Blood Lactate Measurement in Recovery
as an Adjunct to Training
Practical Considerations

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Analysis of blood lactate levels during recovery from a controlled exercise bout has become a popular technique for monitoring and modifying training regimens. The purpose of this article is to discuss some practical aspects of measuring and interpreting blood lactate values in training athletes. Training applications of the lactate levels during exercise and the 'anaerobic threshold' are important, and have been dealt with previously (Jacobs 1986). Consequently, this article is limited to a review of research addressing key considerations in measuring and interpreting blood lactate in exercise with a focus on post-exercise (recovery) lactate values. Some of these considerations will also be applicable in monitoring blood lactate levels during exercise.

1. Measuring Blood Lactate

If blood lactate measures are to be used to modify physical training, valid and reliable measurements must be obtained. In the absence of valid and reliable blood lactate data, any positive training responses that occur on the basis of these data occur by chance or by coincidence. Although the details of lactate measurement are often given little attention, subsequent training decisions based on inaccurate data will be erroneous at best, and potentially harmful. Among the issues to be considered in obtaining accurate measures of blood lactate are: sampling site, timing of measurement of peak recovery lactate, sample handling and preservation, sample analysis and calibration and analytical methods.

1.1 Sampling Site

In general, there are 3 major sampling sites: arterial, capillary (arterialised) and venous. Because of associated health risks, arterial sampling is not practical for field measurements and is not discussed here. The most common field sampling site for lactate is the ear lobe or the finger tip, which yield arterialised capillary blood. In many exercise conditions, especially when the sampling site tissue is cold, a good blood flow is difficult to obtain. Blood flow can be increased by warming the sample site in clean hot water; it can also be increased by carefully 'milking' the tissue to move more blood into the area. Although this milking has been thought to dilute the blood sample by introducing extravascular fluid into the sample, evidence suggests this is not the case (Godsen et al. 1991). Blood flow in the finger can also be improved by keeping the finger positioned lower than the hand and arm (below heart level).

When large volumes (more than 0.1 to 0.2ml) of blood or repeated measures are needed, a venous catheter can be inserted at a convenient site. The catheter is kept free-flowing for long periods
by displacing the blood trapped in the catheter with saline or heparinised saline. In this situation, there is the possibility that the catheter flush solution will contaminate the blood sample and artificially lower the lactate level.

Whether the sample is obtained by lancing or via a catheter, contamination by sweat can also be problematic because sweat lactate levels are considerably higher than blood lactate levels (Fellmann et al. 1983; Lamont 1987; Pilardeau et al. 1988). If even a small quantity of sweat is accidentally sampled, erroneously high readings can result. Care should be taken in comparing venous blood with arterial or capillary samples since studies have identified significant differences (Foxdal et al. 1990; Hollmann 1985; Reaburn & Mackinnon 1990).

Regardless of how the sample is obtained, continued lactate production within the red blood cell and clotting in the collected sample can still occur. In many analytical techniques, the sample is promptly mixed with either trichloroacetic acid or perchloric acid, which precludes any concern for clotting or continued glycolysis but raises new concerns for dilutional errors. If the sample is intended for analysis in one of the automated analysers, it may either be analysed immediately, or the red cells lysed with a detergent such as ‘Triton X-100’. If the cells are lysed, again dilutional errors can occur. If ‘Triton’ is used in lysing, it is important to ensure that the autoanalyzer buffer also contains ‘Triton’. We found that the presence of ‘Triton X’ in the analyzer buffer influences plasma lactate level as well as that in whole blood (Bishop 1992a). We have not been successful in using acid lysing with the YSI model 23L (Yellow Springs Instruments, Yellow Springs) analyzer even with relatively large concentrations of buffer (Bishop et al., unpublished).

1.2 Timing of Measurement of Peak Recovery Lactate

Lactate level within the exercising body is far from a stable quantity. In addition to variable rates of lactate formation, the blood which initially picks up the lactate from the active muscle is diluted with blood from less active areas of the body. Simultaneously, the lactate is being removed from the blood at variable rates by the heart, liver, less active muscles and other organs. After a vigorous exercise bout the blood at a given sampling site will show, in most cases, a rapid rise to a peak then a steady decline back towards resting levels (as illustrated in figure 1). Since for training applications the peak recovery lactate is of primary interest, the timing of the blood withdrawal after exercise is very important. For example, if the lactate after a 200m swim is assessed in order to extrapolate that value to 4 mmol/L or some other reference point, the time after exercise when the measurement is made may substantially influence the results. It is important to recognise that for discontinuous lactate sampling, identifying an observed highest value specifies neither the magnitude of peak lactate level nor the time at which it occurred. In figure 1, if blood is sampled at 0, 5, and 10 min of recovery, and the highest value is observed at 5 min, the peak could have occurred at point ‘A’ between 0 and 5 min or alternatively at point ‘B’ between 5 and 10 min. Additionally, the magnitude of the true peak is unknown.

There is no longitudinal research which shows that the time of peak recovery lactate remains con-
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stant in the face of rigorous athletic training. Additionally, it is well known that active recovery influences the rate of lactate disappearance (Belcastro & Bonen 1975; Bonen & Belcastro 1976; Evans & Cureton 1983; Gisolfi et al. 1966; Reburn & Mackinnon 1990). The athlete's activity during recovery must be standardised and probably the safest procedure is to keep athletes inactive until after blood samples are taken.

Given that the change in lactate is rapid, exact timing of the blood draw becomes critical. Since timing is crucial, obtaining a good blood flow from either the catheter or the laceration so that the blood sample can be obtained as quickly as possible is important.

Table 1 summarises the literature regarding the mean time of occurrence of peak lactate after exercise. From these studies, the average time of peak lactate probably occurs before 6 min. However, many individuals peak later in recovery. Mader et al. (1978) maintain that the higher the lactate, the later the peak. Our unpublished observation is that postexercise peak lactate is quite variable among individuals independent of level. Immediately after a maximal treadmill test (mean max \( \dot{V}O_2 = 3.10 \pm 0.81 \) L/min; \( 41.2 \pm 6.6 \) ml/kg/min) at either 2.8 or 3.3 m/sec (10 or 12 km/h, 6 or 7 mph), with a 2% grade increase every 2 min, we observed a distribution of peak lactates across time as follows: 4 of 16 individuals attained the highest observed lactate level immediately after exercise, 6 of 16 at 4 min, 1 at 6 min, 3 at 8 min, and 2 at 10 min. Sampling was terminated at 10 min, so some of these could have peaked even later. Siconolfi et al. (unpublished) tested lactate recovery responses in 15 people who performed 3 different treadmill running tests: a very intense brief test with a mean time of approximately 70 sec, a more traditional continuous speed and grade incremented maximal test which varied in duration from individual to individual, and a test with the speed and grade increment individualised so that an approximate \( \dot{V}O_2 \text{max} \) was attained in exactly 12 min. They found the most common time of peak lactate was ap-

<table>
<thead>
<tr>
<th>Reference</th>
<th>No. of athletes</th>
<th>Exercise type</th>
<th>Sample time (min)</th>
<th>Mean times of peak (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robersas et al. (1990)</td>
<td>7</td>
<td>Seated cycle - max</td>
<td>2, 5, 10, 15</td>
<td>2-10 A, V</td>
</tr>
<tr>
<td>Freund et al. (1990)</td>
<td>11</td>
<td>Supine cycle</td>
<td>Continuous</td>
<td>3 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 min at 2.1 W/kg</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Supine cycle</td>
<td>Continuous</td>
<td>0 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80 min at 1.9 W/kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oyono-Enquille et al. (1989)</td>
<td>17</td>
<td>Seated cycle</td>
<td>Continuous</td>
<td>3-5 A, 3-6 V</td>
</tr>
<tr>
<td>McMaster et al. (1989)</td>
<td>5</td>
<td>Swim, max exert</td>
<td>2, 5, 10, 15</td>
<td>0-5 C</td>
</tr>
<tr>
<td>Fric et al. (1988)</td>
<td>7</td>
<td>3 treadmill runs to max</td>
<td>2.5</td>
<td>1-5 C</td>
</tr>
<tr>
<td>Wasserman et al. (1985)</td>
<td>10</td>
<td>Seated cycling</td>
<td>2.5</td>
<td>0-5 A</td>
</tr>
<tr>
<td>Fujitaoka et al. (1983)</td>
<td>19</td>
<td>Treadmill to max</td>
<td>1, 2, 3, 4, 5, 6, 7, 9, 11 . . .</td>
<td>6-9 V^a</td>
</tr>
<tr>
<td>Freund &amp; Zouloumian (1981)</td>
<td>11</td>
<td>Seated cycle 38% max</td>
<td>Continuous</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seated cycle 76% max</td>
<td>Continuous</td>
<td>3 A, 4 V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Supine cycle 80% max</td>
<td>Continuous</td>
<td>2 A, 4 V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Supine cycle 90% max</td>
<td>Continuous</td>
<td>2 A, 3 V</td>
</tr>
<tr>
<td>Poorimans et al. (1978)</td>
<td>11</td>
<td>Seated cycle max</td>
<td>5, 10, 15, 30</td>
<td>0-5 A, V</td>
</tr>
</tbody>
</table>

a Study used active recovery at 55, 65 and 75% of maximum attainable pace.
b Study reports mean time of peak of 7.65 min but sampling was discontinuous.
Abbreviations: A, V, C = arterial, venous, capillary blood sampling site.
proximately 3 min. and in general the time of measured lactate was consistent regardless of protocol although there were some exceptions. The values in Table 1 (excepting Fujitsuka et al. 1982) and the unpublished data all suggest the mean time of observed peak lactate in recovery is faster than the 7.5 min reported in a review by Vandewalle et al. (1987).

Because of the high interindividual variability (Sharp et al. 1984), group mean data are of but limited value in working with individual athletes. However, group mean data do provide a starting point to help identify an individual's likely peak more efficiently. Freund et al. (1986) have developed a mathematical model for describing the actual lactate curve based on data points obtained after a 3 min exercise bout. This work may provide the basis for refining procedures for lactate sampling during recovery.

1.3 Blood Handling and Preservation

Lactate levels in the blood are dynamic. Lactate passes from the muscle to the plasma, and then to some extent into the red blood cells. Numerous studies have examined the relative levels of lactate in the plasma and red blood cells (Buono & Yeager 1986; Daniel et al. 1964; Harris & Dudley 1989). The mobility of lactate and continued erythrocyte lactate production requires that blood samples be handled carefully and consistently. Studies in our laboratory have demonstrated the difference between lactate in whole blood, blood lysed with 'Triton X-100' and plasma (Bishop et al. 1992a).

Williams et al. (1990) illustrate the importance of the type of blood analysis. They point out that using a whole blood analysis results in only the plasma lactate being available for analysis. Since this lactate volume is expressed relative to the volume of the whole sample (i.e. plasma volume plus red cell volume), the result is a lower lactate per unit sample reading. This lower lactate reading is important when comparing among sample types and is a disadvantage to measurement accuracy when lactates are already very low because of physiological status or dilution.

It is a common practice among some athletic teams to collect blood samples into microcentrifuge tubes preloaded with a known quantity of 'Triton X-100' diluted with automatic analyser buffer solution. Since large numbers of samples must be collected rapidly, this technique is used to lyse the red blood cells and stabilise the lactate level. This dilution, although convenient, offers substantial risk of error. Often a 0.05ml quantity of diluent is used with 0.025ml of blood sample. The resulting lactate value obtained in analysis will be one-third of the blood lactate level in the original sample. Any error in the lactate sample or diluent volume will now be multiplied 3 times. Another problem with dilution is that when blood lactate levels are relatively low, dilution results in very low lactate level in the sample to be analysed. As with most analyses, measures of low levels are generally less accurate because of the reduced signal-to-noise ratio (Bishop et al. 1992b). Dilutions can also be a source of error for manual enzymatic techniques for the same reasons.

Since stability of lactate levels is always an important concern, an alternative to the use of 'Triton X' in buffer as a diluent is the use of a sodium fluoride/potassium oxalate mixture to prevent blood clotting and arrest red cell glycolysis. This technique maintained stable lactate levels in blood incubated at 38°C for 20 min (unpublished observation). When samples must be stored for several hours before analysis, our experience has been that separating the plasma by centrifugation improves the lactate stability of the samples (Bishop et al. 1992a). Buono (1986) reports that the supernatant of blood samples rendered protein-free by treatment with perchloric acid may be stored frozen for up to 90 days without affecting lactate levels.

When comparison of lactate levels of samples handled in different ways are required, regression equations that permit interchanging plasma and blood lactate level have been published (Bishop et al. 1992b), but do not provide the degree of precision needed for monitoring athletes. Since small changes in an athlete's recovery lactate are important, consistency in blood handling is essential.
1.4 Sample Analysis and Calibration

Fundamental to all measurement is a reference point by which accuracy is established. In lactate measurement this is set by carefully calibrating the measurement system against standards of known lactate level. Calibration standards are available from companies which sell lactate analysers and analysis kits. Calibration must be performed frequently to ensure accuracy. It is crucial that calibration be performed close to, and preferably just above and just below, the values of lactate levels expected. For example, if a lactate level of 4 mmol/L is anticipated, and a 2:1 dilution is involved, levels of 1 to 2 mmol/L are expected and calibration should be at approximately 1 and 3 or 4 mmol/L. Two-point calibration above and below the expected level is generally preferred because linearity between the calibration point and the measured point cannot be assumed.

1.5 Analytical Methods

Lactate level is typically determined by enzymatic conversion of lactate to some more easily measured substance. This can be accomplished with manual chemistry or with automated analysers. Two popular manual techniques are available in kit form from Boehringer Mannheim (Indianapolis) and from Sigma (St Louis) and are used internationally. A very basic technique is the Strom modification of the Baker-Sumerson procedure which was the standard procedure for many years (Strom 1949).

Current manual enzymatic methods of lactate analysis spectrophotometrically measure the reduced nicotinamide-adenine dinucleotide (NADH) level as an index of lactate level (Boehringer Mannheim 1985; Sigma 1988). A small sample (about 0.5ml) of blood diluted with an equal amount of perchloric acid is utilised in the assay and this method is reported to be linear up to blood lactate levels of 6.7 mmol/L (Sigma) and 10 mmol/L (Boehringer Mannheim). Gutmann and Wahlefeld (1974) report a coefficient of variation of 2% at 4.4 mmol/L for the method utilised in the Boehringer Mannheim lactate analysis kit.

The Yellowstone Instruments (YSI) automated system uses a 3-layer membrane, with the middle membrane containing a lactate oxidase compound which catalyses the production of hydrogen peroxide and pyruvate from lactic acid and oxygen. The hydrogen peroxide thus produced diffuses through one side of the triple membrane and, on contact with a platinum electrode, yields electron flow proportional to peroxide production. The YSI machine requires 25μl of blood and is reported to be linear up to 15 mmol/L (Yellow Springs Instruments 1985). This particular machine has been validated against other methods and found to be reasonably accurate (Bishop et al. 1992b; Weil et al. 1986). Other automated analysers have been used including that by Roche (Roche Bioelectronics, Basel), Kodak model DT60 (modified) or DT60 II (Rochester) and Anolox (London), but reports of their validity are not available in the scientific literature.

Both manual and automatic methods of measuring lactate offer certain advantages. Manual techniques require an initial purchase of basic chemistry equipment plus a spectrophotometer. Once the procedure is established, it offers the advantage of being able to perform most of the analysis on a large number of samples simultaneously. On the other hand, manual methods can be more cumbersome to set up and operate when only a few samples must be analysed each day or each week, and require more technical skill than automated systems.

Automated analysers offer the advantage of convenience and ease of operation. They can be quickly and easily used to analyse a single sample or a dozen. Immediate feedback can be provided to the athlete. However, each sample must be introduced individually into the analyser, so when very large numbers of samples must be analysed, a lot of time is required. These analysers are relatively expensive. Additionally, the consumables used in automated analysers generally have a relatively short shelf life. If only a few samples are
run every 6 to 8 weeks, the cost per sample can be high.

2. Safety

The safety of both the exerciser and the person drawing the blood is paramount. To protect the exerciser, sterility and cleanliness must be maintained. This requirement cannot be met when cleaned skin, lancets or capillary tubes subsequently come into contact with unclean hands, tissues or other materials. In the same way, repeatedly dipping the bloodied fingers of several different exercisers into the same container of warm water is unsafe. People handling anyone else's body fluids should protect themselves from exposure through consistent use of eye protection, face masks and gloves. Used lancets, capillary tubes and bloodied materials should be disposed of properly in labelled biohazard containers. The safety or infection control department of a local hospital or health clinic can be contacted to arrange final disposal of all biologically hazardous materials. After blood work, all areas should be cleaned with a disinfectant. Adding a small quantity of chlorine bleach or other disinfectant to containers receiving used blood, such as the waste bottle of automatic analysers, will also help to lower health risks.

3. Curve Interpretations

The ultimate goal in measuring recovery lactate levels is to be able to make some educated interpretation of changes in lactate responses so that physical training can be optimised. This interpretation is complex. One way in which recovery blood lactate has been used in training athletes is in monitoring the lactate response to a given exercise stress such as a swim at a certain percentage of maximum speed. These data are often portrayed in a graph of lactate versus swim speed such as that shown in figure 2 (also see Mader et al. 1976; Madsen & Lohberg 1987; Olbrecht et al. 1985). A shift in the lactate curve, to the right for example ('post' in figure 2), suggests improved physical performance (i.e. greater speed of movement for a given lactate level) [Madsen & Lohberg 1987; Maglischo et al. 1982]. Mader et al. (1976) suggest that these lactate curves are highly repeatable. In contrast, unpublished data collected in our laboratory indicated considerable test-retest variability for 3-point lactate curves (Scurlock, unpublished data).

The lactate response per unit speed curve can be affected by any of the following:

- A training response resulting in an increased metabolic capacity would influence lactate curves. Madsen and Lohberg (1987) suggest that the lactate response to a 400m swim test reflects aerobic changes and the results of a 50m swim reflect anaerobic changes.

- A training response resulting in an increased lactate removal rate would affect lactate curves. Brooks (1985), among others, has been instrumental in emphasising the importance of lactate removal rate for the lactate level. Freund et al. (1989, 1990) have demonstrated that the ability to remove lactate is impaired after prolonged exercise.
Presumably, this ability can be modified with training.

- Increased economy (improved biomechanical efficiency) would influence lactate curves. This effect is probably most pronounced in swimming tests. As the biomechanical efficiency of propulsion increases by whatever means, more speed will result per unit of energy independent of any physiological changes.

- An error in lactate sampling due to combinations of timing errors, handling errors and sample contamination would affect lactate levels. Madsen and Lohberg (1987) demonstrate the need to measure carefully, standardize procedures, environment, and time of day, and ensure adequate rest before lactate trials.

- Lactate curves could be influenced by alterations in diet, rest or other factors which might influence muscle glycogen status. Although the effects of muscle glycogen stores on recovery lactate levels have not been studied, several studies (Ivy et al. 1981; Jacobs 1981; Yoshida 1984) suggest that diet influences lactate levels during exercise which in turn could affect recovery lactate levels. Jacobs (1981) suggested that muscle glycogen must fall quite low to affect lactate levels. Fric et al. (1988) found that the observed mean recovery peak lactate level was significantly higher when athletes had 2 days of rest compared with values attained after strenuous exercise for 1 or 2 days before testing.

- Alterations in environment may affect lactate curves. Jacobs (1986) in his review of lactate measures during exercise reported evidence to suggest that temperature influences lactate levels, probably because of alterations in blood distribution. Substantial altitude changes between tests would definitely affect the lactate curves, as would differences in running track composition or swimming pool length due to their influence on speed.

- In swimming, an alteration in combinations of pulling and kicking might affect recovery lactate. For example, a study in our laboratory found significant differences in lactate levels for pulling alone and kicking alone compared with swimming (Meyer et al. 1988).

Additional information has been gleaned from lactate recovery values. Madsen and Lohberg (1987) suggested that an increase in the observed lactate level after an all-out effort implies increased ability to produce and tolerate lactate, and is generally interpreted to mean improved performance potential. On the basis of this observed peak lactate level, alterations in training have been suggested. If the peak lactate is low relative to competitive norms, Madsen and Lohberg recommend more anaerobic and less aerobic training (1987).

Mader et al. (1976) maintain that lactate values can be used to: (a) set training intensities; (b) objectively evaluate metabolic adaptations to training; (c) determine the optimal blend of aerobic and anaerobic training; and (d) identify young athletes with particularly promising metabolic capacities. Treffene et al. (1979) found distinctive differences in lactate recovery values in sprinters compared with endurance swimmers which implies some classifying of athletes may be possible. Olbrecht et al. (1985) found that the velocity associated with a lactate level of 4 mmol/L, extrapolated from recovery lactate curves generated from 2 × 400m swims, correlated highly (r = 0.97) with swim speed for a 30 min swim and much less well with post-swim lactate (r = −0.58). Mader et al. (1976) report agreement (correlation not provided) between lactate curves and maximal lactate after competition; however, Sharp et al. (1984) found the correlation between lactate predictions and measured lactate levels after competition to be low (r = 0.61) with a standard error of 0.05 m/sec (approximately 3.5 sec for a 200m swim). In one of the few training studies using lactate recovery curves, Maglischo et al. (1982) studied 6 swimmers and reported that the lactate values shifted in accordance with expectations. Sharp et al. (1984) studied 12 swimmers over 4 months of training and found that the lactate curve shifted in accordance with expectations and also that the curve of heart rate vs speed closely paralleled the lactate curve.

Despite the views and data presented, changes in the recovery lactate response to exercise can, in some instances, have little to do with physiology. A rightward or downward shift in an athlete's curve for lactate vs speed (fig. 2) could be due to better
training or the interpretation of some researchers (Mader et al. 1978; Madsen & Lohberg 1987; Maglischo et al. 1982), or in contrast it could also be due to factors having little to do with training.

4. Conclusions

There are several measurement issues that need to be considered in the use of blood lactate to prescribe and evaluate physical training. The issue of appropriate timing of blood sampling is probably the most crucial of these. Other considerations include techniques to minimise potential dilutional error, techniques to ensure accurate analysis, and care and consistency in sampling and processing methods. Careful consideration should be given to the interpretation of changes in lactate response.

We feel the most accurate lactate data and interpretation can be obtained by observing the following procedures:

A. Both automated and manual analysis techniques should be frequently calibrated at a level near that to be measured.

B. Consistent methods should be used in blood handling. If blood dilution is utilised, extreme care must be taken in measuring both diluent and sample. Diluent quantity should be kept as small as possible to minimise multiplicative error and to maintain lactate levels as high as possible within the upper limit of the analytical method.

C. Sampling techniques should be perfected to ensure that the time of sampling is consistent and multiple samples should be taken. When possible, sampling times should be clustered around the individual athlete's previous time of peak lactate level. Generally, sampling should be frequent within the first 5 min of recovery.

D. Environments, time of day, warmup and recovery should be standardised as much as possible (Madsen & Lohberg 1987).

E. In interpreting the results of changes in lactate response to a particular work bout or bouts, consideration should be given to alternative explanations of why changes occurred.

5. Future Research

There are also numerous questions concerning lactate measurement that need investigation to ensure that useful information is gleaned from lactate monitoring. Among these questions are the following:

- Does the lactate level curve in recovery shift in time and change shape with training/detraining? Is the time of peak recovery lactate related to the slope of the lactate curve during exercise for a given individual (see Freund et al. 1986)? Does this affect sampling time and applications?

- Can changes in lactate levels either during exercise or in recovery, in association with training, really be meaningfully interpreted and applied? Some researchers (e.g. Robinson et al. 1991) raise important questions concerning the applicability of lactate measurement to training. Research studies which could definitively examine the utility of lactate monitoring are difficult to execute but much needed.

- To what extent can heart rate be reliably used to provide information similar to lactate information? Heart rates are much more easily altered by, for example, environment, but perhaps this disadvantage can be overcome.

- Is one particular training intensity especially better than others? Does any incremental rise in training intensity produce a similar rise in fitness independent of the location of any particular lactate point? Can the recovery lactate curve be more efficiently shifted by a particular training intensity?

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