Validity of Critical Velocity as Swimming Fatigue Threshold in the Competitive Swimmer

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The purpose of this investigation was to determine whether the critical velocity (CV) as the swimming speed which can be theoretically maintained for a very long time without exhaustion could be applied to estimate the swimmer’s endurance performance. CV was based on the concept of critical power originality established by Monod and Scherrr (1965) and extended by Moritani et al. (1981), and expressed as the slope of a regression line between swimming distance (D) at each velocity and its sustained time (T).

Seventeen highly trained swimmers were instructed to swim the four different swimming distances (50 m, 100 m, 200 m and 400 m) at maximal effort using the swimming pool. In the results of CV, the regression relations between D and T were expressed in the general form, D = a + bxT, with r² showing higher than 0.997 (p < 0.001). These results indicate extremely good lineality. Furthermore, VO₂max during incremental exercise test, swimming speed corresponding 4 mM of blood lactate concentration (V-OBLA) and mean velocity in the 200 m and 400 m freestyle (V-200 and V-400) were measured on nine subjects. Significant correlations were found between CV and V-OBLA (r = 0.862, p < 0.01), CV and V-200 (r = 0.781, p < 0.01), CV and V-400 (r = 0.999, p < 0.001), V-OBLA and V-400 (r = 0.869, p < 0.01) and V-200 and V-400 (r = 0.776, p < 0.01).

These data suggest that CV can be determined by performing several maximal effort swimming (50 m, 100 m, 200 m and 400 m events) and a stopwatch only, and CV can be adopted as an index for assessing the physical performance without blood sampling and employing highly expensive equipments.

Key words: Competitive swimming, OBLA, VO₂max, Critical velocity

The maximal oxygen uptake (VO₂max) has generally been utilized as a physiological index for assessing aerobic capacity in athletes and numerous investigations have reported the relationship between endurance performance and blood lactate related parameters (Allen et al. 1985; Farrell et al. 1979; Kumagai et al. 1983; Olbrecht et al. 1985; Tanaka et al. 1984; Yoshida et al. 1987, 1989, 1990). Recently, Costill et al. (1985) and Ribeiro et al. (1990) found a low correlation between VO₂max and the swimming performance either in the 365.8 m and 400 m freestyle. On the other hand, a strong correlation with the swimming performance has been found in regard to the swimming speed corresponding 4 mM of blood lactate concentration (OBLA) which has been, on the basis of the correlation, used as a useful
criterion of the training intensity for the competitive swimmer (Madsen and Lohberg 1987; Maglischo et al. 1982; Skinner 1987). However, the athletes and the coaches have tended to refuse blood sampling.

Monod and Scherrer (1965) found a linear relation between the total work done at each work rate and its duration during the local muscular exercise and defined the critical power (CP) as the intensity of exercise which could be maintained for a very long time without exhaustion. CP was determined by the slope of the regression line based on the total work performed and the corresponding time until exhaustion. Moritani et al. (1981) extended the concept of CP to total body work performed on a cycle ergometry and found a strong relationship between CP and the ventilatory threshold.

Recently, Jenkins and Quigley (1990) reported that CP could be employed as a simple and inexpensive method for estimating the work rate that can be maintained continuously during cycle ergometry. We have recently applied the CP concept to competitive swimming by using the swimming flume and defined the critical velocity (CV) as the swimming speed which can be theoretically maintained for a very long time without exhaustion (Wakayoshi et al. 1992). In such preceding study made by us (Wakayoshi et al. 1992), CV was expressed as the slope of linear regression line between swimming distance (D) at each velocity and its sustained time (T). The regression analysis of D and T (9 subjects) showed extremely high linearity ($r^2 > 0.998$).

The purpose of this investigation was to determine whether CV as the swimming speed which can be theoretically maintained for a very long time without exhaustion could be applied to estimate the swimmer’s endurance performance.

**METHODS**

**Subjects.** The subjects who volunteered for this study were seventeen male trained swimmers (the subjects who participated in the tests of $\dot{V}O_{2\text{max}}$ and OBLA were nine swimmers). The subjects were informed of the nature and risks involved in participation in the experiments and signed a statement of informed consent.

Measurement of $\dot{V}O_{2\text{max}}$. Individual maximum aerobic power was determined during incremental swimming test in the swimming flume. Subsequently the subjects performed a 3 min warm-up at 0.9 m/s of swimming speed and had the recovery time for 3 min. The actual test was then started at 1.0 m/s of initial speed. Swimming speed was increased by 0.1 m/s until 6 min from starting time and thereafter by 0.05 m/s every min until the subject reached voluntary exhaustion. During the incremental swimming test, the subjects breathed through a low resistance J-valve. Expired gas was analyzed every 30 s (AE-280, Minato Medical Science, Osaka, Japan) for measurements of oxygen uptake ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$) and minute ventilation ($\dot{V}e$). The highest $\dot{V}O_2$ value obtained during the incremental swimming test was recorded as $\dot{V}O_{2\text{max}}$.

Blood lactate tests and determination of onset of blood lactate accumulation. The onset of blood lactate accumulation (OBLA) has been selected as an index for blood lactate accumulation and used for evaluating endurance ability in this study. By plotting each subject’s blood lactate concentrations against swimming speed and connecting the data points, it is possible to calculate the swimming speed at which a blood lactate accumulation of 4 mM (OBLA) occurred (Madsen and Lohberg 1987; Maglischo et al. 1982; Skinner 1987).

In the present study, using the indoor swimming pool 25 m long (the temperature was maintained between 29 and 30°C), the swimmers covered four times on 200 m swimming at constant velocities at 80 %, 85 %, 90 % and 95 % of their 200 m best time and the once on 200 m swimming at maximum effort. A resting period longer than 30 min was provided between trials. Arterialized capillary
blood was taken from the finger tip before, immediately after, and 3 and 5 min after each test bout. Blood lactate was analyzed by an enzymatic membrane method (YSI23L, YSI Co. LTD.), which had been calibrated against a standard concentration of lactate solution.

Determination of critical velocity. Figure 1 illustrates an example for determining CV using the swimming pool and indicates relationship between the swimming distance (meter) and the time (second) that the swimmer took to swim its distance. The subjects were instructed to swim the different distances of 50 m, 100 m, 200 m and 400 m at maximum effort. We never instructed to swim at constant velocity for the subjects. Then, the time taken to swim each distance was measured. Rest periods were provided between test bouts for at least 3 hours. The test was carried out 2 events per day selected by random sampling. Those points in Fig. 1 were accurately situated on a line defined by relationship between the swimming distance (D) and the time (T) taken to swim it.

Swimming velocity (V) multiplied by T makes D;

\[ D = V \times T \]  

(1)

The equation of regression line can be expressed as follows:

\[ D = a + b \times T \]  

(2)

\[ V = a/T + b \]  

(3)

Theoretically, if we could set the swimming velocity level at which one can perform indefinitely \((T \rightarrow \infty)\), \(a/T\) will approach zero and \(V\) will approach \(b\). Therefore, \(CV\) can be expressed as the slope of the regression line:

\[ CV = b \]  

(4)

RESULTS

Table 1 shows that the physical characteristics, their speciality, performance records and the data obtained from the tests in the present study. \(\dot{VO}_{2\text{max}}\) during the incremental swimming test for these nine swimmers ranged from 56.9 to 74.3 ml/kg/min with a mean of 64.9 ml/kg/min (SD = 6.7). Velocity of the 400 m freestyle (V-400) ranged from 1.429 to 1.715 m/s with a mean of 1.567 m/s (SD = 0.075). It is apparent that the subjects in the present study are high trained swimmers.

The experimental plots used to determine CV are shown in Figure 1 using example of subject 9. The relations between D and T of CV were expressed in the general form, \(D = a + b \times T\), with value (goodness of fit) showing higher than 0.997 (\(p < 0.001\)) in all subjects. These results of CV indicated extremely good linearity. CV ranged from 1.381 to 1.665 m/s of a mean of 1.511 m/s (SD = 0.078). While, \(V\)-OBLA ranged from 1.388 to 1.654 m/s with a mean of 1.493±0.075 m/s (±SD) was significantly lower than those of CV (\(p < 0.01\)).

Table 2 shows the relationships among CV, \(\dot{VO}_{2\text{max}}\), \(\dot{VO}_{2\text{max}}/kg\), V-OBLA, V-200 and V-400. V-400 was strongly correlated to CV (\(r = 0.999\), \(p <\)
Table 1  The physical characteristics, the performance and test results for each subject

<table>
<thead>
<tr>
<th></th>
<th>CV</th>
<th>r²</th>
<th>V-200</th>
<th>V-400</th>
<th>VO₂max</th>
<th>VO₂max/kg</th>
<th>V-OBLA</th>
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<td>1.000</td>
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</tr>
<tr>
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<td>1.692</td>
<td>1.569</td>
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</table>

Mean 1.511 1.690 1.567 4518 64.9 1.493
S.D. 0.078 0.067 0.075 587 6.7 0.075

CV: critical velocity, V-200 and V-400: velocity of 200 m and 400 m freestyle, VO₂max: maximal oxygen uptake, VO₂max/kg: maximal oxygen uptake per body weight, V-OBLA: swimming velocity at 4mmol/l of blood lactate concentration.

Table 2 Correlation matrix for variables measured by each experiment.

<table>
<thead>
<tr>
<th></th>
<th>CV</th>
<th>VO₂max</th>
<th>VO₂max/kg</th>
<th>V-OBLA</th>
<th>V-200</th>
<th>V-400</th>
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<td></td>
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<td>VO₂max/kg</td>
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<td>.922</td>
<td>1</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>V-OBLA</td>
<td>.862</td>
<td>-.454</td>
<td>-.451</td>
<td>1</td>
<td></td>
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<tr>
<td>V-200</td>
<td>.781</td>
<td>.363</td>
<td>.294</td>
<td>.529</td>
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<td></td>
</tr>
<tr>
<td>V-400</td>
<td>.999</td>
<td>-.086</td>
<td>-.05</td>
<td>.869</td>
<td>.776</td>
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CV: critical velocity, VO₂max: maximal oxygen uptake, VO₂max/kg: maximal oxygen uptake per body weight, V-OBLA: swimming speed at 4mM of blood lactate concentration, V-200: mean velocity of 200 m freestyle, V-400: mean velocity of 400 m freestyle.

p < 0.01, p < 0.05

0.01), V-OBLA (r = 0.869, p < 0.01) and V-200 (r = 0.776, p < 0.01). Furthermore, significant correlations were found between CV and V-OBLA (r = 0.862, p < 0.01), and CV and V-200 (r = 0.781, p < 0.01). However, there was no significant correlation between VO₂max and other indices.

DISCUSSION

The concept of critical power (CP) formulated by Monod and Scherrer (1965) and extended by Moritani et al. (1981) was applied to evaluate the endurance performance in the competitive swimming. We have defined critical velocity (CV) defined as swimming velocity which could be theoretically maintained without exhaustion during swimming in the present study. In the results of CV, the regression equations between swimming distance and time were expressed in the general form, D = a + b × T, with r² (goodness fit) showing higher than 0.997 (p < 0.001) in all subjects. These results indicate extremely good linearity regardless of CV.

For determining the CV, the subjects were instructed to swim the predetermined distance as quickly as they can. Nevertheless, the swimming speed could be never kept at a constant level during swimming. In the previous studies regarding the analysis of competitive swimming races, Craig et al.
(1985) and Wakayoshi et al. (1988) indicated that, with the passage of time in the race, the swimming velocity had a tendency to decrease by decreasing the distance per stroke. However, it can be assumed that the mean velocity calculated from the time (record) to swim the predetermined distance is equal to the maximal speed which the swimmers can maintain for that time. Consequently, in the present study, the maximal mean swimming velocity (V) and the record (T) can be expressed as $V = a/T + b$ and CV can be expressed as the slope of the regression equation relating the swimming distance and the time.

Recently, numerous investigators have used OBLA as an useful and important index for estimating the endurance performance of the runners (Farrell et al. 1979; Kumagai et al. 1983; Yoshida et al. 1987). In fact, the swimming speed at OBLA determined by mathematical procedure in each swimmer has been utilized as an training intensity (Maglischo et al. 1982; Skinner 1987). Furthermore, Obrech et al. (1985) have reported that the swimming speed at 4 mM of blood lactate concentration obtained by using the two-speed test was highly correlated with the performance on a 30 min swimming event. In the present study, significant positive correlations were found between V-OBLA and V-400, and V-OBLA and CV.

In the present study, CV were significantly higher values than V-OBLA (9 subjects). Stegmann et al. (1981) and Stegmann and Kindermann (1982) named the individual anaerobic threshold (IAT) for the

Fig. 2 Relationship between CV and V-400(A), CV and V-OBLA(B), CV and V-200(C), and V-400 and V-OBLA(D).
non-linearity in the increase in blood lactate concentration during the incremental exercise test and have suggested that it was important to determine the work level adopted to each individual rather using a fixed value (e.g., OBLA). They reported that the work rate at a level corresponding to IAT was lower than that of OBLA. Furthermore, Jenkins and Quigley (1990) have shown that well-trained endurance cyclists can tolerate relatively high concentrations of blood lactate (8.9 mM, SD = 1.6) for 30 min. Accordingly, OBLA is an effective method for estimating how high the performance in each swimmer can be physiologically developed by the training effort and comparing the endurance performance among the swimmers. However, it seems that the criterion of CV rather than that of OBLA should be utilized as a standard value for establishing the optimum training intensity in each swimmer.

In conclusion, these data suggest that CV can be determined by performing several maximal effort swimming (50 m, 100 m, 200 m, and 400 m events) and a stopwatch only, and CV can be adopted as an index for assessing the physical performance without blood sampling and employing highly expensive equipments.

REFERENCES
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