Abstract  Over the past few decades, several studies have been conducted on the relationships between peak blood lactate concentration (PBLC) and exercise performance. However, it is still controversial whether PBLC has a correlation with exercise performance, and if it can be a reliable indicator for energy metabolism during short-term high-intensity exercise. Thus, the purpose of the present study is to establish a new reliable indicator. PBLC isn’t able to reflect individual differences in kinetics of post-exercise blood lactate concentration (e.g. different time point of PBLC). Thus, to reflect the individual differences, we focused on the rate of increase in post-exercise blood lactate concentration (RIBLC). Twenty-two male university track athletes were divided into a sprinter group (S: n = 14) and middle- to long-distance runner group (ML: n = 8). 400-m (meter) time trials and blood samplings were conducted to measure exercise performance (average running velocity) and blood lactate concentration. In the present study, PBLC had no significant correlations with average running velocity in both S and ML. The present study supports previous studies that reported no correlations between PBLC and exercise performance. In contrast, significant correlations between RIBLC and average running velocity were observed in both S and ML (r = 0.69, p < 0.001 and r = 0.93, p < 0.01, respectively). RIBLC was significantly higher in ML than S (p < 0.05). It is assumed that RIBLC indicates lactate transport capacity and plays an important role in 400-m sprinting. Based on these results, RIBLC could be a new indicator for energy metabolism during short-term high-intensity exercise.

Keywords  : lactate metabolism, short-term high-intensity exercise, measuring and evaluating method, sprint performance, monocarboxylate transporter

Introduction

Energy production from glycolysis has an important role in performing short-term high-intensity exercise\(^1\). Mainly because of acceleration of glycolysis, lactate production is increased during exercise\(^2,3\). Owing to evaluation of energy production from glycolysis, post-exercise blood lactate concentration has been measured in laboratories and in the field. It has been reported that post-exercise blood lactate concentration has a correlation with performance of short-term high-intensity exercise\(^4,5\). Therefore, post-exercise blood lactate concentration has often been used as an indicator of energy metabolism during short-term high-intensity exercise. However, some studies reported that there were no correlations between post-exercise blood lactate concentration and performance of short-term high-intensity exercise\(^6,7\). Therefore, it has been suggested that post-exercise blood lactate concentration is not always a reliable indicator for the ability of energy metabolism during short-term high-intensity exercise. According to the previous study, it was reported that the time points of peak blood lactate concentration (PBLC), after short periods of maximal treadmill running, varied among individuals\(^8\). Hence, it indicates that the kinetics of post-exercise blood lactate concentration differs among individuals. Individual differences (e.g. the time point of PBLC) may influence the reliability of the indicator. However, previous research related to PBLC did not consider individual differences.

Based on the “Lactate Shuttle Hypothesis”, lactate produced during exercise is transported via the circulatory system into mitochondria-enriched tissues, and then is fully oxidized by mitochondria to produce ATPs\(^9\). In other words, glycolysis not only provides energy to re-establish ATPs, but also distributes energy as a form of lactate among tissues within the whole body. When transporting lactate from working muscles into the circulatory system, a membrane transport protein called monocarboxylate transporter
transporter (MCT) 4 plays an important role\(^9\). David et al. (2009) reported that MCT4 protein levels of working muscle were strongly correlated with the performance of high intensity exercise in well-trained cyclists\(^10\). Therefore, it was assumed that MCT4 plays an important role in performing high intensity exercise.

A previous study reported the characteristics of skeletal muscle enzyme activities and fiber composition in athletes competing in different track events\(^11\). According to the previous study, sprint runners showed characteristics of higher glycolytic enzyme activities and distribution of fast-twitch fibers, whereas higher mitochondrial oxidative enzyme activities and distribution of slow-twitch fibers was observed in middle to long distance runners\(^11\). Dendrai et al. (2004) reported longer time to PBLC in sprint runners than endurance runners after 500-m maximal running, whereas PBLC was the same in both groups\(^12\). The other study also reported faster lactate transport in middle-distance runners than sprint runners after 1 min high-intensity running\(^9\). Therefore, it is considered that lactate metabolism and transportation may differ by individual training status (i.e., sprint trained or endurance trained).

The purpose of the present study was to establish a new indicator for energy metabolism during short-term high-intensity exercise. We focused on the individual differences in kinetics of post-exercise blood lactate concentration. Moreover, it may be important to transport lactate from working muscle into the circulatory system to distribute lactate as energy. Thus, we hypothesized that the rate of increase in post-exercise blood lactate concentration (RIBLC) could be a new indicator for energy metabolism correlating with performance of short-term high-intensity exercise. Furthermore, we also examined the differences between sprinters and middle- to long-distance runners.

**Materials and Methods**

**Subjects.** Twenty-two male university track athletes were divided into sprinter group (S: \(n = 14\)) and middle- to long-distance runner group (ML: \(n = 8\)). All subjects in S mainly competed in 400-m events, whereas all subjects in ML mainly competed in 800-m and 1500-m events. Physical characteristics and seasonal bests of each track event are shown in Table 1. All subjects had been engaged in regular track and field practice (about 4 times per week, 3 hours per session) for at least 2 years. The nature and risk of the study was fully explained to all subjects before obtaining written informed consent. This study was approved by the Research Ethics Committee at The University of Tokyo: No. 430-2.

**Performance tests.** All subjects performed 400-m time trials as performance tests. Preparing 400-m time trials, all subjects were instructed to do warm-up exercises the same way as they ordinarily did before a competition. To avoid the influence of different curvatures of different lanes, all tests were conducted on the fourth lane of an officially recognized all-weather type athletic track. Running times of the first 200-m (split time) and 400-m (goal time) were manually measured with a stopwatch. Test performance was expressed as average running velocity (m/s) of 400-m time trials. Blood lactate concentrations were measured by using a portable lactate analyzer (Lactate Pro 2, Arkray, Kyoto, Japan). Blood samples were collected from earlobes at 1 min before and 0.5, 1, 2, 3, 4, 5, 7 and 10 min after a time trial. After a given trial, subjects were instructed to take passive rest in the sitting position until the final blood sample collection.

**Data analysis.** Peak blood lactate concentration (PBLC) was defined as the highest value of post-exercise blood lactate concentration. The rate of increase in blood lactate concentration (RIBLC) was defined as the value calculated by dividing the amount of increase in blood lactate concentration from post (0.5 min) to “the plateau” by the time required to reach “the plateau”. If the amount of increase in blood lactate concentration between two consecutive time points was less than 1 mmol/l, the former time

<table>
<thead>
<tr>
<th>group</th>
<th>age (years)</th>
<th>height (m)</th>
<th>weight (kg)</th>
<th>seasonal best records (s)</th>
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<tr>
<td></td>
<td></td>
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<td></td>
<td>100-m</td>
</tr>
<tr>
<td>Sprinter (S, (n = 14))</td>
<td>20.7±0.2</td>
<td>1.75±0.02</td>
<td>63.9±1.6</td>
<td>11.6±0.1 (n=9)</td>
</tr>
<tr>
<td>Middle- to long-distance runner (ML, (n = 8))</td>
<td>20.4±0.5</td>
<td>1.73±0.03</td>
<td>59.0±1.6</td>
<td>none</td>
</tr>
</tbody>
</table>

All values are expressed as the mean ± standard error.
point was defined as the time point of plateau. Because the rate of increase in blood lactate concentration tended to be blunt near the time point of PBLC, we avoided using the PBLC and adopted the plateau to correctly evaluate the RIBLC. To evaluate the effects of pacing strategies during the time trials of each subject, we calculated the speed reduction rates by dividing the average running velocity during 200-m to 400-m of the time trials by the average running velocity during 0-m to 200-m of the time trials.

**Statistical analyses.** We used an unpaired t-test to determine differences in values between the two groups. To investigate the relationships between running velocity and PBLC, or running velocity and RIBLC, we used Pearson’s Correlation Coefficients. To investigate the differences in slopes and intercepts of regression equations, we used ANCOVA. All values are expressed as the mean ± standard error. Statistical significance was set at p < 0.05.

**Results**

Average running velocity was significantly higher in S than ML (7.55 ± 0.04 m/s and 7.18 ± 0.11 m/s, p < 0.01, respectively). Time courses of changes in pre- and post-exercise blood lactate concentrations of both S and ML are shown in Fig. 1A. In Fig 1B, time courses are shown of changes in pre- and post-exercise blood lactate concentrations of typical subjects whose RIBLC were 6.40 mmol/l/min (subject A) and 2.97 mmol/l/min (subject B). Average blood lactate concentrations at pre- and post-exercise were not significantly different in S and ML (Pre: 3.0 ± 0.3 mmol/l and 2.6 ± 0.3 mmol/l, Post: 6.8 ± 0.4 mmol/l and 8.0 ± 0.8 mmol/l, respectively). Average RIBLC was significantly higher in ML than S (4.61 ± 0.52 mmol/l/min and 3.69 ± 0.22 mmol/l/min, respectively, p < 0.05, Fig. 2A). No significant difference was observed in blood lactate concentration at the plateau time between S and ML (15.5 ± 0.84 mmol/l and 15.4 ± 0.67 mmol/l, respectively, Fig. 2B). On the contrary, the difference in time required to the plateau was marginally significant between S and ML (2.93 ± 0.22 min and 2.25 ± 0.34 min, respectively, p = 0.09, Fig. 2C). RIBLC was significantly correlated with the average running velocity of a 400-m time trial in both S and ML (2.93 ± 0.22 min and 2.25 ± 0.34 min, respectively, p = 0.09, Fig. 2C). RIBLC was significantly correlated with the average running velocity of a 400-m time trial in both S and ML (r = 0.69, p < 0.01 and r = 0.93, p < 0.001, respectively, Fig. 3A). No significant difference was observed in the slope of the primary regression equations of S and ML (Fig. 3A). A significant difference was observed in the intercepts of the primary regression equations of S and ML (p < 0.001, Fig. 3A). In contrast, average PBLC was not significantly different between S and ML (18.0 ± 0.8 mmol/l and 17.7 ± 0.5 mmol/l, respectively, Fig. 4A). Time required to PBLC was also not significantly different between S and ML (7.86 ± 1.30 min and 5.50 ± 1.07 min, respectively, Fig. 4B). Moreover, PBLC was not significantly correlated with the average running velocity of a 400-m time trial in both S and ML. Other variables including blood lactate concentration at post-exercise, amount of increase in blood lactate concentration between post-exercise and plateau or between post-exercise and PBLC. Also, time to plateau or time to PBLC were not significantly correlated with average running velocity of a 400-m time trial in both S and ML. The average speed reduction rate was not significantly different between S and ML (9.9 ± 1.0% and 9.8 ± 1.1%, respectively). There were no significant correlations between RIBLC and speed reduction rate in both S and ML.

![Fig. 1 Kinetics of blood lactate concentration before and after 400-m trial](image)

**A:** Kinetics of blood lactate concentration before and after 400-m trial shown as line graphs (S: dashed line, ML: solid line). There was no significant difference in blood lactate concentration at any time point between S and ML. **B:** Typical examples for kinetics of blood lactate concentration before and after 400-m trial shown as line graphs. “Subject A” whose RIBLC was 6.40 mmol/l/min was expressed as a dashed line, whereas “Subject B” whose RIBLC was 2.97 mmol/l/min was expressed as a solid line.
Fig. 2  RIBLC, blood lactate concentration at the plateau, and time to the plateau in S and ML after 400-m time trial
A: Significantly higher RIBLC was observed in ML compared to S.  B: No significant difference between S and ML was observed in blood lactate concentration at the plateau.  C: Time to the plateau of ML was marginally quicker than that of S (p = 0.09).
All values were expressed as the mean ± standard error.
*Significantly different from S (p < 0.05)

Fig. 3  Relationships between RIBLC and average running velocity, and between PBLC and average running velocity in S and ML
A: Significant correlations between RIBLC and average running velocity were observed in both S and ML (S: open circle and dashed line, p < 0.01; ML: closed circle and solid line, p < 0.001).  B: No significant correlation between PBLC and average running velocity was observed in either S or ML.

Fig. 4  PBLC and time to PBLC in S and ML after 400-m time trial
A: No significant difference between S and ML was observed in PBLC.  B: No significant difference between S and ML was observed in time to PBLC. All values were expressed as the mean ± standard error.
Discussion

Application possibilities of RIBLC as a new indicator.

In the present study, PBLC was not correlated with the average running velocity of a 400-m time trial (Fig. 3B). According to this result, PBLC might not be a reliable indicator for energy metabolism during short-term high-intensity exercise. It has sometimes been reported that PBLC has no correlation with the performance of short-term high-intensity exercise\(^6,7\). Our present study supports the results of these previous studies. In contrast, RIBLC was significantly correlated with the average running velocity of a 400-m time trial (Fig. 3A). However, rates of increase in blood lactate concentration, calculated using PBLC and time required to PBLC, were not significantly correlated with the average running velocity. Moreover, other variables including blood lactate concentration at post-exercise, amount of increase in blood lactate concentration between post-exercise and plateau or between post-exercise and PBLC, or time to plateau or time to PBLC did not correlate with the performance of short-term high-intensity exercise. These results suggest that RIBLC would be a new indicator for the ability of energy metabolism during short-term high-intensity exercise. It is also suggested that the rates of increase in blood lactate concentration calculated using PBLC and time required to PBLC or the other values are not useful indicators, which supports the value of RIBLC as an indicator. According to Fig. 1B, kinetics of post-exercise blood lactate concentration may vary among individuals. Therefore, to understand energy metabolism during short-term high-intensity exercise, it would be important to take account of individual differences in the kinetics of post-exercise blood lactate concentration. The relationships between average running velocity and RIBLC varied between the two groups (Fig. 3A). According to Fig. 3A, the slopes of primary regression equations were not different, but the intercepts were significantly different between the two groups. Therefore, it is considered that the primary regression equation of ML is shifted upwards compared to that of S, indicating higher lactate production and transport abilities of ML compared to S. By checking the areas of the correlation graph on which RIBLCs are plotted, it might be possible to project which track events are suitable for individuals. In addition, if RIBLC reflects lactate production and transport ability, there is a possibility that RIBLC might be useful for evaluation of the effects of training. In the present study, we did not conduct a training intervention. To clarify the usefulness of RIBLC for evaluation of the effects of training and promote greater understanding of energy metabolism during short-term high-intensity exercise, studies including a training intervention will be necessary.

Energy metabolism during short-term high-intensity exercise. The previous indicator, PBLC, possibly reflects the amount of lactate produced during exercise. However, the new indicator, RIBLC, might reflect how fast lactate would be transported from working muscles into the circulatory system. Based on the lactate shuttle hypothesis, lactate produced during exercise is transported via the circulatory system into mitochondria-enriched tissues, and then fully oxidized by mitochondria to produce ATPs\(^8,14\). According to the previous study, the aerobic energy contribution during 400-m sprinting was 43%, estimated by pulmonary oxygen consumption\(^1\). Therefore, large amounts of energy are produced by the aerobic energy pathway (i.e., mitochondrial oxidation). In addition, it was reported that anaerobic energy production mainly occurred during the early part of high-intensity exercise\(^15\), and the aerobic energy contribution became greater in the later part\(^16,17\). A previous study using Thoroughbred horses reported that muscle glycogen breakdown and lactate production mostly occurred in the first minute of 2 min high-intensity exercise\(^19\). It was also reported that 75%-80% of lactate produced during submaximal exercise was oxidized by mitochondria to provide energy\(^19\). Therefore, these results suggest that energy production by glycolysis and consequent lactate production mainly occur in the early part of high-intensity exercise; whereas in the later part, aerobic energy production plays a greater role in performing high-intensity exercise by oxidizing lactate produced during the former part. Taken together, this evidence and our results possibly suggest that individuals who had higher RIBLC had higher ability to distribute lactate as energy substrates among other tissues (especially slow-twitch muscle fibers and heart muscle) to re-establish ATPs and then performed better.

Monocarboxylate transporters and exercise performance.

Membrane transport proteins called monocarboxylate transporters (MCTs) play an important role in transporting lactate among tissues. MCT-isoform 4 (MCT4), which is abundantly located in fast-twitch muscles, mainly plays a role in the efflux of lactate out of the muscles\(^5\). In contrast, MCT-isoform 1 (MCT1), which is abundantly located in mitochondria-enriched tissues, mainly plays a role in the uptake of lactate into the tissues\(^9\). Therefore, there is a possibility that RIBLC reflects the content of MCT4 protein in working muscle. A previous study reported that the maximal rate of uptake of lactate into the muscle was much slower than that of efflux of lactate out of the muscle\(^9\). Therefore, it is considered that the content of MCT4 protein in working muscle might have a minor effect on RIBLC. Concerning training adaptations, low intensity exercise such as voluntary wheel running increased the MCT1 protein level, but not MCT4 in a mouse study\(^21\). However, high intensity exercise such as sprint interval training increases both MCT1 and MCT4 protein levels\(^12,23\). Moreover, previous studies using well-trained cyclists and Thoroughbred horses reported a strong correlation between MCT4 protein content and performance.
of high-intensity exercise\textsuperscript{10,24}. These results suggest that MCT4 may be closely related to metabolism during high-intensity exercise. MCT4 plays a role in distributing lactate as energy among other tissues, and possibly affects high-intensity exercise performance. Consequently, there is a possibility in the present study, that athletes who have higher skeletal muscle MCT4 protein content could transport lactate rapidly, and efficiently utilize lactate as an energy substrate, resulting in better exercise performance.

\textbf{Metabolic similarities and differences between sprinters and middle- to long-distance runners.} In the present study, there were no significant differences in PBLC (Fig. 4A), the time required to PBLC (Fig. 4B) and the blood lactate concentration at the time of the plateau (Fig. 2B) between groups. Because the maximal rate of lactate production is much greater than that of lactate oxidation, the same PBLC and blood lactate concentration of the plateau indicate that both S and ML group athletes produce almost the same amounts of lactate and energy to re-establish ATPs from glycolysis. This result may suggest that S athletes showed better exercise performance in spite of the same glycolytic energy production. This might be simply because S athletes have a higher economy of sprint running (i.e., mechanical efficiency) than those of ML. Moreover, S athletes ordinarily have higher sprint abilities (e.g., higher top speed) than ML athletes. The difference in energy production from phosphocreatine (PCr) breakdown may have a minor effect, because the energy contribution of PCr breakdown is not so high during short-term high-intensity exercise\textsuperscript{15,25}. In the present study, significant correlations between RIBLC and performance of short-term high-intensity exercise were also observed in both S and ML. These results indicate that rapid lactate transport may be important for both S and ML athletes when performing short-term high-intensity exercise. Regarding the differences in the groups, RIBLC was significantly higher in ML than S. In the present study, there were no differences in the speed reduction rates of 400-m trials, indicating that subjects of S and ML performed the same pacing strategies. Moreover, there were no significant correlations between the speed reduction rates and RIBLC. Therefore, it was supposed that there was only a minor effect on differences in pacing strategies of RIBLC. The difference in RIBLC between groups may be attributed to the quicker time required to plateau in ML, whereas the blood lactate concentration was the same at the time of reaching a plateau in both S and ML. Therefore, it was suggested that subjects of ML showed faster lactate transport abilities compared to those of S. Previous studies reported similar results, which showed faster lactate transport in middle- to long-distance runners than sprint runners\textsuperscript{12,13}. Running distance covered during ML athlete training is usually much longer than that of S athletes. Moreover, ML athletes in this study tend to do sprint interval training, which augments MCT4 protein content and \( \text{VO}_{2\text{peak}} \), about twice a week; but S athletes in this study do this type of training only once or twice a month. Accordingly, ML athletes possibly have higher skeletal muscle capillary densities and \( \text{VO}_{2\text{max}} \) compared to S athletes. In addition, ML athletes in the present study mainly compete in 800-m and 1500-m events, and the aerobic energy contributions of 800-m and 1500-m are 66\% and 84\%, respectively\textsuperscript{15}. Hence, ML athletes should have high aerobic energy production (i.e., mitochondrial oxidation) abilities to be able to perform middle-distance track events. Therefore, ML athletes possibly have higher cardiovascular capacity to transport lactate rapidly, and oxidative capacity to utilize lactate, compared to sprinters\textsuperscript{26}. To summarize these results and evidence, it is suggested that rapid lactate distribution is important for performing high-intensity exercise regardless of different training status (i.e., sprint trained or endurance trained). Additionally, ML athletes showed higher RIBLC than S, indicating higher lactate transport abilities in ML than S. Although we cannot fairly compare the performances of 400-m sprinting between S and ML, due to different sprint abilities (e.g., top speed), lactate transport ability may be important among athletes who have different training status. Generally, it has been considered that the energy metabolisms of S and ML are different in terms of glycolytic energy production (relatively high in S) and oxidative capacities (relatively high in ML). The results of the present study support these ideas of metabolic differences. The differences between groups in the present study would be useful for understanding metabolic differences among different track events or other exercises that are carried out for various exercise durations. However, there was a lack of participants who mainly competed in short sprint events (e.g. 100-m and 200-m) and long distance events (5000-m, 10000-m and road events). Therefore, the findings of this study could not apply to all track events. Future studies including large and varied populations will be needed.

\textbf{Conclusion}

RIBLC correlated with performance of a 400-m time trial and could be a new indicator for the ability of energy metabolism during short-term high-intensity exercise. Additionally, the difference in lactate transport was observed between groups of different track events. This indicates that different types of energy metabolism occur among athletes trained for different track events. When coaching athletes, it may be important to take this difference into account.

\textbf{Conflict of Interests}

K. Katsuyuki, who is an employee of Blue Wych Limited Company, voluntarily participated in this study for experimental design and interpretation of results. The au-
Authors declare that there is no conflict of interests regarding the publication of this article with no funding from any companies.

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