, and there is no correlation between the differences vs. the averaged values, then the methods are equivalent. In all cases the threshold for significance was set at $p < 0.05$. 

Results

Means values for mass and height are listed in Table 1 for both girls and boys. All boys were at Stage 1 for genital development and pubic hair. Nineteen girls were at Stage 1 for breast and pubic hair, while for the remaining girls the combined stage assessment was ≤ 3. The children’s mean MAV was 10.4 ± 1.1 km·h⁻¹, with significantly higher values, \( p < 0.001 \), in boys (11.2 ± 1.1 km·h⁻¹) than in girls (9.9 ± 0.8 km·h⁻¹). The cardiorespiratory values for the graded test and tlim110 are listed in Table 2. For the entire population, peak \( \dot{V}O_2 \), \( p < 0.05 \), and peak HR, \( p < 0.001 \), were significantly higher for the graded test, while the RER and \( V_E \) were significantly higher, \( p < 0.001 \), for the tlim110. There was no significant difference between the maximal values for HR. Only for peak \( \dot{V}O_2 \) (graded test and tlim 100) and RER (tlim 100) did boys demonstrate significantly higher values than girls, \( p < 0.05 \). The results of tlim are listed in Table 3. Running time to exhaustion diminished significantly as the percentage of MAV increased, \( p < 0.001 \), until the tlim110. However, the difference between tlim105 and tlim 110 was not significant. The ANOVA for repeated measures indicated no significant difference between peak HR values measured during each tlim.

Table 1  Age and Anthropometric Characteristics of Children

<table>
<thead>
<tr>
<th></th>
<th>Girls (n = 22)</th>
<th>Boys (n = 12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>9.5 ± 0.7</td>
<td>9.5 ± 0.8</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>36.3 ± 8.4</td>
<td>34.4 ± 7.2</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.39 ± 0.08</td>
<td>1.39 ± 0.05</td>
</tr>
</tbody>
</table>

For 20 children the dlim = f(tlim) relationship was calculated from five tlims, for 12 children it was calculated from four tlims, and for the remaining 2 children it was calculated from three tlims. For the whole group of subjects, linear adjustments were obtained (0.98 < \( r^2 < 0.99 \), \( p < 0.001 \)). The average \( \dot{V}O_2r \) was 6.4 ± 1.0 ml·kg⁻¹·min⁻¹ (range: 4.5–8.2 ml·kg⁻¹·min⁻¹), with no significant difference between boys and girls. The mean values for Cr, MAOD \( v_{\text{crit}} \) (km·h⁻¹ and %MAV), and ADC are listed in Table 4. Except for \( v_{\text{crit}} \) when expressed in km·h⁻¹, \( p < 0.001 \), no significant difference was observed between boys and girls for Cr, MAOD \( v_{\text{crit}} \) (%MAV), or ADC.

The correlations between the values of MAOD and peak \( \dot{V}O_2 \) (graded test) on the one hand, and the measured and calculated parameters from field tests on the other hand, are shown in Table 5. The \( v_{\text{crit}} \) was correlated with peak \( \dot{V}O_2 \) (\( r = 0.73 \), \( p < 0.001 \)) and with MAV (\( r = 0.91 \), \( p < 0.001 \)). The MAOD was moderately correlated with \( v_{\text{crit}} \) (\( r = 0.41 \), \( p < 0.05 \)). No significant correlation was found between MAOD and ADC, \( p = 0.08 \). When the product of MAOD and Cr was calculated, the resulting distance that could theoretically be covered (141.1 ± 40.0 m) was significantly correlated with ADC (\( r = 0.43 \), \( p < 0.05 \)). However, these calculated distances significantly overestimated the ADC, \( p < 0.05 \).
### Table 2  Cardiorespiratory Parameters Measured During Graded and Tlim110 Tests

<table>
<thead>
<tr>
<th></th>
<th>Graded test</th>
<th>Tlim110</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Boys and Girls</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak $\dot{V}O_2$ (ml·kg$^{-1}$·min$^{-1}$)</td>
<td>45.2 ± 6.7</td>
<td>43.3 ± 5.3**</td>
</tr>
<tr>
<td>$\dot{V}E_{max}$ (L·min$^{-1}$)</td>
<td>59.5 ± 10.6</td>
<td>63.4 ± 10.2**</td>
</tr>
<tr>
<td>Resp. exchange ratio</td>
<td>1.04 ± 0.06</td>
<td>1.21 ± 0.09**</td>
</tr>
<tr>
<td>HR max (bpm)</td>
<td>203 ± 9</td>
<td>200 ± 10</td>
</tr>
<tr>
<td><strong>Girls</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak $\dot{V}O_2$ (ml·kg$^{-1}$·min$^{-1}$)</td>
<td>43.3 ± 5.3</td>
<td>42.1 ± 5.3*</td>
</tr>
<tr>
<td>$\dot{V}E_{max}$ (L·min$^{-1}$)</td>
<td>58.2 ± 11.9</td>
<td>63.0 ± 10.6**</td>
</tr>
<tr>
<td>Resp. exchange ratio</td>
<td>1.04 ± 0.07</td>
<td>1.18 ± 0.08**</td>
</tr>
<tr>
<td>HR max (bpm)</td>
<td>204 ± 9</td>
<td>202 ± 11</td>
</tr>
<tr>
<td><strong>Boys</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak $\dot{V}O_2$ (ml·kg$^{-1}$·min$^{-1}$)</td>
<td>48.7 ± 8.1</td>
<td>45.9 ± 4.7**</td>
</tr>
<tr>
<td>$\dot{V}E_{max}$ (L·min$^{-1}$)</td>
<td>61.9 ± 8.1</td>
<td>65.2 ± 9.8</td>
</tr>
<tr>
<td>Resp. exchange ratio</td>
<td>1.04 ± 0.05</td>
<td>1.26 ± 0.11**</td>
</tr>
<tr>
<td>HR max (bpm)</td>
<td>201 ± 7</td>
<td>198 ± 7</td>
</tr>
</tbody>
</table>

*Note:* Tlim110 = time to exhaustion at 110% of maximal aerobic velocity.  
Significantly different from graded test for the same group: *$p < 0.05$; **$p < 0.001$.

### Table 3  Exercise Times to Exhaustion and Peak HR Values for Tlim at Various Percents of MAV

<table>
<thead>
<tr>
<th></th>
<th>Tlim90</th>
<th>Tlim95</th>
<th>Tlim100</th>
<th>Tlim105</th>
<th>Tlim110</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (s)</td>
<td>667 ± 311</td>
<td>380 ± 177*</td>
<td>244 ± 79*</td>
<td>151 ± 47*</td>
<td>129 ± 34</td>
</tr>
<tr>
<td>Peak HR (bpm)</td>
<td>201 ± 9</td>
<td>201 ± 8</td>
<td>200 ± 7</td>
<td>200 ± 7</td>
<td>199 ± 7</td>
</tr>
</tbody>
</table>

*Note:* Tlim = times to exhaustion at 90, 95, 100, 105, and 110% of maximal aerobic velocity.  
*Significantly different from previous column, $p < 0.001$.  

Significantly different from previous column, $p < 0.001$.  


Table 4  Mean Calculated Parameters

<table>
<thead>
<tr>
<th></th>
<th>Girls</th>
<th>Boys</th>
<th>Boys and Girls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr (ml·kg⁻¹·m⁻¹)</td>
<td>0.240 ± 0.032</td>
<td>0.235 ± 0.019</td>
<td>0.238 ± 0.028</td>
</tr>
<tr>
<td>MAOD (ml·kg⁻¹)</td>
<td>34.3 ± 11.8</td>
<td>33.6 ± 13.6</td>
<td>34.1 ± 12.3</td>
</tr>
<tr>
<td>ADC (m)</td>
<td>95.3 ± 32.1</td>
<td>92.8 ± 28.4</td>
<td>94.4 ± 30.4</td>
</tr>
<tr>
<td>V₉₉₀ (km·h⁻¹)</td>
<td>8.4 ± 1.0*</td>
<td>9.7 ± 0.9</td>
<td>8.8 ± 1.1</td>
</tr>
<tr>
<td>V₉₉₀ (%MAV)</td>
<td>84.2 ± 5.8</td>
<td>86.4 ± 1.7</td>
<td>85.0 ± 4.9</td>
</tr>
</tbody>
</table>

*Significantly different from boys, p < 0.001.

Note: Cr = energy cost of running; MAOD = maximal accumulated oxygen deficit; ADC = anaerobic distance capacity; V₉₉₀ = critical velocity.

Table 5  Correlations Between Physiological Parameters and Calculated or Measured Parameters From Field Tests

<table>
<thead>
<tr>
<th></th>
<th>V₉₉₀ (km·h⁻¹)</th>
<th>V₉₉₀ (%MAV)</th>
<th>ADC (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak VO₂ (ml·kg⁻¹·min⁻¹)</td>
<td>0.77 ***</td>
<td>0.44 **</td>
<td>0.02</td>
</tr>
<tr>
<td>MAOD (ml·kg⁻¹)</td>
<td>0.41 *</td>
<td>0.22</td>
<td>0.30</td>
</tr>
<tr>
<td>MAV (km·h⁻¹)</td>
<td>0.91 ***</td>
<td>0.20</td>
<td>0.06</td>
</tr>
</tbody>
</table>

*Significantly correlated: *p < 0.05; **p < 0.01; ***p < 0.001.

Note: V₉₉₀ = critical velocity; ADC = anaerobic distance capacity; peakVO₂ = peak oxygen uptake measured during graded test; MAOD = maximal accumulated oxygen deficit; MAV = maximal aerobic velocity.

Multiple combinations of two tlims were performed in order to calculate the dlim = f(tlim) relationship. Only the children with five tlim measurements (n = 20) were retained for this part of the study. The different calculated V₉₉₀ and ADC were compared to those calculated with five tlims, which was deemed the gold standard. The most accurate calculations were obtained when the dlim = f(tlim) relationship was calculated from tlim110 and tlim90. In this case the mean values for V₉₉₀ and ADC were 9.06 ± 1.05 km·h⁻¹ and 87.7 ± 19.3 m, respectively. These values did not differ significantly from those calculated with five tlims. Significant correlations were found between the parameters of the dlim = f(tlim) relationship when calculated with five tlims and two tlims (tlim110 and tlim90) for V₉₉₀ (r = 0.99, p < 0.001) and ADC (r = 0.71, p < 0.001). In addition, the technique proposed by Bland and Altman (1986) indicated graphically (Figures 2 and 3) that for V₉₉₀ and ADC, all values (minus one for V₉₉₀) were between the limits of agree-
ment. For $v_{\text{crit}}$ ($r = 0.21, p = 0.36$) as for ADC ($r = 0.05, p = 0.82$), no relationship was found between the differences vs. the averaged values.

**Discussion**

The results of the present study indicate that, for running events, the $d_{\text{lim}} = v_{\text{crit}} \cdot t_{\text{lim}} + \text{ADC}$ relationship could be satisfactorily adjusted to the results of prepubertal children ($0.98 < r^2 < 0.99, p < 0.001$) for performances obtained from $t_{\text{lim}}$ at 90%, 95%, 100%, 105%, and 110% of MAV. When five consistent values ($t_{\text{lim}90}, t_{\text{lim}95}, t_{\text{lim}100}, t_{\text{lim}105}, t_{\text{lim}110}$) can be measured, as is the case for adults, this model can be used to describe running performance of prepubertal children. The $v_{\text{crit}}$ was significantly correlated with peak $\dot{V}_O_2$ ($r = 0.73, p < 0.001$), which suggests that this parameter is a good index of a child’s aerobic fitness. Conversely, ADC was not correlated with MAOD.

**CHARACTERISTICS OF CHILDREN**

The peak $\dot{V}_O_2$ ($45.2 \pm 6.7 \text{ ml·kg}^{-1} \cdot \text{min}^{-1}$) was characteristic of moderately active children (Armstrong and Welsman, 2000; Falgairette et al., 1991). The HR max ($203 \pm 9 \text{ bpm}$) and RER (1.04 $\pm$ 0.06) confirmed the maximal level of the graded test. The children’s mean MAV ($10.4 \pm 1.1 \text{ km·h}^{-1}$ at 9.8 $\pm$ 0.7 yrs) was similar to that reported by Berthoin et al. (1996) for 9- and 10-year-old children, 9.4 $\pm$ 0.8 km·h$^{-1}$ and 10.6 $\pm$ 1.2 km·h$^{-1}$, respectively.

The children’s $t_{\text{lim}}$ diminished significantly as the percentage of MAV increased. It is difficult to compare the $t_{\text{lim}}$ to those of others since, to our knowl-
edge, only values for running tlim100 have been reported for children (Berthoin et al., 1996). In that study the reported mean values were 213 ± 112 s (9 yrs) and 252 ± 99 s (10 yrs) for girls, while those of boys were 232 ± 100 s (9 yrs) and 227 ± 87 s (10 yrs). Those reported values are similar to the ones found in the present study (244 ± 79 s) for a mixed population of boys and girls with a mean age of 9.4 years. Conversely, all tlims were lower than those reported for adults (Billat et al., 1995; Blondel et al., 2001; Kachouri et al., 1996).

The lack of difference, p = 0.08, between tlim110 and tlim105 could stem from the hyperbolic nature of the tlim vs. velocity relationship. Indeed, for intensities close to \( v_{\text{crit}} \), small variations in velocity could induce large variations in tlim. However, for high velocities the tlim vs. velocity has a tendency to become linear, and small variations in velocity are associated with smaller variations in tlim than for exercises close to \( v_{\text{crit}} \). This is particularly evident in children for whom the absolute range of velocities (km·h\(^{-1}\)) between two relative velocities (%MAV) is very short.

Our results indicated that at all relative velocities (%MAV) the tlim are lower in children than in adults, and that the differences in tlim increase as the percentage of MAV decreases (Figure 4). Indeed, the time vs. %MAV relationship curve shifts to the left for children. This observation has practical implications for aerobic training in children, as the duration of exercises, at selected percentages of MAV (or peak VO\(_2\)), should not be the same as for adults. During intermittent exercises, for example, the duration of the repetitions certainly must be shortened in children when running at the same percentage of MAV as adults. Therefore, specific recommendations have to be established for children and further studies are needed so that specific exercise sessions can be proposed for training children.
Calculation of the dlim = f(tlim) Relationship. In the present study, the dlim = f(tlim) relationship was calculated with five tlims for only 20 subjects. The number of tlims was chosen in order to accurately represent the relationship. However, for 12 subjects (35% of the population) we failed to measure five consistent values (tlim90 < tlim95 < tlim100 < tlim105 < tlim110). This could be explained by day-to-day variations of physiological parameters, or even of motivation associated with little difference between the velocities at the different percentages of MAV (e.g., 0.45 km·h⁻¹ for a child with an MAV of 9 km·h⁻¹).

The high values of the coefficients of determination (0.98 < r² < 0.99, p < 0.001), together with the calculation of the dlim = f(tlim), underline the adequate nature of the linear model used to describe the relationship. The coefficients of determination are similar to those reported for children in swimming (Hill et al., 1995) or cycling (Fawkner and Armstrong, 2002). On the basis of the results, it could be concluded that exercises leading to exhaustion, reached in 2–3 to 10–12 min, could be retained to calculate the dlim = f(tlim) relationship in children. The relationship could also be calculated from competitive data (time trial data), which could give a slightly better representation than tlim data (Hill et al., 1995).

To provide less time-consuming methods for determining the dlim = f(tlim) relationship, we performed all the combinations of calculations with only two tlims. Only the subjects with five tlims (n = 20) were included for this analysis. In each case the v_crit and ADC parameters were compared to those obtained using five tlims, assumed to be the gold standard. It was when the dlim = f(tlim) relationship was calculated from tlim110 and tlim90 that the highest correlations between measures of v_crit (r = 0.99, p < 0.001) and ADC (r = 0.71, p < 0.001) were obtained. In

![Figure 4. Relationships between tlim and % of MAV for the children in the present study and those of nonspecifically aerobic-trained adults (Blondel et al., 2001; Kachouri et al., 1996) and aerobic-trained adults (Billat et al., 1995).](image-url)
addition, the measures were not significantly different and the technique of Bland and Altman (1986) indicated graphically significant agreement between the two methods (Figures 1 and 2). Furthermore, for both \( v_{\text{crit}} \) and ADC, no relationship was found between differences vs. averaged values, indicating that an additional simplification could also result in the measurement of the two tlims during the same day.

As demonstrated by Bishop and Jenkins (1995), two measurements of tlim taken the same day, with a sufficient rest period, could be proposed. Indeed, Fawkner and Armstrong (2002) have observed that the critical power of children measured from three tlims carried out on the same day with a 3-hr recovery period between each was not significantly different from the critical power calculated from tlims performed on different days. It could be of particular interest for children, who recover more quickly than adults after intensive exercise (Hebestreit et al., 1993).

**Parameters of the dlim = f(tlim) Relationship.** The mean values for \( v_{\text{crit}} \) and ADC cannot be compared to those reported in the literature since, to our knowledge, no study had focused on this topic for pre- or postpubertal children. The absolute \( v_{\text{crit}} \) (km·h\(^{-1}\)) was significantly lower than the values reported for adults (Blondel et al., 2001; Kachouri et al., 1996). Similar findings have been reported for swimming exercises by Hill et al. (1995), who demonstrated that absolute \( v_{\text{crit}} \) increased with age. A greater difference can easily be explained by a higher Cr in children than in adults (Daniels et al., 1978) despite similar peak \( \dot{V}O_2 \) (Falgarette et al., 1991). However, when expressed as a percentage of MAV (85%), the results in children were of a level similar to those of adults for running events: 85 to 90% (Billat et al., 1995; Blondel et al., 2001; Kachouri et al., 1996).

This is an interesting result, as \( v_{\text{crit}} \) has been presented as an index of aerobic endurance (time limit for running at velocities lower than that associated with \( \dot{V}O_2\text{max} \)) (Léger, 1996), which does not differ significantly from the velocity corresponding to the 4 mmol·L\(^{-1}\) blood lactate concentration (Lechevalier et al., 1989), or the velocity at maximal lactate steady state (Mocellin et al., 1991) in adults. However, despite \( v_{\text{crit}} \), ventilatory anaerobic thresholds (Reybrouck et al., 1985), or the onset of blood lactate accumulation (Sid-Ali et al., 1991) occurring at a similar or higher percentage of peak \( \dot{V}O_2 \) (or MAV) in children than in adults, children demonstrated lower tlim at all relative velocities (Figure 4). Thus the interpretation of the different physiological thresholds (or \( v_{\text{crit}} \)) as an index of aerobic endurance has to be questioned, as it implies that maximal time to exhaustion is longer in children than in adults.

The ADC of the children (94.4 ± 30.4 m) represented less than 50% of the values obtained in adults: 187 ± 86 m (Kachouri et al., 1996) or 216 ± 59 m (Billat et al., 1995). These results are in accordance with the lower values for ADC reported by Hill et al. (1995) in young swimmers, and consistent with those obtained when comparing the anaerobic capacity of children and adults by means of MAOD measurement (Carlson et al., 1998) or Wingate tests (Armstrong et al., 2000).

The measurement of \( v_{\text{crit}} \) and ADC are of some help in explaining the lower tlim in children, and also in explaining the increase of tlim100 with age (Berthoin et al., 1996). The linear relationship between dlim and tlim [dlim = \( (v_{\text{crit}} \cdot t_{\text{lim}}) + \text{ADC} \)] is mathematically equivalent to the hyperbolic relationship tlim = ADC / (\( v - v_{\text{crit}} \)). This equation indicates that tlim could be improved by increasing ADC or
by decreasing the $v_{\text{crit}} - v$ difference. As shown in this study, the ADC parameter is considerably lower in children than in adults. However, the $v_{\text{crit}} - v$ difference proved to be lower in children. In children with MAV of 10 km·h$^{-1}$ and a $v_{\text{crit}}$ of 85% of MAV, for example, the $v_{\text{crit}} - v$ difference is 1.5 km·h$^{-1}$, while for adults with an MAV of 15 km·h$^{-1}$ and a similar relative $v_{\text{crit}}$ (85% of MAV), the $v_{\text{crit}} - v$ difference will be equal to 2.2 km·h$^{-1}$. During growth, the combined evolution of ADC and $v_{\text{crit}} - v$ difference are among the parameters that could help explain an increase in $t_{\text{lim}}$.

**Physiological Significance of the $v_{\text{crit}}$ and ADC Parameters.** Our results indicate that $v_{\text{crit}}$ was significantly correlated with peak $\dot{V}O_2$ ($r = 0.73; p < 0.001$) and with MAV ($r = 0.91; p < 0.001$), an index of aerobic performance. This result is in line with those of Fawkner and Armstrong (2002), who reported significant correlations between critical power and peak $\dot{V}O_2$ ($0.91 < r < 0.95; p < 0.001$) and ventilatory threshold ($0.75 < r < 0.77; p < 0.001$). Others have also found significant correlations between swimming $v_{\text{crit}}$ and performances over 400 m (Wakayoshi et al., 1992) and 457 m or 1509 m (Hill et al., 1995). These different results indicate that the $v_{\text{crit}}$ is a good index of aerobic power and aerobic performance in children. No relationship was found between ADC and $\text{MAOD}$, $p = 0.08$. The mean calculated $\text{MAOD}$ ($34.1 \pm 12.3 \text{ ml·kg}^{-1}$) was close to that reported by Carlson and Naughton (1998) for children of the same age. However, a large variability of $\text{MAOD}$ was observed, as demonstrated by a high coefficient of variation.

In the present study, a simplified method of determining $\text{MAOD}$ was performed using resting $\dot{V}O_2$ and CR. More submaximal $\dot{V}O_2$ are certainly needed to calculate the $\dot{V}O_2$ vs. velocity relationship and to more accurately determine $\text{MAOD}$. In adults the ADC parameter was found to be a reflection of anaerobic fitness ascertained from cycle ergometry (Jenkins and Quigley, 1991). However, for running events the ADC has not been related to indicators of anaerobic capacity (Housh et al., 1992). Establishing how much distance can be covered using the $\text{MAOD}$ provided an alternative determination of the anaerobic capacity of the children. This distance was significantly correlated with ADC ($r = 0.43, p < 0.05$) but was also significantly higher. However, Hill et al. (1995) showed that, for children, correlations between ADC and peak lactate concentration were only observed for those children for whom the most accurate adjustment of the $d_{\text{lim}} = f(t_{\text{lim}})$ relationship was obtained.

In general, the results reported in the literature indicated that the determination of the ADC parameter was more protocol-dependent, and that ADC values presented a lower correlation with other indicators of anaerobic capacity than does $v_{\text{crit}}$ with indicators of aerobic power (Hill, 1993; Vandewalle et al., 1997). Nevertheless, the validity of ADC measurement to evaluate children’s anaerobic capacity requires further research.

**Conclusions**

In children, the $d_{\text{lim}}$ vs. $t_{\text{lim}}$ relationship can be calculated with running times to exhaustion ranging between 2 and 10 min. The $v_{\text{crit}}$ seems to be an interesting predictor of children’s aerobic power. Conversely, the use of ADC as a predictor of anaerobic capacity requires further examination. From a practical point of view, the relationship can be accurately calculated only from $t_{\text{lim}90}$ and $t_{\text{lim}110}$, or
even with performances over 2 min or 10 min. By knowing the \( \text{dlim} = f(t\text{lim}) \) relationship, we can predict the performance of children over a wide range of times or distances. However, further studies are needed to test the sensitivity of \( v_{\text{crit}} \) and ADC to training or its evolutions with growth and maturation. In addition, studies are needed to test the accuracy of prescribing exercise intensities for training with the \( v_{\text{crit}} \) as a velocity criterion.

**Acknowledgment**

The authors wish to express special thanks to the children for their enthusiasm and participation, the teachers from the Illies primary school for their welcome and availability, and the Inspection Pédagogique du Nord, particularly Mr. Fromont for allowing the experiments.

**References**


Blondel, N., Berthoin, S., Billat, V., and Lensel, G. (2001). Relationship between run times to exhaustion at 90, 100, 120, 140% of \( v\dot{V}O_2\text{max} \) and velocity expressed relatively to critical velocity and maximal velocity. *Int. J. Sports Med.* 22: 27-33


Received May 31, 2002; accepted in final form November 20, 2002.