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For any swimmer, a hyperbolic relationship links velocity ($v$) and stroke rate (SR) to time to exhaustion ($t$). The asymptotes of these relationships are called Critical Velocity (CV) and Critical Stroke Rate (CSR). Both could be maintained, at least in theory, indefinitely. This review presents the origins of these two concepts, their physiological / biomechanical underpinnings to emphasis their usefulness for training. Coaches should appreciate the ease in using the CV model to set training loads, monitor training effects, and predict performance. The CSR concept is very recent and should be further investigated. However, current available knowledge suggests there is merit in using the two parameters for training.

INTRODUCTION
Understanding that physiological assessment of athletes is inherent to a good training process, laboratory testing in Sports and Exercise Science are becoming more and more accessible to athletes and a wide range of testing procedures are today recommended in the literature for cyclists (15) and runners (26). Physiological assessment should be sport-specific (3), but routine measurements are technically limited in swimming (41), assessing the physiological potential of a swimmer remains challenging. A number of ‘field’ tests have been developed. Smith et al. (41) acknowledge, in a review on the physiological and psychological tools used in the evaluation of swimmers, that the first-level of evaluation should be the competitive performance itself. The use of the individualised swimming speed versus time performance ‘curve’ based on a series of criterion effort has appeared attractive and appealing for physiological assessment in swimming (41). The ‘critical swimming velocity’ concept could provide the basis to analyse the effects and trends brought about through training, predict future competitive performance, and provide recommendations for continued directional training. Alongside the critical velocity concept (CV), a critical stroke rate (CSR) concept has been proposed in swimming (11). The purpose of this review is to address the usefulness of CV and CSR for swimming training. Because of a lack of evidence concerning the validity and reliability of the second parameter that can be derived from the CV concept (the Anaerobic Distance Capacity, ADC), its usefulness for training is not presented in the present review.

ORIGINS OF THE CONCEPTS: THE CRITICAL POWER CONCEPT
The CV and CSR concepts are extensions of the critical power concept originally introduced by Monod and Scherrer fifty years ago (35). Attempting to improve the understanding of the local work capacity of one muscle or one synergistic muscle group, these authors highlighted that local work ($W$) and time to exhaustion ($t$) were linearly related (Equation 1). The slope of the relationship, called Critical Power (CP), was defined as a ‘threshold of local fatigue’ while the y-intercept (a) was corresponding to a reserve of energy.

\textbf{Equation 1:} $W = a + CP.t$
CP can also be derived from the $P-t$ relationship. The higher the power, the lower the time to exhaustion so that the $P-t$ relationship is hyperbolic, with CP being its asymptote. Indeed, when time tends to the infinity, power tends to CP. CP is therefore mathematically defined as the power that can be maintained indefinitely.

The 2-parameter model has been one of the first physiological models applied to human endurance (1). Indeed, it was used few years later to model world records dating from 1965 in swimming, running, speed skating, and cycling (14). The aims were to predict performances and to explain the limits of human endurance. A $d-t$ relationship (Equation 2) equivalent to equation 1 of Monod and Scherrer (35) was proposed. The $y$-intercept of the relationship (Anaerobic Distance Capacity, ADC; (23)) was therefore a distance in meters which could be run on oxygen reserves and the energy supplied by anaerobic metabolism, while the slope (CV; (23)) was interpreted as a maximal rate of synthesis of these reserves by aerobic metabolism. This application of the CP concept to cyclic activities is not without assumptions that are better detailed in Dekerle et al. (8).

Equation 2: $d = \text{ADC} + CV \cdot t$

In the latter stage of the 20th century, most of the works on the models of Monod and Scherrer (35) and Ettema (14) were conducted to affine the methodology used to plot the $W-t$ and $d-t$ relationship, and better define the physiological meanings of the different constants. The numerous post hoc interpretations of the slope and the $y$-intercept of the $d-t$ and $W-t$ relationships these last 50 years have permitted a better understanding of the physiological meanings of the above-mentioned parameters.

CRITICAL VELOCITY IN SWIMMING.

Methodology and reliability.

Three equivalent models can be used to calculate Critical Velocity in swimming (CV). Indeed, CV is represented by the slope of the $d-t$ relationship (Equation 2; Panel A, Figure 1), the asymptote of the $v-t$ relationship (Panel B, Figure 1), and the $y$-intercept of the $v-1/t$ relationship. The relationship the most used in swimming to derive CV is the linear $d-t$ one (Panel A, Figure 1). This is certainly due to its easy application from the plot of two or more swimming performances over time.

Performances recorded on several events allow critical velocity to be determined (Figure 1, Panel A). It is however important to remember that the value of this slope is dependent on the exhaustion times used to plot the relationship (8, 13) (influence of the energetic cost in swimming). It is therefore recommended to include in the model tests or races that enable VO$_2$max to be reached (between 2 and 15 min). Competitive distances ranging from 200 to 1500m can be advised in swimming (33, 49). According to these requirements, and in a wish to make the determination of critical speed easy and rapid for coaches, the suggestion of Wakayoshi et al. (47) and Dekerle et al. (11) to base this determination on only two performances (200m and 400m) seems today pertinent.

However, using only two performances to derive CV would decrease its level of reliability. This has to be considered when using the $d-t$ relationship to predict performance or monitoring effects of periods of training. It can be noticed that CV determination has been shown to be reliable even if exhaustion times are variable (21,
and physiological responses at CV have also been shown in swimming, to be reproducible (4).

Figure 1: illustration of two different but equivalent representations of the 2-parameter CV model.

Definition and validity.

According to its mathematical definition, CV has firstly been thought to correspond to a sustainable intensity and has been compared to parameters such as the maximal lactate steady state (MLSS; highest intensity that can be maintained without any drift in the blood lactate concentration ([La])) or the onset of blood lactate accumulation (OBLA; intensity corresponding to a 4-mmol.L\(^{-1}\) of [La] during an incremental test). Wakayoshi et al. (47) and Brickley et al. (4) obtained steady [La] values during several 400-m blocks performed at CSV (around 3-4 mmol.L\(^{-1}\)). But the 30-45 sec of rest enabling blood samples to be taken between the blocks could have helped the swimmer keeping his motivation, limiting the drift of [La] and maintaining a ‘relatively’ good efficiency. Stroking parameters have indeed been shown to change, with progressive stroke rate increases and stroke length decreases within and between the 400-m blocks (4). Most authors today agree that CV does not correspond to a sustainable intensity. In fact, swimmers can hardly maintain their CSV for longer than 30-40 min (unpublished data from our laboratories) and CV has been shown to be close to the velocity of a 30-min test (11) and higher than MLSS (10) and OBLA (12, 40, 47, 48). Similar responses and exhaustion times have been recorded on treadmill and ergocycle (5, 7, 17, 22, 34, 36, 39).

CV is today defined as the upper limit of the heavy intensity domain, i.e. the highest intensity that does not allow VO\(_2\)\(_{\text{max}}\) to be attained during a constant load exercise (19). Below CV, progressive drifts of blood [La], heart rate and VO\(_2\) (‘slow component’) are observed but maximal values are not reached. The slow component of VO\(_2\) is not great enough for VO\(_2\)\(_{\text{max}}\) to be attained. Capillary blood [La] can attain 8-10 mmol.L\(^{-1}\). These speeds can be maintained from an hour (exhaustion times usually recorded at MLSS) to 30-40 min. High inter-individual variations were also reported (Brickley et al., 2002). In swimming, CV would refer to a 2000-m performance. Above CV, because of the slow component phenomena, VO\(_2\)\(_{\text{max}}\) should be elicited. The work of Hill and collaborators (19, 20) corroborates this definition in running and cycling but this has not yet been directly verified in swimming. However, it is in line
with several findings reported in the literature. CV has been shown in swimming to be a 
good indicator of the capacity of the aerobic energy system (43). Several studies 
confirmed this finding in young swimmers (6, 42). CV is lower than the end velocity of 
an incremental test, traditionally identified as the maximal aerobic velocity (around 92-
96% of the 400-m velocity in trained swimmers (4’15 up to 4’45)). It is highly 
correlated to OBLA (45, 47, 48), the average 400-m velocity (45, 47, 48), and MLSS 
(10). The first belief that CV was sustainable for a very long period of time was a 
misinterpretation of the mathematical (and not physiological) definition of CV, i.e. the 
intensity that can be maintained “in theory” indefinitely.

THE USE OF CRITICAL VELOCITY IN SWIMMING?

Setting training intensities
CV allows demarcating two different intensity domains and should be used as a 
reference to set training intensities. The 400-m pace is usually used by coaches for this 
purpose. However, two swimmers with similar performances on 400 m can have 
different aerobic potentials (Figure 2). One can swim a 1500 m quicker than the other 
one (and so on, for short races). The physiological stress to exercise of long duration 
will be different for the two swimmers. It is important to properly individualise training 
loads to optimise the physiological adaptations while avoiding overtraining especially 
when accuracy in the definition of the training loads is required as higher levels of 
performance.

Figure 2: Schematic of the speed-time relationship of two different swimmers 
having different aerobic potentials.

Using CV for aerobic training programs offers great potential. It allows better setting of 
continuous, long and short interval training for each. Continuous training (2000-3000m) 
and long interval training at and below CV would induce great lactic acid production 
leading to accumulation of H⁺ that would be buffered and La⁻ that would be oxidised in 
different body cells. An example of long interval training could be 6 to 10 x 400m 
swum at CV with 15-sec rest. Indeed, several 400-m blocks performed at CV can be 
swam with steady [La] values (around 3-4mmol.L⁻¹) when separated by 30-40s of rest 
(4). Among all acute adaptations, we could expect a great improvement of the buffering 
capacity and oxidative potential of several body cells on top of the muscular ones (18). 
This increase in the buffering capacity has been shown to well explain the improvement 
of performance of trained athletes (30).
The other interest in swimming above CV relies on the hypothesis that to improve the \( V_O_{2\text{max}} \) of trained athletes, \( V_O_{2\text{max}} \) has to be solicited, and thus for a long time (2). Short interval training could then appear as one of the most interesting forms of training since it enables the time spent at \( V_O_{2\text{max}} \) to be up to threefold those recorded during a continuous training. Short interval training presents other interests: 1) since the fifties, it is used by long and middle distance runners to train at speeds close to competitive ones (2). In swimming, it therefore enables to swim at stroke length and stroke rate ratio close to the competitive ones. 2) It induces a greater lipid solicitation for a given work done compared to continuous training (for example, 15 sec at 100% of \( V_O_{2\text{max}} \), 15 sec rest, compared to an hour at 50% of \( V_O_{2\text{max}} \)). Consequently, greater physiological adaptations (especially a greater oxidative capacity of the type 2 muscle fibres; lower muscular glucose and glycogen and greater lipid reliance for a given intensity after training). It has even been evocated that in highly trained population, performances can ‘only’ be envisaged using short interval training (2, 30). On top of the improvements of the aerobic capacity and power, increase in anaerobic capacities has also been observed after a period of short interval training in trained athletes (2, 30). Adequate long and short interval training above CV (20-30 x 100m at 110% CV, 30-s rest; 1min at 120% CV, 1min rest for 20 min) would therefore enable \( V_O_{2\text{max}} \) (very high heart rate and stroke volume) to be solicited and maintained for a very long time.

Central and peripheral adaptations occur with training performed around CV but it can be expected that the peripheral adaptations induced by swimming at and below CV would be less predominant with the increase in the intensity, the central adaptations becoming even more important.

Interval training swum around CV has been mentioned to be of great interest for improving aerobic and anaerobic potentials of swimmers. On top of these physiological adaptations, this kind of training allows swimming at high race paces while challenging the aerobic potential (200- up to 1500-m pace in this case). Training at race pace is important, especially in swimming where swimming coordination (42), energetic cost (6), and technical efficiency are changing depending on the velocity. Short interval training would enable to focus on the swimming techniques whose swimmers should attempt to maintain efficient while fatigue progressively develops during such long aerobic work performed around CV.

**Monitoring training effects and predicting performance**

A few studies conducted in laboratories have shown the 2-parameter model to be affected by training (24, 25). Aerobic training has a positive effect on CV (32). In swimming, MacLaren and Coulson (31) reported an increase and steady state in CV determined from the performances over a 50, 100, 200, and 400-m race, after a 8-week aerobic training period and a 3-week anaerobic training period, respectively. The results concerning the intercept of the \( d-t \) relationship were not reported as consistent.

Recently, Dekerle and Carter (in press) analysed the changes in CV during the last century of swimming Olympic performances. The greater improvements of long distance performance compared to shorter ones between two Olympic Games induced an explainable increase of CV. Plotting the \( d-t \) relationship would enable to monitor the effects of training on CV over a season (Figure 3) but further investigations are required to clarify the methodology that has to be used (number of performances required to plot the \( d-t \) relationship). Regarding the findings concerning the intercept of the \( d-t \) relationship.
relationship, we would suggest being prudent when interpreting its value and change over time.

**Figure 3: Effects of aerobic and anaerobic training on the d-t relationship.**

As shown in rowing (27) and running (16), when knowing the equation of the $d-t$ relationship, it is possible to predict performance. Again, this should be confirmed or infirmed in swimming by further research. However, because of the good linearity of the relationship, coaches can try to predict performance as long as they are ranging between around 2 and 30 min (8).

**A PLACE FOR CRITICAL STROKE RATE?**

Alongside the endurance-time relationship, the CP concept has recently been extended in swimming to characterise the stroke rate (SR) – $t$ relationship (11). Several studies have illustrated the hyperbolic SR – velocity curve (9, 28, 29, 37, 46). Indeed, when attempting to swim faster, a swimmer will increase his SR. This increase in SR will be detrimental to the stroke length (SL) above a given sub-maximal intensity (MLSS or OBLA (9, 28, 29, 37)). Consequently, the longest the race is, the lowest the speed is, and the lowest the SR is. Dekerle et al. (11) suggested that the SR-$t$ relationship could be modelled using a hyperbolic model, the asymptote being called Critical Stroke Rate (CSR). CSR is mathematically defined as the highest SR that can be maintained indefinitely, i.e. for a very long period of time.

The determination of CSR does not required extra-tests to be performed compared to the CV determination. It relies on the record of the SR of each performance. The hyperbolic SR-$t$ relationship can then be modelled (Figure 4, Panel B). To simplify the modelling, Dekerle et al. (11) proposed another model equivalent to the hyperbolic SR-$t$ one. This procedure enables a quick and easy determination of CSR by using a simple linear regression method. Indeed, CSR is also represented by the slope of the “number of stroke cycles” (N=SR x $t$) – $t$ relationship (Figure 4, Panel A).

No study has yet tested the reliability of the CSR concept and further investigations should also focus on its validity. However, Dekerle et al. (11) reported regression line coefficient of 0.99-1 when modelling the N-$t$ relationship (performances over a 50, 100, 200, and 400m swim). CSR was not significantly different and was highly correlated to the average SR of a 30-min test. Moreover, when swimming at CV, the nine participants spontaneously adopted SR values similar to CSR. Similarly, when having to swim at the imposed CSR, participants swum at CV.
It is today acknowledged that SR/SL ratio should be monitored during training in order to control and even improve stroke efficiency. When preparing a repetition, alongside the set of distance/duration, intensity, number of repetitions, and duration and form of the recoveries, coaches should control the SR/SL ratio in order to preserve a good technical gesture. When considering the results of Dekerle et al. (11), it could even be suggested that a given SR could be imposed during training repetitions rather than the usual time “allowed” to cover a given distance. Because training is just about “pushing the limits of the swimmer”, the aim in aerobic swimming training performed at CV could consist in maintaining CV with a lower SR than CSR, or maintaining CSR while swimming faster than CV. This would require higher SL to be adopted and maintained.

As explained above, it is known that training at race pace is of importance for technical aspects of the strokes. Therefore, this training strategy relying on the multiple combinations linking the stroke parameters (“task constraint” strategy) should be performed at any velocity of the race spectrum. The SR-t relationship that supports the CSR concept could then represent a very useful tool for coaches.

CONCLUSION
The actual knowledge on the application of the CV concept seems sufficient to underlie its interests for training. The d-t relationship is a useful tool for setting training intensities, monitoring training effects, and predicting performances. However, “luckily” for researchers, further research is required to confirm its meaningfulness in swimming (responses at and above CV) and usefulness for training (among all, effects of training at intensities around CV, effects of training on the d-t relationship, kicking vs full stroke CV, prediction of performance). Almost all the studies conducted on the CV have been conducted on trained swimmers whose 400-m performance ranged from 72-84% of the world record. Published data on elite international swimmers will help to create strong performance indicators. More work on the Critical Stroke Rate concept is needed that incorporates an input from coaching, biomechanics, motor control, and physiology.
REFERENCES


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