Blood Lactate Diagnostics in Exercise Testing and Training

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A link between lactate and muscular exercise was seen already more than 200 years ago. The blood lactate concentration (BLC) is sensitive to changes in exercise intensity and duration. Multiple BLC threshold concepts define different points on the BLC power curve during various tests with increasing power (INCP). The INCP test results are affected by the increase in power over time. The maximal lactate steady state (MLSS) is measured during a series of prolonged constant power (CP) tests. It detects the highest aerobic power without metabolic energy from continuing net lactate production, which is usually sustainable for 30 to 60 min. BLC threshold and MLSS power are highly correlated with the maximum aerobic power and athletic endurance performance. The idea that training at threshold intensity is particularly effective has no evidence. Three BLC-orientated intensity domains have been established: (1) training up to an intensity at which the BLC clearly exceeds resting BLC, light- and moderate-intensity training focusing on active regeneration or high-volume endurance training (Intensity < Threshold); (2) heavy endurance training at work rates up to MLSS intensity (Threshold ≤ Intensity ≤ MLSS); and (3) severe exercise intensity training between MLSS and maximum oxygen uptake intensity mostly organized as interval and tempo work (Intensity > MLSS). High-performance endurance athletes combining very high training volume with high aerobic power dedicate 70 to 90% of their training to intensity domain 1 (Intensity < Threshold) in order to keep glycogen homeostasis within sustainable limits.

Keywords: lactate threshold, maximal lactate steady state, training, intensity, volume

The chemical basics of lactate diagnostics go back for more than 200 years. The start was possibly in Stralsund, a Hanse town on the German Baltic sea. As early as 1780, the Swedish pharmacist Carl Wilhelm Scheele discovered lactate in sour milk and named it mjölksyra (milk acid). Twenty eight years later, Jöns Jakob Berzelius described lactate in extracts from muscles of hunted stags and linked it with muscular exercise.1 During the subsequent 50 years, Berzelius’s observations were confirmed and extended by Justus von Liebig, who found that lactate

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is always present in dead muscle tissue,\(^2\) and by Emil Heinrich du Bois-Reymond, who observed the effect of lactate on muscle contraction.\(^3\)

In 1891, the concept of tissue hypoxia as a cause of lactate formation was first put forward by Arkai and Zillessen.\(^4,5\) Tissue ischemia still serves as a highly effective way to activate glycolysis and achieve high lactate concentrations.\(^6\) However, elevated lactate levels do not indicate ischemia per se. Any steady state or decrease of the blood lactate concentration (BLC) as frequently observed during prolonged constant power,\(^7\)–\(^11\) irrespective of how much the BLC is elevated above resting levels, is consistent with continuous lactate production under fully aerobic conditions.\(^12\)–\(^14\)

As early as at the beginning of the last century, a systematic stream of well-coordinated in vitro and in vivo experiments by Archibald Vivian Hill and Otto Fritz Meyerhof led to the first consistent and still widely accepted theory describing muscular metabolism as an open thermodynamic system\(^15\) with lactate production and respiration as integral factors of metabolic energy production.\(^16\) In 1922, Hill and Meyerhof were awarded the still only Nobel Prize crediting exercise physiological/biochemical research. Their work laid the foundation also for subsequent research on lactate as substrate of aerobic metabolism based on intra- and intercell and intertissue shuttle processes, including lactate as substitute for glucose as fuel for oxidation in the brain during exercise.\(^8,12,13,17\)–\(^23\)

Recent studies discussed lactate as an indicator of the activation of the use of carbohydrate as fuel for aerobic metabolism,\(^24\) and suggested oxygen radical generation by metabolic stress-induced increases in lactate and mitochondrial oxygen uptake as factor of structural impairment of cellular integrity\(^25\) and as transcriptional activators and signals of adaptive cell response.\(^14\)

Experimental basics of most current testing protocols have already been seeded during the third decade of the last century by investigators like Ole Bang, who carefully described and analyzed BLC during and after incremental (INCP), short-term high-intensity (STHIP), and prolonged constant power (CP) tests.\(^7\) Clear experimental evidence that lactate production is possible even with no increase in lactate, and that aerobic skeletal muscle metabolism may be regarded as the main factor of lactate removal during exercise was provided by Hermansen and Stensvold.\(^8\)

Subsequently, the development of an enzymatic-photometric micromethod to analyze lactate reduced the required volume of specimen to 20 µL of capillary blood usually taken from the fingertip or the ear lobe.\(^26\) This new method was feasible for BLC measurements under laboratory and also field conditions. This method, however, is now being almost replaced by less manual work-intensive enzymatic-amperometric and microphotometric techniques.\(^27\) The fact that the BLC shows specific responses to INCP, STHIP, and CP tests\(^7,8\) led to a still lasting boom in lactate measurements in exercise physiology and sports medicine. Consequently, nowadays blood lactate diagnostics serves as standard element of exercise testing and prescription in top-class endurance athletes but also of numerous commercial leisure exercise programs.

Testing

The BLC discriminates the metabolic response to exercise intensity and duration clearly during INCP and CP tests. The possibly most common endurance testing procedure is the INCP combined with the analysis of changes in BLC associated
with the increase in power. Usually INCP tests start at a power reflecting moderate exercise intensity. The exercise intensity is subsequently increased by given increments at given times. Over a range of low power increments, the BLC remains more or less at resting level before it increases slowly but progressively during subsequent steps in power (Figure 1).

**Figure 1** — Example of BLC during INCP; the BLC does not increase during increasing power up to an intensity of 48%; at 4 mmol·L⁻¹ exercise intensity is 66%, which is lower than the MLSS intensity of 83% of maximum power at test termination.

Lactate thresholds are generally accepted performance indicators. The first BLC-based threshold concept termed the *aerobic-anaerobic threshold*²⁸ detected the power at a BLC of 4.0 mmol·L⁻¹ during an INCP test with relatively long lasting stages of 5 min at minimum. This threshold, also termed the 4 mmol·L⁻¹ threshold, was based upon empirical observations that long lasting constant exercise was sustainable if the BLC stabilized after an initial increase indicating equilibrium between lactate appearance and elimination (Figure 2). A constant BLC indicates that the rate of glycolytic lactate generation is similar to its use as fuel for the aerobic metabolism. A decrease in BLC appears if more pyruvate and lactate are aerobically consumed than generated via anaerobic glycolysis. If the rate of glycolytic lactate generation exceeds the corresponding rate of aerobic lactate utilization, the resulting net lactate accumulation and increase in the BLC indicate a demand of anaerobic metabolic energy. During prolonged running exercise, a constant BLC was frequently seen above BLC baseline but rarely above 4.0 mmol·L⁻¹.²⁸

Shortly after Mader et al.²⁸ had published their threshold idea, an excessive number of other threshold concepts were put forward and this process is still ongoing. Due to this “threshold inflation,” it is nowadays almost impossible to verify the correct number of different threshold concepts published internationally. However,
most threshold concepts reflect just slight variations of procedures developed in the 1970s and 1980s.29–43

The idea of the aerobic-anaerobic threshold28 was that it may detect an exercise intensity at or close to the highest prolonged CP at which, after an initial increase, a constant BLC is observed. The intention to verify this idea led to the concept of the maximal lactate steady state (MLSS).10,44 The MLSS is measured during a series of prolonged CP tests and defines an exercise intensity that is usually sustainable for 30 to 60 min.45,46 It detects the highest aerobic power without metabolic energy from continuing net lactate production. This MLSS power is highly correlated with the maximum aerobic power. The between-subject variability of the MLSS is rather high and the MLSS is rarely found at a BLC of 4 mmol·L⁻¹. MLSS values between 1.9 and 7.5 mmol·L⁻¹ have been reported, which corresponded to exercise intensities between 54 and 83% of the maximum power measured during INCP testing. Surprisingly, MLSS, and MLSS intensity are independent of maximum power.47 There is evidence that the MLSS differs between different sports even if performed by the same athlete.48,49 Consequently, depending on the individual but also on testing conditions, the MLSS may reflect a BLC close to that typically found at rest or at a higher BLC, which may be significantly beyond 4 mmol·L⁻¹ (Figure 2). Under selected conditions, the average MLSS power may be close or similar to the power corresponding to a specific BLC threshold measured during a selected INCP testing program. However, even then the preciseness of individual MLSS power predictions via INCP testing remains moderate. Therefore, threshold determinations are likely to under- or overestimate individual MLSS power.10,44,48,50

Obviously differently defined thresholds determine different points on the BLC power curve. These points reflect either (a) selected BLC values, (b) defined increases in BLC above baseline or (c) specific changes in the steepness of the BLC power curve or (d) combinations of BLC measurements during INCP testing, at INCP test termination and during recovery.30,31,51 Thresholds detecting the power
at which the BLC increases above resting BLC and the MLSS indicate a range of exercise intensities that require a significant increase in the glycolytic rate to fuel aerobic pyruvate utilization. However, this increase in BLC during the initial phase of steady-state exercise does not indicate anaerobic metabolism. The corresponding dynamic steady-state BLC response is functionally identical to the pharmacokinetic principle that explains an increase of a drug in the blood when applied via a constant flow infuser and metabolized at the rate of infusion. Consequently, the analysis of the BLC response during INCP and CP discriminates between three intensity domains reflecting three qualitatively different metabolic situations: (1) intensities that do not require an increase in the glycolytic rate that increases the BLC above resting BLC (Intensity < Threshold), (2) intensities causing an increase in the glycolytic rate that leads to a BLC steady state higher than resting BLC, which is matched by the rate of aerobic pyruvate utilization and therefore an aerobic metabolic condition (Threshold ≤ Intensity ≤ MLSS), and (3) intensities that require a glycolytic rate that cannot be matched by aerobic pyruvate combustion indicating the demand of anaerobic glycolytic energy (Intensity > MLSS) (Figure 2).

From a practical point of view, the direct determination of the MLSS is no real option for regular routine performance testing. Direct determination of the MLSS requires three to seven different CP tests of sufficient duration all conducted at different days with sufficient recovery periods in between. The duration of MLSS tests should be 30 min or longer because the time required to establish a BLC steady state increases if the steady state of the BLC is increased. A MLSS of about 7 mmol·L⁻¹ may require approximately 15 to 20 min until a steady state is established. This is hardly compatible with normal training routines and is incompatible with economical workflow of a performance testing service unit. Although discriminating well between steady-state and non-steady-state conditions, attempts with two tests only, an INCP test plus a second INCP test with very few but long-lasting stages (Figure 3 and 4) were not fully convincing in detecting MLSS power. Therefore, threshold testing will keep its value for endurance testing just by clear definition of how a specifically defined point on the BLC power curve can be found.

Any point on the BLC power curve as specified by current threshold concepts is an objective test interpretation which does not require maximum effort of the tested individual toward the end of the INCP. It is therefore motivation independent and also less stressful than testing other endurance indicators requiring maximum effort. However, each specific threshold concept detects its own point on the BLC power curve. Depending on the specific threshold concept, these may reflect exercise intensities close to baseline BLC or higher. There is no convincing evidence that any concept is better than another. Most thresholds are well correlated with other threshold concepts, and more importantly with performances in real and simulated competition in various endurance events. However, those threshold concepts corresponding to higher BLC values tend to provide slightly higher coefficients of correlation with nontreshold measures of endurance. The latter is explained by the more or less exponential shape of the BLC to power relationship during INCP. Threshold concepts detecting the power which causes an increase in BLC above baseline analyze the flat part of the BLC power curve. Here small variations in BLC are associated with substantial changes in power. The variability of modern lactate analyzers is low with ~2% at BLC below 2 mmol·L⁻¹, ~1% at BLC 2 to 6 mmol·L⁻¹ and ~1.5% if repetitive analyses of the same specimen cover a range of
Figure 3 — BLC during INCP. A: not specifically trained subject (maximum oxygen uptake mL·kg\(^{-1}\)·min\(^{-1}\)). B: internationally successful endurance athlete (maximum oxygen uptake 77 mL·kg\(^{-1}\)·min\(^{-1}\)).

Figure 4 — BLC during three-step INCP test with 12 min stage duration. A: not specifically trained subject. B: internationally successful endurance athlete.
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BLC between 0.6 and 11.7 mmol \cdot L^{-1}.\textsuperscript{27} However, this does not include the variability of repeated blood sampling. The combined variability of blood sampling and analysis is in the magnitude of 3 to 7%. Analyzing the steeper part of the BLC power curve reduces the effect of this variability on power predictions.

The identical threshold concept will provide different results if the INCP test varies in terms of increase in power over time.\textsuperscript{29,50,52,67} A steeper increase in power over time shifts the BLC power curve to the right, indicating an effectively nonexistent improvement in aerobic fitness. Therefore, it may lead to confusion and inappropriate conclusions about testing results if it is not clearly documented which specific threshold concept is used in combination with which testing program. However, as long as the identical threshold concept is used under identical testing conditions, this is a minor issue for cross-sectional or longitudinal assessments of changes in the endurance capacity.

Identical testing conditions include also the identical setup of handlebars and saddle of regularly calibrated cycle ergometers and identical treadmills used at identical inclinations. These factors affect the biomechanical efficiency and therefore the shape of the BLC power curve.\textsuperscript{29,52} In selected buildings even the position of a treadmill in the laboratory may affect running economy due to modified resonance oscillations of floor and building. Environmental factors get even more important under field conditions. The BLC power curve is highly sensitive to running surfaces,\textsuperscript{52} temperature,\textsuperscript{68–70} altitude, and timing of testing at altitude.\textsuperscript{71}

A further pitfall for comparing field and laboratory testing is that running tests on treadmills include given increments in running velocity after constant periods of running, which results in a linear increase in speed over time. Contrary to the latter, field running tests are mostly designed as numerous constant distances and running velocity is increased by shortening the time set for each subsequent identical distance. Compared with treadmill and ergometer testing in the laboratory, the decreasing duration of, for example, running or cycling at subsequent increased velocities over a given distance, shifts the BLC power curve to the right under field conditions. Furthermore, high-speed events like cycling and speed skating require test interruptions for blood sampling, which include relative long deceleration and acceleration periods before and after BLC sampling, which affect the power profile of a test and therefore the BLC–speed relationship.\textsuperscript{48,52,72}

Training

Exercise testing should ideally transfer directly into training. Consequently, the idea that a lactate threshold may identify a clearly defined metabolic state made it tempting to utilize a point on the BLC power curve as orientation for training advice.\textsuperscript{28} The original idea was that a running speed below the 4 mmol \cdot L^{-1} threshold intensity would be appropriate for endurance training covering distances between 5 and 8 km. Distances between 3 and 5 km should reflect threshold intensity, and highly intensive running training requires running speeds above threshold intensity.\textsuperscript{28} How this led to proposals that training at threshold intensity might be particularly effective remains unclear. Very early anecdotal evidence suggested that top athletes did not respond favorably to substantial training volumes at threshold intensity. This led to speculations that threshold BLC may decrease with increasing endurance, which was one reason for boosting the search for individual threshold concepts particularly
in the late 70s and early 80s. The subsequent inflation of the number of different threshold concepts made the term threshold-orientated training even more confusing.

Selected studies on moderately trained, untrained or deconditioned subjects described that threshold training works. However, it remains unclear whether threshold intensity really matters in untrained subjects. In untrained subjects and recreational athletes also various other training programs lasting between 2 and 12 weeks were comparably successful as long as the training generated additional but also sustainable regular metabolic demand. The supposedly rather blunt consideration that endurance training works as long as the mix in exercise intensities accumulates substantial but sustainable metabolic demand irrespective of threshold intensities may get credibility by the fact that successful endurance athletes do not spend much effort on threshold training. Depending on seasonal variations, top athletes competing in middle and long distance events train 70 to 90% of their endurance training at intensities corresponding to BLCs below 2 mmol·L⁻¹. Also, the remaining training includes more effort at intensities corresponding to BLCs above 6 mmol·L⁻¹, which is likely to be higher than usually measured thresholds.

Based on these observations, a number of BLC-oriented endurance training zones have been developed. They basically mirror the above-mentioned three BLC-related intensity domains: (1) training up to an intensity at which the BLC clearly exceeds resting BLC, equivalent to light and moderate training focusing on active regeneration or high-volume endurance work mostly lasting between 1 and 6 h (Intensity < Threshold); (2) heavy endurance training at work rates supposedly up to MLSS intensity lasting 30 to 90 min (Threshold ≤ Intensity ≤ MLSS); and (3) severe exercise intensity training between MLSS and maximum oxygen uptake intensity organized as interval and tempo work normally lasting up to 30 min (Intensity > MLSS). Interestingly, the volume of training spent on domain 2 is rather low even compared with that of domain.

Studies that tried to intensify the training in athletes by increasing the training volume at threshold intensity combined with a reduction of hours spent at intensities near resting BLC did not report any favorable and some reported even detrimental effects compared with more low intensity training. The fact that selected subjects already hit MLSS intensity at BLC levels of around 2 mmol·L⁻¹ may partly explain why some do not tolerate substantial training volumes at intensities corresponding to BLC levels significantly higher than 2 mmol·L⁻¹. It is possibly also reasonable to speculate that the high between-subject variability of the MLSS may explain why in highly trained endurance athletes and also in less endurance trained but physically active individuals the postexercise autonomic response discriminated between training below and above threshold intensity independent of endurance capacity and individual training volume, but not between training below or above MLSS intensity. However, this does not explain why untrained subjects and recreational athletes seem to tolerate these higher training intensities better than top athletes. Nevertheless, the above-mentioned training studies suggest that identical BLC-oriented intensity domains, such as (1) Intensity < Threshold, (2) Threshold ≤ Intensity ≤ MLSS, and (3) Intensity > MLSS, have different metabolic meanings and adaptive consequences in untrained and highly endurance trained individuals.

The test results displayed in Figure 3 present BLC acute responses as frequently observed during INCP tests with untrained and highly endurance trained individuals. In untrained subject A (maximum oxygen uptake: 48 mL·kg⁻¹·min⁻¹), the BLC
increased during the first and with each subsequent increment in power. Therefore, intensity domain 1 (Intensity < Threshold) could not be clearly identified. In highly trained athlete B (maximum oxygen uptake: 77 mL·kg\(^{-1}\)·min\(^{-1}\)), BLC increased during the initial stage but decreased at the subsequent stage. Above 200 W, the BLC clearly increased with every increase in power. In both individuals, the MLSS power of 160 and 305 W, respectively, was near a power at 4 mmol·L\(^{-1}\) corresponding to 63 and 69\% of maximum oxygen uptake in subjects A and B. Subject A terminated a CP test at 150 W after 55 min whereas athlete B was able to exercise at 295 W for more than an hour. As expected, both A and B terminated a three-step test with 12-min stages prematurely at a power higher than MLSS intensity (Figure 4). In spite of the fact that MLSS power and maximum power were 90\% and 67\% higher in athlete B than in athlete A, the BLC to exercise intensity (% of maximum oxygen uptake) relationship was very similar and did not discriminate convincingly between untrained and highly trained individuals. Both show a similar pattern of intensity-related increases in BLC during INCP; both show similar BLC responses at similar exercise intensities between resting BLC and MLSS; and both terminate exercise above MLSS intensity rather quickly (Figure 3 and 4). Neither a specific point on the BLC power curve nor the time to exhaustion at power slightly below and above MLSS or the corresponding BLC provide a clue why untrained subjects and recreational athletes seem to tolerate training at intensities between threshold and MLSS better than high-performance athletes.

However, the highly endurance trained athlete B obviously performed at higher power than the untrained individual A. Therefore, the test results of subjects A and B reflect greatly different metabolic demands at similar intensities related to BLC-oriented intensity domains. Estimation of the relative pyruvate combustion based on indirect calorimetry during INCP\(^{24,96}\) reveals that subject A oxidizes approximately 30 mmol·min\(^{-1}\) of pyruvate at MLSS power of 160 W combined with a maximum pyruvate combustion rate of approximately 53 mmol·min\(^{-1}\) at 270 W at test termination (Figure 5A). This is substantially less than athlete B. With approximately 29 mmol·min\(^{-1}\), athlete B already matches the carbohydrate combustion of subject A at the intensity where the BLC started to increase above resting level. The corresponding power of 200 W was 25\% higher than the MLSS power of subject A, indicating that at the same carbohydrate use athlete B covered only 73\% of the total metabolic rate from carbohydrate whereas subject A relied to 95\% on carbohydrate oxidation (Figure 5B). At MLSS power of 305 W, athlete B matched the carbohydrate demand of 53 mmol·min\(^{-1}\) (91\% carbohydrate oxidation) seen in subject A at maximum power (Figure 5B). At MLSS intensity, the carbohydrate demand of B is approximately 75\% higher than that of A although both had a fairly similar BLC response at MLSS intensity during INCP and CP tests (Figure 3 and 4).

Recreational athletes usually train three to five times weekly, equivalent to 3 to 10 h/wk. Ambitious programs for beginners comprise three to four training sessions per week accumulating 1 to 4 h/wk.\(^77\) This is significantly less than high performance endurance athletes may train. Most top endurance athletes train 15 to 20 h/wk but selected endurance events seem to require up to 30 h of training and up to 12 training sessions per week.\(^91\) The combination of substantial differences in metabolic demand at given exercise intensity and training volume between untrained, recreational, and high-performance athletes seems to provide the clue for different adaptive responses to training at given BLC-related exercise intensities.
Figure 5 — Glycolytic rate, rate of aerobic pyruvate and fatty acid combustion as a function of cycling power. A: not specifically trained subject. B: internationally successful endurance athlete.
During 20 min exercise at 150 W (60% VO$_{2}$max, 4.0 mmol·L$^{-1}$), which is slightly below MLSS intensity, subject A would reduce his muscle glycogen by approximately 54 g based on a fuel mix of 94% carbohydrate (CHO) and 6% fatty acid oxidation (FAO). This is equivalent to a decrease of muscle glycogen of 13% in a well-nourished untrained 75 kg male. Increasing the training volume to 1 h on 4 d/wk would be a hard training regime for this subject but still without any risk of accumulative glycogen depletion at a normal diet (Figure 6).

**Figure 6** — BLC and daily cycling distance as function of training hours per day; training BLC levels higher than indicated by the dotted lines A and B or cycling distances higher than solid lines A and B would cause accumulated unsustainable glycogen depletion. A: not specifically trained subject—metabolic demand is too low to deplete glycogen stores unsustainably, irrespectively of during 4 h training per week. B: internationally successful endurance athlete—metabolic demand is so high that 10 to 15 h of training at BLC levels between 2 and 4 mmol·L$^{-1}$ is a risk of accumulated glycogen depletion.

Under the assumption that MLSS power is sustainable for up to approximately 1 h of exercise, 15 h of training at MLSS intensity is hardly possible. However, neither recreational nor top athletes train continuously at the same intensity. For recreational athletes, a threshold-oriented training regimen had been proposed comprising 46% training in intensity domain 1 (Intensity < Threshold), 35% in domain 2 (Threshold ≤ Intensity ≤ MLSS), and 19% in domain 3 (Intensity > MLSS). Reducing the training of top athlete B from 15 to 10 h/wk, a training volume equivalent to that of a very ambitious recreational athlete, could result in 4.5 h at 150 W (37% VO$_{2}$max, 1.8 mmol·L$^{-1}$, 66% CHO, 34% FAO), 3.5 h at 250 W (58% VO$_{2}$max, 3.0 mmol·L$^{-1}$, 84% CHO, 16% FAO) and 2 h at 400 W (90% VO$_{2}$max, > 7.0 mmol·L$^{-1}$, 98% CHO, 2% FAO) with an accumulated training induced glycogen demand of 2.1 kg equivalent to 360 km of road cycling per week. Assuming a
fully recovered muscle glycogen content of 100 mmol·kg$^{-1}$ of wet muscle mass and five training sessions per week, approximately 78% of muscle glycogen needs to be refilled during and after every training day. The latter carbohydrate demand is high but still manageable.$^{98,99}$ Keeping the latter intensity profile and increasing the training volume by 50% to 15 h, the resulting 540 km of road cycling per week is still a relative low training volume for a top endurance athlete. However, this would extend the training-related glycogen demand to approximately 630 g per training day. This demand is only sustainable if the training is distributed over two training sessions per day separated by about 4 to 6 h, combined with a carefully designed nutritional program maximizing glycogen replenishment and/or substantial carbohydrate intake during the training session.$^{98,99}$ At the given intensity profile, any further increase in training volume would be likely to result in unsustainable accumulated glycogen depletion.

Although borderline in terms of sustainability, the latter training volume is still low for a top endurance athlete training 10 to 12 times per week.$^{92}$ However, the volume of training can only increase if the demand of glycogen is kept within sustainable limits. This is supported by convincing empiric evidence that top athletes dedicate approximately 70 to 90% of their training volume to the intensity domain 1 (Intensity < Threshold), although the distribution of the remaining training volume between intensity domain 2 (Threshold ≤ Intensity ≤ MLSS) and domain 3 (Intensity > MLSS) remains less clear. If the weekly training volume of 15 h is redesigned, for example, to an intensity profile of 80% in domain 1 (Intensity < Threshold), 5% in domain 2 (Threshold ≤ Intensity ≤ MLSS), and 15% in domain 3 (Intensity > MLSS), then the corresponding weekly glycogen demand decreases to 2.4 kg and is well sustainable even with seven to nine training sessions per week but combined with a reduction in the weekly cycling distance to 500 km. However, if the training volume is pushed to the sustainable limit, the latter intensity profile provides a reserve to increase training volume of athlete B to roughly 20 h and 650 km/wk. An increase of the training volume to approximately 30 h as seen in some training weeks of professional cyclists would require that athlete A limits cycling intensity to a BLC not higher than 1.5 mmol·L$^{-1}$ throughout the entire week. Under these relative unusual conditions, A could cycle almost 900 km per week (Figure 6).

**Conclusions**

The BLC is sensitive to changes in exercise intensity and duration. Multiple BLC threshold concepts define objectively testable but different points on the BLC power curve of various INCP test programs. The identical threshold concept will provide different results if the INCP test varies in terms of increase in power over time. Many BLC thresholds detect a point on the BLC power curve that is between the lowest power at which the BLC starts to increase above resting BLC and MLSS power. The MLSS is measured during a series of prolonged CP tests and detects the highest aerobic power without metabolic energy from continuing net lactate production. MLSS power is usually sustainable for 30 to 60 min. MLSS power is highly correlated with the maximum aerobic power, athletic endurance performance, and BLC thresholds. However, MLSS and MLSS intensity are highly variable and no threshold concept can predict MLSS power precisely. BLC thresholds are
useful for cross-sectional or longitudinal endurance assessments as long as the same threshold concept is used under identical testing conditions.

The idea that training at threshold intensity may be particularly effective is a myth, and without evidence. Three BLC-oriented intensity domains have been established: (1) training up to an intensity at which the BLC clearly exceeds resting BLC, equivalent to light and moderate training focusing on active regeneration or high-volume endurance work mostly lasting between 1 and 6 h (Intensity < Threshold); (2) heavy endurance training at work rates supposedly up to MLSS intensity lasting 30 to 90 min (Threshold ≤ Intensity ≤ MLSS); and (3) severe exercise intensity training between MLSS and maximum oxygen uptake intensity normally lasting up to 30 min (Intensity > MLSS). During short-term training interventions in untrained subjects and recreational subjects, a focus on intensity domain 2 (Threshold ≤ Intensity ≤ MLSS) was comparably as successful as various combinations of all three intensity domains. In high-performance endurance athletes, it is essential to link training intensity and volume in order to keep glycogen homeostasis within sustainable limits. The combination of very high training volume and high aerobic potential of top-performance endurance athletes reasons that 70 to 90% of their training is dedicated to intensity domain 1 (Intensity < Threshold). The remaining training is variably spent on domains 2 (Threshold ≤ Intensity ≤ MLSS) and 3 (Intensity > MLSS).

References


