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Blood Lactate Steady State during Interval Training: New Perspectives on Something Already Known

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ABSTRACT

International Journal of Exercise Science 17(2): 941-953, 2024. The purpose of this study was to confirm that blood lactate concentrations can be maintained at moderate to high steady state values during an entire interval training (IT) session (repetitions + rest). Forty-eight trained swimmers and track athletes performed four IT protocols consisting of 6-10 bouts between 1 and 3-min at ~5-10 mmol/L blood lactate concentrations with a passive recovery of 60 to 180-sec. Performance times were measured at every bout, while blood lactate concentrations and heart rate during recovery every other bout. One-way ANOVA was performed for comparisons and r-squared for the effect size (ES). Performance times were stable throughout each IT protocol (75 ± 8 and 77 ± 5-sec [swimmers and track athletes]; 67 ± 3-sec [swimmers]; 64 ± 3-sec [swimmers]; and 135 ± 6-sec [swimmers]). Despite some minor differences ($p<0.05$; ES, 0.28 to 0.37, large), blood lactate concentrations were maintained stable at moderate to high values during each IT protocol (5.85 ± 1.47 mmol/L; 5.64 ± 1.03 mmol/L; 9.29 ± 1.07 mmol/L; and 9.44 ± 1.12 mmol/L). HR decreased significantly from the beginning to the end of recovery ($p<0.05$; ES, 0.93 to 0.96, large). In conclusion, moderate to high blood lactate steady state concentrations can be sustained for ~20 to 60-min during an entire IT session (repetitions + rest) at a stable performance. This approach can optimize performance by stimulating the metabolic demands and the pace strategy during the middle section of endurance competitive events.

KEY WORDS: Interval exercise, endurance exercise, maximal lactate steady state, endurance performance

INTRODUCTION

Blood lactate (BLa) serves as a biomarker for proper physiological strain responses during exercise (9). BLa concentrations are the result of processes that produce and catabolize lactate contributing to its appearance and disappearance in blood, respectively (7), where greater exercise intensity results in greater increases in circulating lactate concentrations, because the

rate of lactate appearance is faster than the rate of disappearance (37). The maximal lactate steady state (MLSS) is the highest BLa concentration that can be maintained during prolonged sub-maximal constant workload (≤ 1 mmol/L increase after 10-min of exercise) (2), having a high variability between subjects and exercise modality (3), with MLSS concentrations ranging from 1.9 to 7.5 mmol/L (4). A typical methodological strategy of many endurance coaches and athletes to enhance exercise performance is interval training (IT) which involves repeated short to long bouts of high-intensity exercise (≥MLSS speed or power) interspersed with recovery periods of light exercise or rest (5). This method has proven to be successful in performing higher volumes of high-intensity training (26) compared to continuous high-intensity exercise which can only be tolerated for a limited time (25), resulting in a greater metabolic stress and potentially superior training adaptations.

Previous studies have reported higher external loads and BLa concentrations after discontinuous [5:1 exercise:rest ratio] (4.4 to 4.9 mmol/L) compared to continuous MLSS exercise protocols (3.7 to 4.1 mmol/L) (12,16), suggesting that higher BLa steady state levels can be achieved during high-intensity interval exercise. Indeed, in athletes sustained moderate (~5-6 mmol/L) to high (~10-11 mmol/L) BLa levels have been reported after IT bouts (11,38). However, these measurements were performed only at the beginning of the recovery period, leaving uncertainty as to whether they could be maintained throughout the whole recovery period. Although it can be assumed that BLa was maintained throughout the recovery periods (e.g. 1-3 min) of IT, there is currently no concrete evidence to support this assertion.

Many sports disciplines including swimming and running have a high glycolytic demand reaching post-competition BLa levels >6 mmol/L (17,42) which are higher than the traditional levels of MLSS attained by athletes. Furthermore, athletes typically compete in endurance races at a stable external load (i.e., speed) during the middle portion of the competition (31,41). This suggests that BLa levels are likely to remain constant during this section, although BLa may exhibit hyperbolic behavior in events >5-min at intensities >MLSS (4). Therefore, during training it is crucial to attain high BLa steady state concentrations (i.e., equal production and removal rates) (7) for prolonged periods and at a stable external load at values close to the demands of the competition, so these metabolic processes can be used optimally during official events. Inspired by this background, we developed a line of research based on the hypothesis that BLa can be sustained at moderate (5-7 mmol/L) to high (8-10 mmol/L) concentrations throughout repetition and recovery periods of different interval exercises with a total time of ~20 to 60-min.

METHODS

Participants

Forty-eight trained athletes (40 swimmers and 8 track athletes; 41 men and 7 women; mean ± SD: age 19.41 ± 4.53 years; body weight 70.88 ± 6.89 kg; height 179.02 ± 6.42 cm) volunteered to participate in at least one of the four studies (eighteen subjects participated in one but only one subject in all four). The number of athletes were selected according to their level of performance (at least national level by ranking) at the time of carrying out the present studies in the city of

Rosario, Santa Fe, Argentina. The national level athletes had at least 4 years of training and competition experience and had a weekly training volume of 14 to 20-h/week at the time of the IT interventions. All subjects were encouraged to avoid medications or nutritional supplements before each procedure. Training and nutrition were controlled 24 hours before the experimental trial. The study was performed in accordance with the Declaration of Helsinki along with the ethical standards of the International Journal of Exercise Science (29). All the athletes and their legal guardians were fully informed of the experimental procedures and gave their written informed consent before participating in the study.

Protocol

Before the exercise protocol, a hyperemic ointment (Finalgon® CPD Wärmecreme, A. Nattermann & Cie. GmbH, Frankfurt, Germany) was applied to the earlobe. Subsequently, a lancet puncture was applied and a BLa concentration sample (0.7 uL blood) based on whole blood measurement was analyzed by a portable meter (Lactate Plus, Nova Biomedical, Waltham, MA, USA). The meter was calibrated according to the manufacturer's recommendations. BLa values >10 mmol/L were corrected according to the equation [BLa = 3.997+0.628*Lactate Plus value] (27).

Heart rate (HR) was monitored using a non-water resistant telemetric device (Polar Electro Oy A1, Kempele, Finland) that provided data on a second-by-second basis. For track athletes, the devices were placed prior to the protocol; while for swimmers, the device was held by a trainer and strapped to the athlete immediately at the end of each interval and during the passive recovery (PR).

The subjects maintained their usual training load during the experimental periods. Study 1 was executed in one of the special preparation periods of the 2016 season. Studies 2 and 3 were carried out in the same period of the 2019 season. Finally, study 4 was developed in one of the general preparation periods of the 2020 season. BLa values between ~5-10 mmol/L during exercise are criteria for reaching maximum oxygen uptake ($\dot{V}O_{2max}$) or high fractions of it (11,38). In order to reach these intensities, exercise protocols consisted of 1-3 minutes high-intensity intervals at BLa concentrations within ~5-10 mmol/L at ~70-90% of best performance time over specific competition distance in the current season, with a PR of 60 to 180-sec. The interval lengths used in the present studies (i.e., >1-min) were based on (1) preliminary testing and (2) the lower metabolic stress imposed by short intervals (i.e., <1-min) at the same external workload (14). Regarding PR, we followed the recommendations for long intervals and recovery periods ≤3-min (10). In the swimming protocols, the performance pace times were adjusted by a collaborator, if required. Swimmers (studies 1-4) performed the exercise protocol in a usual 25-m swimming pool, while track athletes (study 1) performed it on a familiarized and calibrated motorized treadmill (Kip Machines Kr 320, Rosario, Santa Fe, Argentina) with a 1% gradient (22).

In study 1, ten trained swimmers (7 men and 3 women) and eight trained track athletes (4 men and 4 women) with an age range 15-23 yrs., respectively, were recruited. After a 15-min warm-

up, swimmers performed a stable high-intensity interval exercise consisting of 10 x 100-m [5 front crawl; 3 back stroke; 2 breast stroke] at BLa concentrations within 5-7 mmol/L (~80-85% of the best distance performance time), with 60-sec PR, while track athletes performed 10 x 400-m run at BLa concentrations within 5-7 mmol/L (~70-75% of the best distance performance time), with 60-sec PR. In bouts 2, 4, 6, 8, and 10, BLa was measured at the beginning (10-sec) and end (50-sec) of PR, while HR was measured at the beginning of PR. As HR at the end of PR was not measured, it was estimated as 80% of the HR measured at 10-seconds of PR, as reported previously (34,38) and subsequently confirmed in study 2.

In study 2, eleven male trained swimmers with an age range 16-38 yrs. were recruited. After a 15-min warm-up, swimmers performed a stable high-intensity interval exercise consisting of 10 x 100-m [front crawl] at BLa concentrations within 5-7 mmol/L (~80-85% of the best distance performance time), with 90-sec PR. The PR was increased with respect to study 1. At bouts 2, 4, 6, 8, and 10, BLa and HR were measured at the beginning (10-sec), middle (50 sec), and end (80-sec) of PR.

In study 3, ten male trained swimmers with an age range 16-38 yrs. were recruited. After a 15-min warm-up, swimmers performed a stable high-intensity interval exercise consisting of 6 x 100-m [front crawl] at BLa concentrations within 8-10 mmol/L (~85-90% of the best distance performance time), with 180-sec PR. Compared to study 1 and 2, swimming speed was increased to reach higher BLa values; and consequently, the PR was extended. At bouts 2, 4, and 6, BLa and HR were measured at the beginning (10-sec), middle (twice: 50 and 110-sec), and end (170-sec) of the PR.

In study 4, nine male trained swimmers with an age range 16-19 yrs. were recruited. After a 15-min warm-up, swimmers performed a stable high-intensity interval exercise consisting of 10 x 200-m [front crawl] at BLa concentrations within 8-10 mmol/L (~87-92% of the best distance performance time), with 180-sec PR. Compared to study 3, the relative and absolute volumes were extended with the purpose of analyzing the durability of high BLa values. At bouts 2, 4, 6, 8, and 10, BLa and HR were measured at the beginning (10-sec), middle (twice: 50 and 110-sec), and end (170-sec) of PR.

Statistical Analysis

Normal distribution of data was examined with the Shapiro-Wilk test. We performed a repeated measures analysis using a separate one-way ANOVA or Friedman test in combination with post hoc testing (Tukey´s or Dunn´s multiple comparison test) to compare performance times across all bouts (main factor); and the BLa and HR every two bouts (main factor), during each protocol. The level of significance was $p<0.05$ for all statistical analyses. Effect sizes (ES) were calculated in the repeated measures ANOVA using r-squared (r^2) and classified as small (0.01), medium (0.09), or large (0.25). Statistical analyses were performed with using GraphPad Prism software for Windows (v. 8.0.1 GraphPad Prism Software Inc, San Diego, CA, USA).

RESULTS

All data were normally distributed, except for the performance times of the swimmers (i.e., 10 x 100-m) from study 1 probably due to the different swimming strokes used. Data are presented as mean ± standard deviation (SD).

Performance times: The performance times were stable in each of the four IT protocols, except for repetition times 2 and 5 in study 4 which were different between each other ($p<0.05$) (Table 1). In study 1, the mean performance time of swimmers and track athletes were 75 ± 8-sec and 77 ± 5-sec, respectively. No differences in performance times were observed between men and women in swimming (73.68 ± 8.67-sec vs. 77.59 ± 8.71-sec; $p = 0.53$; r^2 ES, 0.05) and in running (75.60 ± 3.26-sec vs. 79.08 ± 5.97; $p = 0.35$; r^2 ES, 0.15). Meanwhile, male swimmers in studies 2, 3, and 4 had an average performance time of 67 ± 3-sec, 64 ± 3-sec, and 135 ± 6-sec, respectively.

Table 1. Performance times (seconds) of exercise protocols in studies 1 to 4, Mean ± SD.

Study	Modality		R1 (sec)	R2 (sec)	R3 (sec)	R4 (sec)	R5 (sec)	R6 (sec)	R7 (sec)	R8 (sec)	R9 (sec)	R10 (sec)
1	Swim	Mean	75.3	75.7	74.5	75.1	74.4	75.1	75.1	74.8	74.1	74.6
		SD	6.6	8.2	8.3	9.1	8.9	9.4	9.2	8.9	8.0	8.4
	Running	Mean	78.1	77.8	77.8	77.8	77.0	77.0	77.0	77.0	77.0	77.0
		SD	4.7	5.0	5.1	5.1	4.9	4.9	4.9	4.9	4.9	4.9
2	Swim	Mean	67.5	67.4	67.2	67.3	67.2	66.8	67.2	67.1	67.7	67.8
		SD	2.9	2.9	3.4	3.4	3.8	3.8	4.1	3.7	3.3	3.2
3	Swim	Mean	63.5	63.3	63.8	63.8	64.8	64.7				
		SD	2.8	2.9	3.9	3.3	4.0	4.0				
4	Swim	Mean	134.6	134.3*	134.8	134.9	136.1*	135.3	136.3	136.0	136.4	136.1
		SD	7.0	5.6	5.5	5.2	6.0	6.1	6.5	5.9	6.5	6.9

Abbreviations: R1, repetition 1; R2, repetition 2… R10, repetition 10; sec, seconds.
*p = 0.0380, R2 vs. R5 in study 4.
r^2 ES, 0.32 (large).

Study 1: The mean BLa concentration during the IT protocol was 5.85 ± 1.47 mmol/L. BLa concentrations remained similar and stable within ~1 mmol/L during the last ~15-min of exercise (repetition + rest) (Fig. 1a), ranging from of 4.97 to 7.15 mmol/L. However, some differences ($p<0.05$) in BLa concentrations were observed between the beginning of the PR after the second bout (5.05 ± 1.51 mmol/L) vs. the beginning and the end of the PR after the tenth bout (6.61 ± 1.10 mmol/L and 6.71 ± 1.07 mmol/L, respectively); and the end of the PR after the second bout (5.03 ± 1.80 mmol/L) and the beginning of PR after the sixth bout (5.75 ± 1.24 mmol/L) vs. the end of PR after the tenth bout (6.71 ± 1.07 mmol/L).

The mean HR during the IT protocol was 162 ± 20 bpm. HR reached peaks of 175 to 183 bpm at the end of the interval bouts and their values decreased significantly ($p<0.05$) at the end of the

PR during all the interval bouts (Fig. 1a). For further details, refer to the supplementary material (Table S1, Page 1).

Study 2: The mean BLa concentration throughout the IT protocol was 5.64 ± 1.03 mmol/L. No differences were observed between BLa concentrations throughout the entire exercise protocol (~26-min; repetition + rest) and although they tended to decrease towards the end of the PR, these were maintained stable within ~1 mmol/L (Fig. 1b), ranging from 4.60 to 7.04 mmol/L. The mean HR during the IT protocol was 139 ± 26 bpm. HR reached peaks of 168 to 173 bpm at the end of the interval bouts and their values decreased significantly ($p<0.05$) at the middle and the end of the PR during all the interval bouts (Fig. 1b). For further details, refer to the supplementary material (Table S2, Page 2-3).

Study 3: The mean BLa concentration during the IT protocol was 9.29 ± 1.07 mmol/L. BLa concentrations remained similar and stable within ~1 mmol/L during the last ~12-min of exercise (repetition + rest) (Fig. 1c), ranging from 8.61 to 10.40 mmol/L. However, some differences ($p<0.05$) in BLa concentrations were observed between the end of the PR after the second bout (8.21 ± 1.09 mmol/L) vs. the middle part of the PR after the second bout (9.06 ± 1.01 and 8.95 ± 1.03 mmol/L, respectively) and the beginning and middle part of the PR after the fourth bout (9.68 ± 0.73, 10.03 ± 0.83, and 9.95 ± 0.89 mmol/L, respectively). BLa concentrations were also different ($p<0.05$) at the end of the PR after the fourth bout (9.18 ± 0.77 mmol/L) vs. the middle part of the PR after the fourth bout (10.03 ± 0.83 and 9.95 ± 0.89 mmol/L, respectively).

The mean HR during the IT protocol was 134 ± 25 bpm. HR reached peaks of 167 to 174 bpm at the end of the interval bouts and their values decreased significantly ($p<0.05$) at the middle and end of the PR during all the interval bouts (Fig. 1c). For further details, refer to the supplementary material (Table S3, Page 4-5).

Study 4: The mean BLa concentration during the IT protocol was 9.44 ± 1.12 mmol/L. BLa concentrations remained similar and stable within ~1 mmol/L during the last ~40-min of exercise (repetition + rest) (Fig. 1d), ranging from 8.17 to 10.58 mmol/L. However, some differences ($p<0.05$) in BLa concentrations were observed between the end of the PR after the second (8.47 ± 1.19 mmol/L) vs. the beginning and the middle part of the PR after the second bout (9.36 ± 1.34, 9.30 ± 1.14, and 9.04 ± 1.26 mmol/L, respectively) and the middle part of the PR after the sixth bout (9.93 ± 1.06 mmol/L). BLa concentrations were also different ($p<0.05$) at the end of the PR after the fourth bout (9.32 ± 0.99 mmol/L) vs. the middle part of the PR after the fourth bout (10.04 ± 0.90 mmol/L), and at the end of the PR after the eighth bout (8.78 ± 1.19 mmol/L) vs. the beginning of the PR after the eighth bout (9.53 ± 1.24 mmol/L).

The mean HR during the IT protocol was 133 ± 25 bpm. HR reached peaks of 170 to 173 bpm at the end of the interval bouts and their values decreased significantly ($p<0.05$) at the middle and the end of the PR during all the interval bouts (Fig. 1d). For further details, refer to the supplementary material (Table S4, Page 6-9).

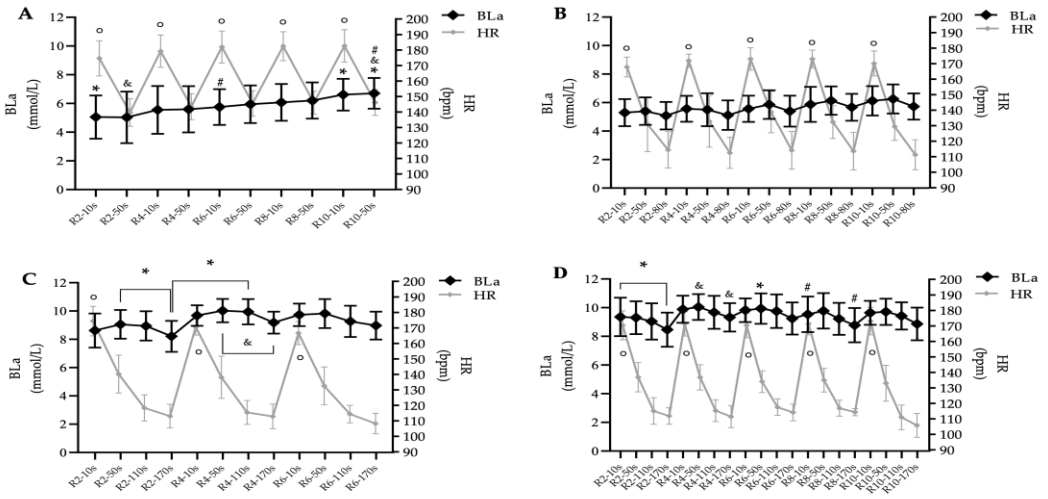

Figure 1. Blood lactate (BLa) and heart rate (HR) during passive recovery (PR). 10 x 100-m with 60-sec PR (a). 10 x 100-m with 90-sec PR (b). 6 x 100-m with 180-sec PR (c). 10 x 200-m with 180-sec PR (d). Refer to text for further details.
*p<0.05, BLa R2-10s vs. R10-10s and R10-50s; &p<0.05, BLa R2-50s vs. R10-50s; #p<0.05, BLa R6-10s vs. R10-50s; with an overall BLa r^2 ES, 0.29 (large); °p<0.05, HR 10-s vs. 50-s in R2 to R10; with an overall HR r^2 ES, 0.96 (large) (A).
°p<0.05, HR 10-s vs. 50-s and 80-s in R2 to R10; with an overall HR r^2 ES, 0.93 (large) (B).
*p<0.05, BLa R2-170s vs. R2-50s, R2-110s, R4-10s, R4-50s and R4-110s; &p<0.05, BLa R4-170s vs. R4-50s and R4-110s; with an overall BLa r^2 ES, 0.37 (large); °p<0.05, HR 10-s vs. 50-s, 110-s and 170-s in R2 to R6; with an overall HR r^2 ES, 0.93 (large) (C).
*p<0.05, BLa R2-170s vs. R2-10s, R2-50s, R2-110s and R6-50s; &p<0.05, BLa R4-50s vs. R4-170s; #p<0.05, BLa R8-10s vs. R8-170s; with an overall BLa r^2 ES, 0.28 (large); °p<0.05, HR 10-s vs. 50-s, 110-s and 170-s in R2 to R10; with an overall HR r^2 ES, 0.95 (large) (D).
Abbreviations: R2-10-s, passive recovery at 10-s after repetition 2; R2-50-s, passive recovery at 50-s after repetition 2; and so on.

DISCUSSION

By applying multiple measurements during the intervals and rest periods, to our knowledge, this is the first study to report BLa steady state levels throughout an entire stable IT session (repetitions + rest). Indeed, BLa concentrations were sustained, overall within ~1 mmol/L, at moderate to high values – between ~5-10 mmol/L – for a total time of ~20 to 60-min.

Previous studies in endurance athletes have shown that BLa concentrations can reach moderate (~5-6 mmol/L) or high (~10-11 mmol/L) levels during long intervals (≥1-min recovery) for periods of time ranging between ~20 to 50 minutes (11,34,38). Moreover, in young swimmers BLa levels of ~5-6 (40) and ~8-9 mmol/L (1) have been reported during IT of ≤30-min at a stable speed with short recovery periods (≤40-sec). Even though it could be assumed that BLa steady

state levels were reached in the former studies, they either measured BLa immediately after one interval (11,38,40) or at the middle and/or end of the interval exercise protocol (1,34), leaving uncertainty on whether BLa can be sustained during the recovery periods and throughout the entire IT session. Prior evidence has shown that a 2-min recovery period after each interval optimize high-intensity long length IT performance (33). Therefore, it is important to maintain stable BLa levels during the recovery period to promote balanced BLa production and removal rates (7). As a result, the strength of our findings is not only reporting similar or higher BLa concentrations (up to 10 mmol/L) than previous studies, but also to confirm that these values can be maintained during an entire IT session for up to 60 minutes. However, it is important to highlight the high intra-individual variability of the BLa values measured in the present study (i.e., ~2 vs. ~1 mmol/L, respectively), which may be related to the ability to metabolize lactate at the individual level (8), or potential inaccuracies of portable lactate analyzers (up to 7%) (39). Despite this variability, the BLa values measured in the present study corresponded to high-intensity training zones typically used by middle-endurance athletes (i.e., 4-8 and 8-12 mmol/L) (19). Although evidence suggests that high-intensity continuous exercise at high BLa steady state concentrations (~9 mmol/L) can be sustained for longer periods (30-min) (20), these efforts are often associated with intensities that reach $\dot{V}O_{2max}$ and thus can only be tolerated for short continuous periods in athletes (<10-min) (25). Hence, these intensities are typically prescribed as IT to accumulate higher volumes of high-intensity training (26).

During continuous and incremental exercise, lactate appearance and disappearance rates (i.e., lactate turnover); can increase BLa levels up to 4-5 mmol/L (28) and to ~10 mmol/L (37), respectively. However, to our knowledge, it is unknown whether similar responses occur during IT. Lactate traverses cell membranes via monocarboxylate transporters (MCT). MCT1 is abundantly expressed in skeletal muscle oxidative fibers and the heart (6) and MCT4 in fast twitch muscle fibers (23). Previous evidence has shown that the activity of key enzymes linked to skeletal muscle lactate metabolism increase proportionally to exercise intensity (36). In addition, during 30-sec all-out intervals with 4-min PR, glycolytic metabolic intermediates were reported to be elevated up to 10-fold during the rest period (30). Hypothetically, our results could be explained by the high rates of lactate production during the exercise bouts and the high rates of lactate removal (major fate is oxidation during exercise; i.e., ~80%Ox (28)) throughout the PR, where lactate transport is facilitated by MCTs. Moreover, as the concentration of glycolytic metabolic intermediates are most likely elevated, potentially this would lead to further muscle lactate production and efflux into the blood. Finally, because with some protocols BLa tended to decrease at the end of the PR (Fig. 1 b-d) and in line with the lactate shuttle theory (8), we suggest that this stems from the uptake and oxidation of circulating lactate by other tissues (i.e., heart) and reuptake by working oxidative muscle. Future studies using muscle biopsies or radioisotopes must confirm this hypothesis.

Practical application: Many endurance competitive events lasting more than ~1.5 minutes request a dominant aerobic energy contribution (13,21,35), and a high glycolytic demand expressed by the high peak BLa concentrations observed in competitions, including swimming (~6 to 14 mmol/L) (42), track (~9 to 16 mmol/L) (17), cycling, and rowing (≥10 mmol/L) (18,32).

In these events, athletes typically adopt, in the middle section of competition, a competitive strategy of a stable external load (i.e., power; speed) (15,21,31,41), which most likely results in BLa steady state concentrations. Therefore, we propose that the IT protocols of the present study could lead to a specific stimulation of lactate production and removal rates, reproducing a similar metabolic environment (i.e., moderate to high BLa levels) (17,18,32,42) and pace strategy during the middle section (15,21,31,41) of endurance competitive events over a prolonged period of time.

In a practical way and based on the event's requirements (17), a 5000-meter specialist track athlete could apply eight sets of 800-meter stable performance interval bouts at high BLa steady state concentrations (8-10 mmol/L) with a 2-minute rest period between sets. By doing so, he/she may experience lower metabolic disturbances at the same or greater external load and possibly complete their final lap faster in their competitive event and, consequently, improve performance based on the relationship between middle laps with final time in competitions lasting more than ~1.5 minutes (31). Similar to our protocols, previous studies have reported that middle-distance runners during training typically use interval lengths of 1 to 4-min at BLa concentrations within 8-12 mmol/L with a 1 to 3-min recovery period (19). In addition, our approach could be applied in events lasting <1-min where the glycolytic demand is greater. Figure 2 shows preliminary test data of an elite kayaker training at his competition distance (200-m) at BLa concentrations of ~14 mmol/L during the last ~20-min (repetitions + rest). Finally, this approach could also be applied in team sports where the external load is alternated yet high BLa concentrations are reached. For example, in football (soccer) BLa peaks reached during the game can be ~8 mmol/L (24).

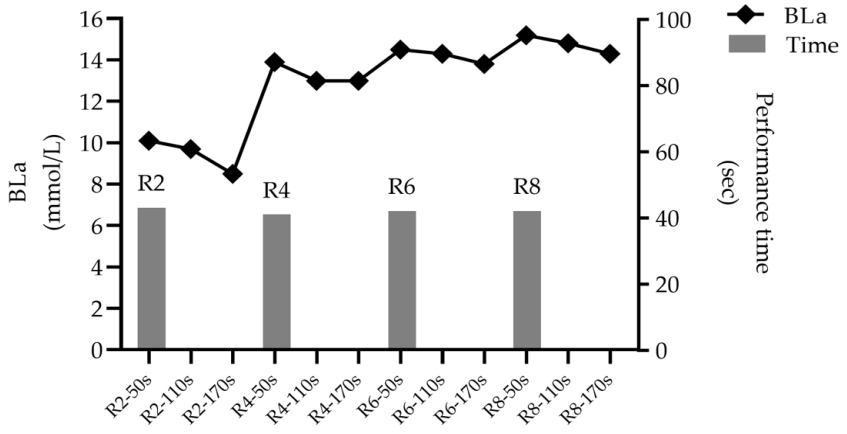

Figure 2. Blood lactate (BLa) and performance time in 8 x 200-m (~43-sec) with 180-sec passive recovery (PR) (~30-min; repetition + rest) from a kayak athlete. BLa values >10 mmol/L were corrected according to the equation of Mazza et al. (27).
Abbreviations: R2, repetition 2 and so on; R2-50-s, passive recovery at 50-s after repetition 2; R2-110-s, passive recovery at 110-s after repetition 2; and so on.

Limitations and future directions: One of the limitations of the present study was that we did not measure oxygen uptake ($\dot{V}O_2$) during the IT protocols. That being said, HR follows a similar pattern and is closely related to $\dot{V}O_2$ (11,38), so it can be assumed that the $\dot{V}O_2$ followed a similar pattern. Furthermore, our work was mainly developed in male trained swimmers and we understand that BLa concentrations at MLSS during continuous exercise may differ between modalities (3) and between sexes. Future studies should use different exercise modalities and participants of different performance levels to explore the individual response in more detail, as well as a larger number of females, to explore possible sex differences. Finally, given that the protocols were developed with a fixed absolute volume, we encourage that future research should apply protocols to exhaustion, accounting for durability and tolerance between subjects.

Conclusion: In conclusion, we demonstrate moderate to high BLa steady state concentrations during an entire IT session (repetitions + rest) at a stable performance for ~20 to 60-min. Based on these findings we confirm the possible assumptions that BLa is sustained during IT rest and propose this approach to stimulate moderate to high BLa steady state concentrations (i.e., high lactate production and removal rates) during prolonged high-intensity interval exercise and consequently optimize performance according to the metabolic needs and pace strategy adopt during middle section of endurance competitive events.

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REFERENCES

1. Almeida T, Pessôa Filho D, Espada M, Reis J, Sancassani A, Massini D, et al. Physiological responses during high-intensity interval training in young swimmers. Front Physiol 12: 662029, 2021.

2. Beneke R. Methodological aspects of maximal lactate steady state-implications for performance testing. Eur J Appl Physiol 89(1): 95–9, 2003.

3. Beneke R, Von Duvillard S. Determination of maximal lactate steady state response in selected sports events. Med Sci Sports Exerc 28(2): 241–6, 1996.

4. Beneke R, Hütler M, Leithäuser R. Maximal lactate-steady-state independent of performance. Med Sci Sports Exerc 32(6): 1135–9, 2000.

5. Billat V. Interval training for performance: A scientific and empirical practice. Special recommendations for middle- and long-distance running. Part I: Aerobic interval training. Sports Med 31(1): 13–31, 2001.

6. Bonen A. Lactate transporters (MCT proteins) in heart and skeletal muscles. Med Sci Sports Exerc 32(4): 778–89, 2000.

7. Brooks GA. Anaerobic threshold: Review of the concept and directions for future research. Med Sci Sports

Exerc 17(1): 22–34, 1985.

8. Brooks GA. The science and translation of lactate shuttle theory. Cell Metab 27(4): 757–85, 2018.

9. Brooks GA. The "Anaerobic Threshold" concept is not valid in physiology and medicine. Med Sci Sports Exerc 53(5): 1093–6, 2021.

10. Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle: Part I: Cardiopulmonary emphasis. Sports Med 43(5): 313–38, 2013.

11. Cipryan L, Tschakert G, Hofmann P. Acute and post-exercise physiological responses to high-intensity interval training in endurance and sprint athletes. J Sport Sci Med 16(2): 219–29, 2017.

12. Dittrich N, de Lucas R, Beneke R, Guglielmo L. Time to exhaustion at continuous and intermittent maximal lactate steady state during running exercise. Int J Sports Physiol Perform 9(5): 772–6, 2014.

13. Duffield R, Dawson B, Goodman C. Energy system contribution to 1500- and 3000-metre track running. J Sport Sci 23(10): 993–1002, 2005.

14. Festa R, Monsalves-Álvarez M, Cancino J, Jannas-Vela S. Prescription of high-intensity aerobic interval training based on oxygen uptake kinetics. Int J Sports Med 44(3): 159–68, 2023.

15. Garland SW. An analysis of the pacing strategy adopted by elite competitors in 2000 m rowing. Br J Sports Med 39(1): 39–42, 2005.

16. Grossl T, de Lucas RD, de Souza KM, Guglielmo LGA. Time to exhaustion at intermittent maximal lactate steady state is longer than continuous cycling exercise. Appl Physiol Nutr Metab 37(6): 1047–53, 2012.

17. Gupta S, Stanula A, Goswami A. Peak blood lactate concentration and its arrival time following different track running events in under-20 male track athletes. Int J Sports Physiol Perform 16(11): 1625–33, 2021.

18. Hartmann U, Mader A, Hollmann W. Heart rate and lactate during endurance training programs in rowing and its relation to the duration of exercise by top elite rowers. FISA Coach (11): 121–41, 1990.

19. Haugen T, Sandbakk Ø, Enoksen E, Seiler S, Tønnessen E. Crossing the golden training divide: The science and practice of training world-class 800- and 1500-m runners. Sports Med 51(9): 1835–54, 2021.

20. Jenkins DG, Qnigley BM. Blood lactate in trained cyclists during cycle ergometry at critical power. Eur J Appl Physiol Occup Physiol 61(3–4): 278–83, 1990.

21. Jeukendrup AE, Craig NP, Hawley JA. The bioenergetics of world class cycling. J Sci Med Sport 3(4): 414–33, 2000.

22. Jones AM, Doust JH. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. J Sports Sci 14(4): 321–7, 1996.

23. Kobayashi M. Fiber type-specific localization of monocarboxylate transporters mct1 and MCT4 in rat skeletal muscle. Kurume Med J 51(3–4): 253–61, 2004.

24. Krustrup P, Mohr M, Steensberg A, Bencke J, Klær M, Bangsbo J. Muscle and blood metabolites during a soccer game: Implications for sprint performance. Med Sci Sports Exerc 38(6): 1165–74, 2006.

25. Laursen P, Shing C, Jenkins D. Reproducibility of the cycling time to exhaustion at VO2peak in highly trained cyclists. Can J Appl Physiol 28(4): 605–15, 2003.

26. Laursen PB. Training for intense exercise performance: High-intensity or high-volume training? Scand J Med Sci Sport 20(SUPPL 2): 1–10, 2010.

27. Mazza JC, Festa RR, Cosolito P, Ruffo L, Prieto S, Gurovich AN. Comparison of whole blood lactate values between YSI 1500 Sports and Lactate Plus. Med Sci Sports Exerc 47(5S): 13–4, 2015.

28. Mazzeo RS, Brooks GA, Schoeller DA, Budinger TF. Disposal of blood [1-13C]lactate in humans during rest and exercise. J Appl Physiol 60(1): 232–41, 1986.

29. Navalta JW, Stone WJ, Lyons TS. Ethical issues relating to scientific discovery in exercise science. Int J Exerc Sci 12(1): 1–8, 2019.

30. Parolin ML, Chesley A, Matsos MP, Spriet LL, Jones NL, Heigenhauser GJF. Regulation of skeletal muscle glycogen phosphorylase and PDH during maximal intermittent exercise. Am J Physiol - Endocrinol Metab 277(5): 890–900, 1999.

31. Robertson E, Pyne D, Hopkins W, Anson J. Analysis of lap times in international swimming competitions. J Sport Sci 27(4): 387–95, 2009.

32. Schumacher Y, Mueller P. The 4000-m team pursuit cycling world record: Theoretical and practical aspects. Med Sci Sports Exerc 34(6): 1029–36, 2002.

33. Seiler S, Hetlelid KJ. The impact of rest duration on work intensity and RPE during interval training. Med Sci Sports Exerc 37(9): 1601–7, 2005.

34. Seiler S, Sjursen J. Effect of work duration on physiological and rating scale of perceived exertion responses during self-paced interval training. Scand J Med Sci Sport 14(5): 318–25, 2004.

35. Spencer MR, Gastin PB. Energy system contribution during 200- to 1500-m running in highly trained athletes. Med Sci Sports Exerc 33(1): 157–62, 2001.

36. Spriet LL, Howlett RA, Heigenhauser GJF. An enzymatic approach to lactate production in human skeletal muscle during exercise. Med Sci Sports Exerc 32(4): 756–63, 2000.

37. Stanley W, Gertz E, Wisneski J, Morris D, Neese R, Brooks G. Systemic lactate kinetics during graded exercise in man. Am J Physiol 249(6 Pt 1): E595-602, 1985.

38. Stepto NK, Martin DT, Fallon KE, Hawley JA. Metabolic demands of intense aerobic interval training in competitive cyclists. Med Sci Sports Exerc 33(2): 303–10, 2001.

39. Swart J, Jennings C. Use of blood lactate concentration as a marker of training status. South African J Sports Med 16(3): 1–5, 2004.

40. Toubekis AG, Vasilaki A, Douda H, Gourgoulis V, Tokmakidis S. Physiological responses during interval training at relative to critical velocity intensity in young swimmers. J Sci Med Sport 14(4): 363–8, 2011.

41. Tucker R, Lambert MI, Noakes TD. An analysis of pacing strategies during men's world-record performances in track athletics. Int J Sports Physiol Perform 1(3): 233–45, 2006.

42. Vescovi JD, Falenchuk O, Wells GD. Blood lactate concentration and clearance in elite swimmers during competition. Int J Sports Physiol Perform 6(1): 106–17, 2011.