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RELEVANCE OF LACTATE THRESHOLD IN ENDURANCE SPORTS: A REVIEW

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ABSTRACT
Over 200 years of research has firmly established the concept of Lactate to be of paramount importance in athletes, specially endurance athletes. A detailed understanding has evolved regarding the role of lactate in anaerobic and aerobic metabolism of glucose, and its relation to different exercise intensity is better understood than ever before. However, multiplicity of concepts related to evaluation of lactate levels and interpretation with regards to exercise prescription and training has confounded sports scientists as well as coaches. This review article summarises the works done in the field and their implication in training. It further discusses the different concepts of Lactate thresholds, their utility and validation. It further suggests that while most concepts of LT are independently valid, they should not be used interchangeably.

KEYWORDS: Lactate, Endurance Sports, Lactate Threshold, Lactate Curve, Aerobic, Anaerobic, MLSS

INTRODUCTION

The concept of Lactate, in conjunction with associated concepts of Lactate metabolism, production, removal, threshold and steady state, is considered to be a basic value for any sports scientist. However, various studies using different and seemingly contradictory methods have confounded students and scientists alike.

Historical perspectives of Lactate

Lactate/ lactic acid, with an history spreading over more than 200 years, was first discovered in sour milk by a Swedish scientist, Carl Wilhelm Scheele in 1780 and was named 'Mjolksyra' meaning 'acid of milk' and find its wide application in food, leather and pharmaceutical industry with wider scope and research in the field of biotechnology.[1,2]

In 1807 or 1808 quoted in literature, Jons Jakob Berzelius, another Swedish scientist, for the first time described lactate in muscles of hunted stags and observed that the amount of lactate in the muscle is proportional to the amount of exercise that the muscle has performed.[2-4] It was Berzelius who also discovered pyruvic acid.[2]

During the subsequent 50 to 70 years, various researchers added to the lactate research in muscle tissue that lactate is always present in dead muscle tissue and the effect of lactate on muscle contraction. In 1891, for the first time the concept of tissue hypoxia as a reason for lactate formation was hypothesized by Arkai and Zillessen.[5]

In early 20th century, conducting in-vivo and in-vitro experiments, Archibald Vivian Hill and Otto Fritz Meyerhof, proposed that muscular metabolism as an open thermodynamic system with lactate and respiration being integral factors to metabolic energy production for which they were awarded Nobel prize in 1922 for Physiology or Medicine.[6,7]

Further research in lactate metabolism in muscle tissue paved way for lactate anion produced in the muscle by glycolytic pathway, now being known to be used as a substrate by various shuttle mechanisms under fully aerobic conditions. Research experiments by Hermansen and Stenshold have shown that lactate production is possible even with no increase in lactate and that lactate removal from the muscle is mainly dependent on the aerobic skeletal muscle metabolism during exercise.[5,8]

A key aspect in lactate research was the experiments conducted on Lactate dehydrogenase (LDH), an enzyme that catalyzes lactate formation. Otto Meyerhof, in 1908, first demonstrated the action of LDH during his experiments on muscle tissue metabolism.[9] Kaplan et al hypothesized that two monomeric subunits namely H (Heart) and M (Muscle) formed tetrameric organisation of LDH isoenzymes which on combination form 05 different isoenzymes.[10] The recent annotations of these monomers are A (heart) and B (muscle) with LDH1 through LDH5 being the isoenzymes. An important postulation with various experiments by different groups of researchers, though the exact role of isoenzymes are still to be understood, was that H subunit aids in oxidative metabolism of pyruvate by directly inhibiting its conversion to lactate and entering the oxidative pathway whereas the relative insensitivity of M subunit to pyruvate inhibition resulted in anaerobic conversion of pyruvate to lactate in the muscle.[8,10]

With respect to the intracellular location, LDH being soluble glycolytic enzyme, is predominantly present in the 'I' band of the striated muscle. Further research revealed that the M subunit of LDH is localised mainly to Sarcoplasmic reticulum of glycolytic skeletal muscle i.e. Type II Skeletal muscle while the H subunit is found mainly in the mitochondria of both striated muscles and liver.[11-13] Thus paving way for the concept of lactate shuttle proposed by Brooks et al in 1999 to maintain the lactate production and lactate clearance.[14]

Lactate Kinetics in Energy Metabolism

Lactate was once considered as a waste product of anaerobic metabolism and had been attributed for onset muscle fatigue and decrement in exercise performance. Over the last three to four decades, the understanding of lactate's role in energy metabolism has evolved.[2,15,16]

Lactate is now considered as a link between glycolytic and aerobic pathway wherein it is considered as an end product of glycolytic pathway which then becomes a substrate for mitochondrial aerobic pathway elsewhere.[17] The understanding of the lactate kinetics and its role became much clearer after the introduction of the concept of Lactate shuttle by Brooks et al.[8] This shuttling between the producer cells to consumer cells fulfils at least three main purposes for lactate namely, as a major energy source, as a major gluconeogenic precursor and as a signalling molecule in energy metabolism.[16-18]

a. Lactate production:

As the energy demand increases, energy is supplied in the form of Adenosine Tri Phosphate (ATP) immediately by ATP- phosphocreatine pathway. Further demand is achieved by Anaerobic glycolysis.[18] The rate of energy production depends on the substrate and rate limiting enzymes. As increase in pyruvate would negatively inhibit further glycolysis and increase in demand for energy, results in pyruvate getting reduced to lactate catalyzed by LDH. Further this conversion of pyruvate to lactate also causes immediate replenishment of redox potential namely $NADH/NAD^+$ levels for further continuation of glycolysis pathway as depicted in Figure 1.[18,19]

Lactate acidosis

Lactic acidosis/ metabolic acidosis which was once considered as a reason for onset of fatigue has been undergoing debate in the recent decades. It has been argued that metabolic acidosis results due to conversion of pyruvate to lactate and the accumulating H+ ions inhibit further muscle contraction. However, this hypothesis is being challenged due to recent studies demonstrating the limited effects of inhibition of muscular contraction due to induced acidosis and other in vitro studies demonstrating beneficial effects of acidosis like protective effects from hyperkalemic force depression, greater oxygen delivery by hemoglobin, ventilatory stimulation, enhanced muscular flow and increased cardiovascular drive.[15,20] Thus it clear that role of lactate in acidosis and muscular fatigue needs reassessment.

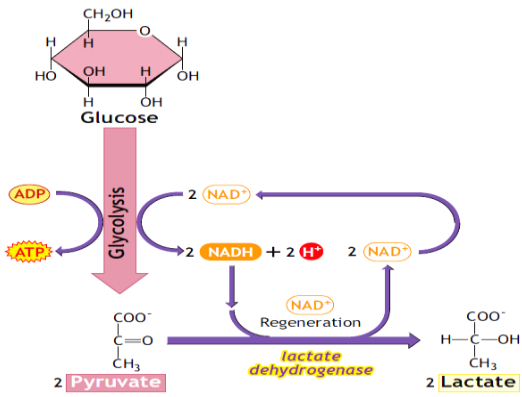

Fig 1: Role of lactate in energy production by anaerobic glycolysis.[18]

b. Lactate removal and fate:

Ole Bang was the first to observe that levels of lactate increased with increasing exercise but started decreasing after 10-20 min of steady state of exercise was reached.[20] He concluded that initial increase in lactate was removed continuously during the steady state of exercise as an accessory process until no more excess lactate left in the active exercising muscle. The concept of lactate shuttle wherein this excess lactate becomes a substrate for energy production as well as a cell signalling molecule both by intracellular and extracellular shuttling mechanisms has reverted the traditional concept about lactate as end product.[8,16,20] The lactate kinetics as hypothesized by van Hall G is shown in Figure 2.[20]

Lactate is shuttled by the monocarboxylate transporters (MCTs) across the mitochondria as well as other cells. Lactate thus produced is mainly shuttled to inactive skeletal muscles, liver, heart muscle and kidneys for being used as a source of energy by oxidative metabolism. In liver, the shuttled lactate gets converted to pyruvate and further ends up in conversion of glucose and glycogen by the process of gluconeogenesis. This lactate shuttle is named as Cori's cycle.[18-21]

During exercise, the oxidation of lactate by adjacent skeletal muscle reaches up to 75% while the remaining is used for gluconeogenesis in liver and kidneys.[15,22] Lactate is now considered as a readily available fuel for oxidation in the muscle since LDH catalyzed conversion from pyruvate to lactate and vice versa has been observed as a near-equilibrium state and does not appear to be limiting. Also, increasing blood lactate levels has been found to downregulate the free fatty acid and glucose utilization as energy substrate. Moreover, lactate uptake is dependent on concentration gradient and not limited by transporter unlike insulin dependent glucose transport. Thus lactate acts as a fast and efficient fuel source.[20] A Schematic representation of lactate shuttle and Cori's cycle is depicted in Figure 3 and Fate of lactate is shown in Figure 4.

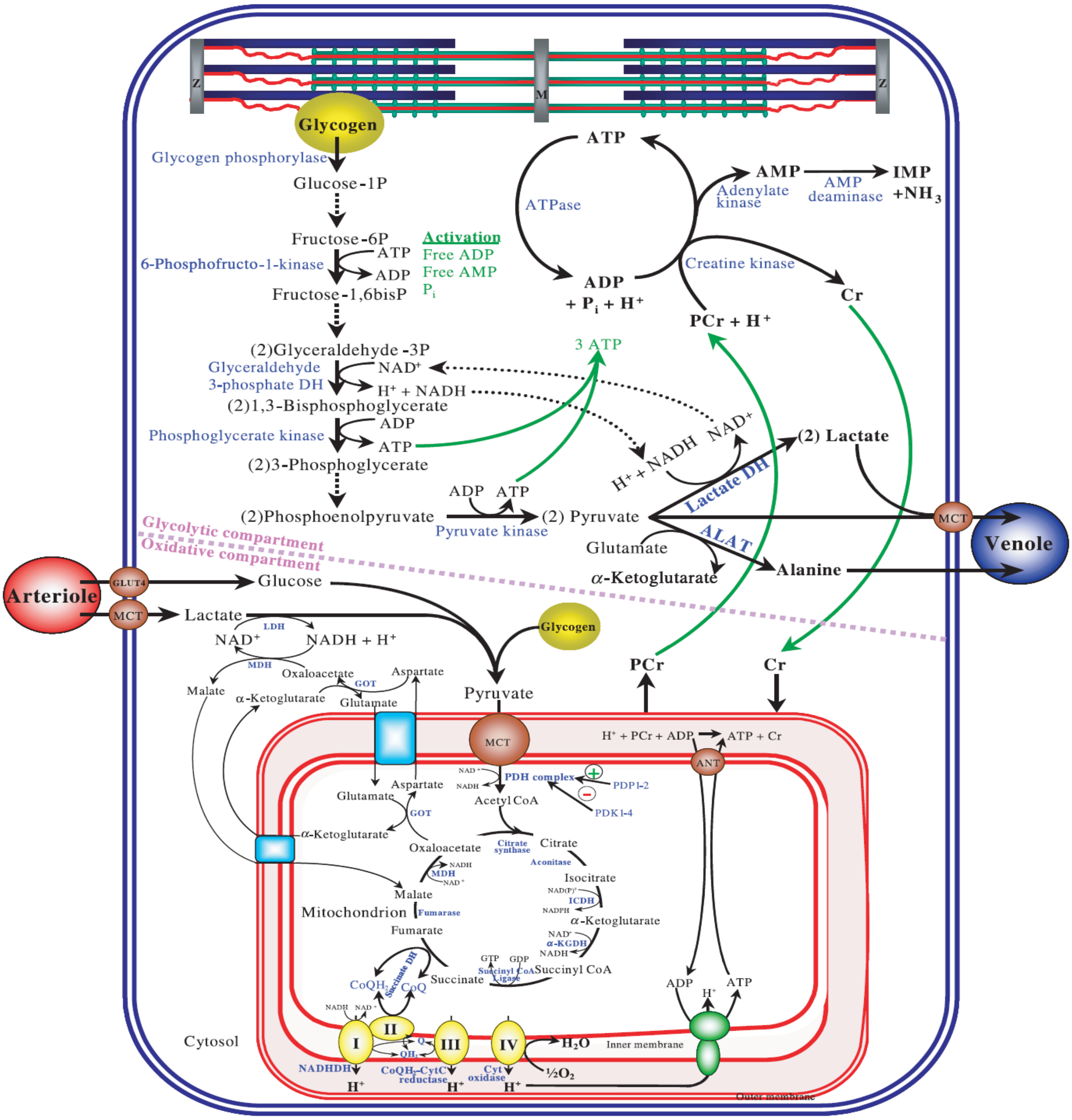

Fig 2: Lactate Kinetics: The process adjacent to the myofibril details the glycolytic glycogenolysis / glycolysis) process of energy production. The oxidative component of energy production is detailed in the mitochondria (red rounded rectangle). Reproduced from Van Hall G. Lactate kinetics in human tissues at rest and during exercise. Acta Physiol (Oxf) 2010;199(4):499-508.[20]

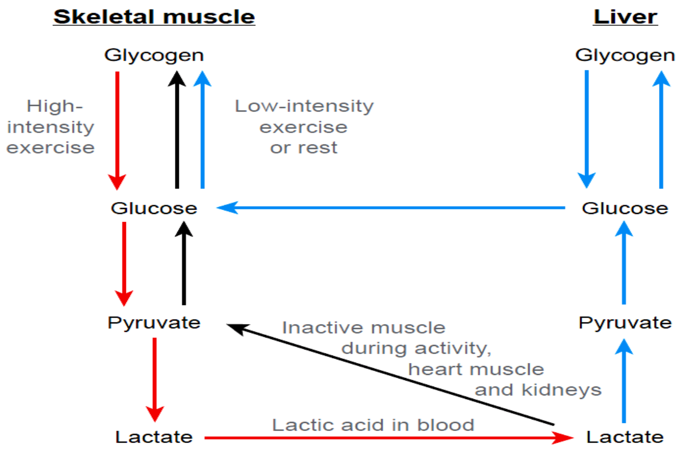

Fig 3: A schematic depiction of Lactate shuttle and Cori's cycle.[19]

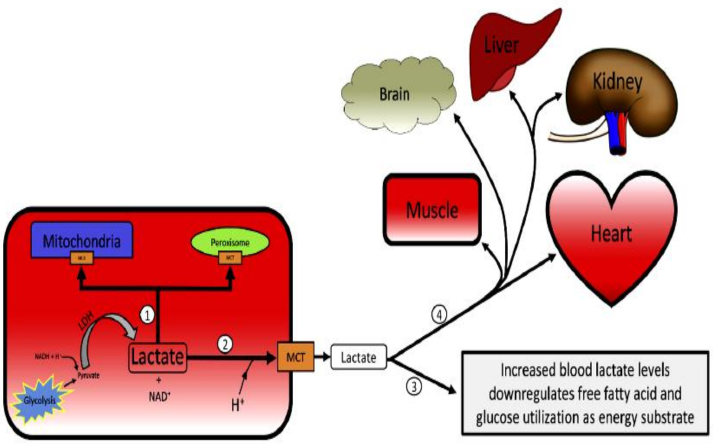

Fig 4: Fate of lactate.[15]

Lactate kinetics and blood lactate curve

During an incremental exercise activity, constant increase in load results in increased demand on energy supply. Which in turn results in continuous energy production by immediate anaerobic glycolytic pathway. This results in continuous production of lactate also termed as rate of lactate appearance in the blood (R_a) and as discussed earlier, this is accompanied by increased lactate clearance by various lactate shuttling mechanisms also termed as rate of lactate disappearance from the blood (R_d).[18,21,23] The conversion of pyruvate to lactate is inevitable due to the high glycolytic catalyzing capacity of LDH at thermodynamic equilibrium and high level of pyruvate (substrate) formation due to high energy demand during continuous incremental exercise.[23]

When the rate of entry of lactate into the blood equivalent to the rate of disappearance i.e. $R_a = R_d$, this is called the steady state. The net metabolic lactate turnover (R_t) thus is equal to R_a and R_d at this steady state ($R_t = R_a = R_d$). However, a point occurs during the incremental exercise (non-steady state), where-in the lactate clearance (Rd) is not able to maintain an equilibrium with the lactate appearance (R_a). This invariably results in increase in the blood lactate concentration above the baseline which is termed as blood lactate accumulation ($R_a > R_d$).[23] With increasing load, this blood lactate concentration increases disproportionately during the exercise. A typical blood lactate curve plotted against the increasing load depicted in watts is shown in Figure 5.[15]

Blood lactate curve is an illustration of lactate kinetics during exercise. During the initial stage of the exercise, there is minimal increase in blood lactate level from baseline. This initial rise is due to immediate demand for energy and activation of anaerobic glycolysis until the activation of the cardiovascular drive takes place. As soon as the blood supply is enhanced at the active muscle level, resulting in more oxygen supply, the energy demand is met by the aerobic mechanism. Thereafter, the blood lactate returns to level close to baseline. During this steady state of exercise, when the energy demand is met by the increased blood flow and aerobic pathway, R_a is maintained in equilibrium with R_d. Hence the blood lactate curve increases as a linear function to the increasing load.[23,24]

However, as the load increases, the rate of conversion of pyruvate to lactate increases. The rate of production of lactate increases rapidly as opposed to the rate of clearance of lactate by various mechanisms. This corresponding workload beyond which there is disproportionate non-linear increase in blood lactate accumulation is called commonly as onset of blood lactate accumulation (OBLA) or lactate threshold (LT) or lactate break point.[19,23,50] The initial hypothesis of R_a being the sole factor for lactate threshold due to anaerobiosis has been refuted by various researchers during the 1970s, an era which has been termed ‘lactate revolution’.[26] Later, the model of R_a increase with workload along with concomitant inadequate R_d by the active muscle has been postulated. Inefficient clearance of lactate shuttle mechanisms within the active muscle also have been implicated in onset of blood lactate accumulation.[8,16,23,27] The relation between R_a, R_d and LT are shown in Figure 6.[23]

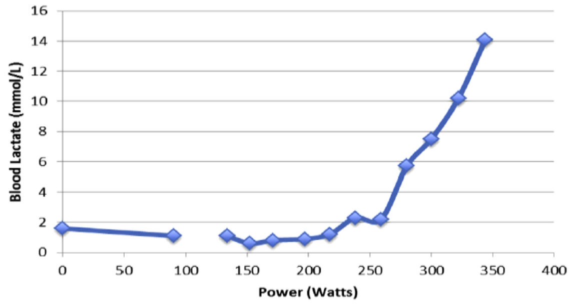

Fig. 5: Blood lactate curve: Blood lactate concentrations are plotted against power during an incremental exercise using cycle ergometer. It can be noticed as exercise grade increased beyond 250 watts, there was rise in blood lactate concentration above the baseline. This point is called onset of blood lactate accumulation (OBLA).[15]

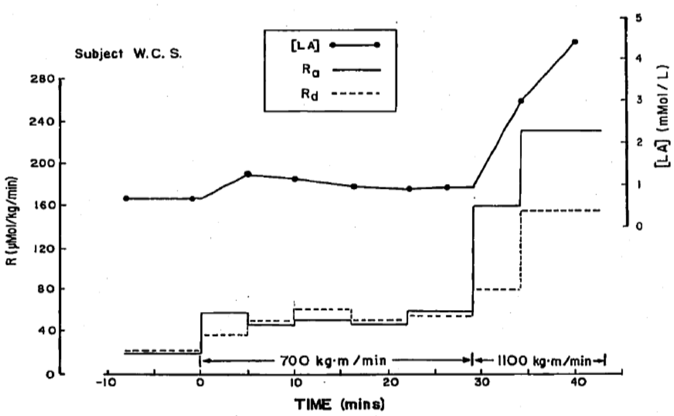

Fig 6: Relation between Lactate appearance (R_a), Lactate disappearance (R_d) and Lactate Threshold (LT) in a subject from rest to submaximal steady state (700 kgmmin^{-1} range) to maximal exercise (1100 kgmmin^{-1} range).[23]

Blood lactate curve interpretation and determinants

Cardiorespiratory endurance, considered one of the key component of the cardiorespiratory fitness, can be defined as the ability to perform large-muscle whole body exercise at moderate to high intensities for extended periods of time.[28,29] According to Pate and Kriska (1984), the aerobic endurance performance is determined by maximal oxygen uptake (VO_{2max}), lactate threshold (LT) and oxygen cost of activity or economy.[28,30]

Graded exercise testing is commonly used to evaluate the aerobic performance in athletes as well as in clinical studies. Blood lactate is measured during this incremental exercise and is plotted against the workload. A typical schematic representation of the blood lactate curve is represented in Figure 7.[5,24,31] blood lactate curve is interpreted for lactate threshold and relative workload at LT for evaluation of aerobic endurance performance as well as prescription of training program[31,32]

The entire blood lactate curve can be considered as an aerobic-anaerobic transition with increased intensity of the endurance event based on the lactate revolution concept.[14,26,27] In 1979, Kindermann et al developed a framework based on this concept for performance diagnosis and training prescription as shown in Figure 7.[32] It is generally accepted that a rightward shift of the blood lactate curve with training as an indicator of improvement in endurance performance i.e. lower blood lactate at a given workload whereas a left shit of the curve is considered worsening of the endurance performance.[33-35]

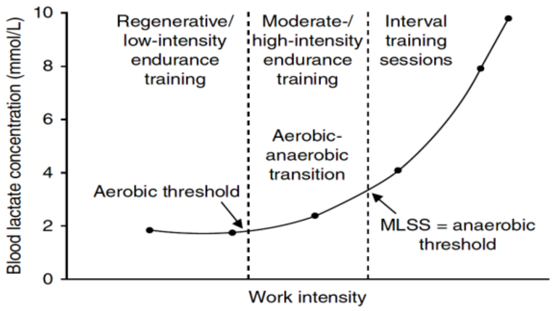

Fig 7: A schematic Blood lactate curve depicting an aerobic- anaerobic transition framework.[24]

During the incremental exercise testing, two break points happen in the blood lactate curve. First lactate breakpoint in low intensity is considered an elevated blood lactate above resting blood lactate levels. This initial rise in blood lactate has been originally called has anaerobic threshold by Wasserman determined by gas exchange parameters.[36] This terminology has been used by various researchers and has caused considerable confusion in the literature.[38,27,23]

According to the Kindermann framework, this first rise in blood lactate was named as aerobic threshold (LT_{Aer}), since this breakpoint marks the upper limit of aerobic metabolism that enables the individual to involve in activity lasting for hours.[24,31] The application of this LT_{Aer} intensity in training prescription has been used in enhancing cardiorespiratory fitness in recreational athletes, cardiac rehabilitation in patients and in elite athletes for low intensity regenerative training sessions.[31,36,39-41]

Exercise intensities above the LT_{Aer} can be used for prescription of aerobic endurance activities lasting up to ~4 hours, the blood lactate curve depicting a steady state with incremental load during this period of exercise.[42] With increasing intensity, again a rise in blood lactate is witnessed which is disproportionate increase with increasing workload. This second rise in blood lactate is called as lactate turnpoint or anaerobic threshold or anaerobic LT (LT_{An}).[24,38] This region of blood lactate curve between LT_{Aer} and LT_{An} has been named the aerobic- anaerobic transition zone wherein there is continuous lactate accumulation and oxidation and clearance of lactate occurs due to the lactate shuttle mechanisms dynamically to maintain a steady state.[5]

The terminal constant load during the incremental exercise which maintains a steady state depicting the highest equilibrium between lactate appearance and lactate disappearance i.e. $R_a = R_d$ and beyond which there is a transition of aerobic metabolism to anaerobic metabolism is called the maximum lactate steady state (MLSS).[43,44] At an intensity corresponding to this MLSS, an individual would be able to perform an exercise for about 45 – 60 minutes with researchers attributing major adaptations in the oxidative capacity of the muscle to clear lactate to maintain this highest steady state of blood lactate.[32,45] As this point, namely the LT_{An} varies between individuals and as well dependent on the motor pattern of the exercise, an individual blood lactate curve evaluation has been suggested.[46,47] Intensities above MLSS have been used to guide interval training sessions in different endurance sports.[31,48,49]

Determinants: Overall lactate levels are known to be influenced by the glycogen content of the muscle, depletion of which may happen due to a low carbohydrate diet or a preceding exhaustive exercise.[50,51] Blood lactate levels were found to be lower in these individuals resulting in a downward shift of the blood lactate curve, which needs to be correctly interpreted.[24] In addition, factors like muscle fibre composition, glycolytic and lipolytic enzyme activity, capillary density and mitochondrial density in the muscle may also determine the blood lactate curve.[24,52]

The measurement procedures like the factors involved in the graded exercise test namely grading duration, starting and subsequent load increments and model used for derivation of the blood lactate curve also greatly influence the blood lactate curve.[53,54] The methodology of blood lactate measurement like site and method of blood sampling as well as analyzing methods also affects the blood lactate curve.[24,55-57]

Lactate Threshold Concepts in Endurance Performance Evaluation

Lactate threshold in over 200 years of literature has been mentioned in various ways by different researchers.[2] Terminologies like lactate turn point, lactate threshold, OBLA, MLSS, anaerobic threshold, ventilatory threshold, lactate equivalent, lactate minimum speed and individual anaerobic threshold have been confusing and were difficult to apply in the field of performance evaluation universally.[24,36,42,46] In 2009, Faude et al had conducted a review of literature on lactate concepts and had located around 25 LT concepts using various exercise testing protocols.[24]

Lactate threshold concepts reviewed in literature were categorized into three broad categories as fixed blood lactate threshold (LT_{fix}).[58,61] aerobic lactate threshold concepts (LT_{Aer})[32,62-65] and anaerobic lactate threshold concepts (LT_{An}). [42,46,66,68] LT_{fix} concepts were set at blood lactate levels of 2, 2.5, 3 till a maximum of 4 mmol/L.LT_4 i.e. 4mmol/L Lactate threshold was originally described by Mader et al[85] and later described by various researchers as the OBLA and it is the most commonly used LT_{fix} concept even today in exercise testing.[59,69,70]

LT_{Aer} has been described by various researchers as the first significant nonlinear abrupt marked systematic rise above baseline blood lactate levels[24,32,62-64] Though the visual definition for observation of the rise seems simple and obvious, practically problems have been encountered with minimal changes in blood lactate curve in the initial stages of graded exercise tests creating confusion in documentation by researchers.[71] Objective LT_{Aer} concepts like 0.2 mmol/L increment from baseline,[60] 0.5 mmol/L increment[65] or 1 mmol/L increment above baseline[72] have been proposed. In addition, Beaver and colleagues have used a log- log transformation to assess the first rise in blood lactate.[73] The LT_{Aer} concepts have been tabulated in table 1.

All the lactate threshold concepts that were related close to MLSS or the sudden disproportionate increase in the blood lactate curve were assigned in LT_{An} category.[24] Originally. LT_4 was considered closest to the MLSS as it was highest fixed blood lactate that was sustainable for a longer duration of intense endurance activity.[58] However, it was found that a fixed LT_4 did not consider the inter-individual differences as well as underestimated LT in the anaerobically trained individual and overestimated in aerobically trained individuals. Hence individualized anaerobic threshold concepts were introduced by various researcher.[42,46,67,74] Various LT_{An} concepts are depicted with the researchers group who developed in table 2.

Table 1. Aerobic lactate threshold concepts (LT_{Aer}).

Researchers group	LT_{Aer} Concept
Yoshida et al Ivy at al	Blood lactate begins to increase above baseline[62,63]
Kinderman et al Tanaka et al Yoshida et al	Blood lactate exhibits a marked/systematic/significant/non-linear/sharp/abrupt sustained increase above baselineValue [32,61,64,75,76]
Weltman et al	An elevation in blood lactate above baseline at least 0.2mmol/L due to error of lactate analyzer[60]
Hughson at al	Blood lactate increases 0.5 mmol/L above resting concentration[65]
Coyle et al Hagberg et al	Blood lactate increases 1 mmol/L above baseline (i.e. lactate at low intensity corresponding to 40–60% VO2max)[77,78]
Bishop et al Amann et al	Preceding a blood lactate increase by 1mmol/L or more[72,79]
Kindermann et al Skinner et al	First significant elevation of lactate level (approximately 2 mmol/L)[32,80]
Beaver et al	Plasma lactate concentration begins to increase when log blood lactate is plotted against log (work intensity)[73]
Farrell et al	Rise in delta lactate (onset of plasma lactate accumulation)[81]
Dickhuth et al Roecker et al	Minimum lactate equivalent (blood lactate divided by oxygen uptake or work intensity)[82-84]

Table 2. Anaerobic lactate threshold concepts (LT_{An}).

Researchers group	LT_{An} Concept
Stegmann et al	Tangent to blood lactate curve from recovery curve where blood lactate is equal to the value at end of graded exercise test[46]
Keul et al	Tangent to blood lactate curve at 51^{o}[67]
Simon et al	Tangent to blood lactate curve at 45^{o}[68]
Berg et al	Intersection point between tangent for the minimum lactate equivalent and the linear function for the final 90 sec of GXT[85]
Bunc et al	Intersection between the exponential regression of the lactate curve and the bisector of the tangents of the upper and lower parts of the lactate curve[74]
Dickhuth et al	1.5 mmol/L above minimum lactate equivalent[82,84]
Baldari and Guidetti	The second lactate increase of at least 0.5 mmol/L from the previous value[86]
Cheng et al	Maximal distance from blood lactate curve to the line formed by its endpoints (D_{max})[87]
Bishop et al	Maximal distance from blood lactate curve to the line formed by the point before the first rise in blood lactate and the value at cessation of exercise (D_{mod})[72]
Smith et al	The final running velocity before the observation of a sudden and sustained increase in blood lactate between LT_{Aer} and VO_{2max} (Lactate turnpoint velocity)[88]
Tegtbur et al	Minimum in blood lactate during graded exercise test after high intensity exercise (Lactate minimum speed)[89]

Validation of LT concepts

Large number of research studies conclude that LTs are criterion measure for endurance performance [32,58,59,90-92] It is particularly evident that lactate threshold is superior to the maximal oxygen uptake (VO_{2max}) when assessing endurance performance in a homogenous group of athletes given the disadvantages arising due to necessity of maximal effort, dependency on motivation, attitude of the subject, difficulty in measurement during high intensity exercise, or lacking sensitivity of small changes in endurance capacity.[31,62,78,81] The obvious gold standard for validating LT concepts is the competition performance. However, many factors like indoor or outdoor, sport type, surface, sex, age, and athletes' endurance level are confounders. As an alternative, the results of laboratory test that simulates the actual competition event can be used for validation of the LT concept.[24]

MLSS, considered as a highest constant steady state for a longer period of time without a continuous rise in blood lactate, also has been used to compare the LT concepts for the purpose of exercise intensity prescriptions.[24,44] The gold standard method to identify MLSS is by performing several constant load trials of at least 30 minutes' duration on different days at various exercise intensities. An increase in blood lactate of not more than 1 mmol/L between 10 and 30 minutes during the constant load trials procedure is best suited for determination of MLSS.[24] A typical blood lactate curve response during constant load trials for MLSS determination is shown in figure 8.

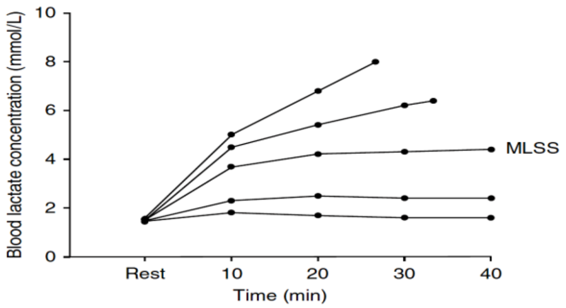

Fig 8: Blood lactate curves during constant load trials of determination of MLSS.[24]

Surrogate parameters of lactate threshold

As identifying the LT, aids in evaluation of the endurance performance as well as in prescription of exercise training intensities, various surrogate parameters are used at this threshold.[94,79,88,90-92] After establishment of the 'point of optimum ventilatory efficiency' by Hollman et al, Wasserman and McIllroy determined this intensity by plotting ventilation versus oxygen uptake and named it anaerobic threshold.[36,95] These were the times measurement of the blood lactate was in its inception and was tedious to measure during the incremental exercise.

Many physiological parameters have been proposed given that these parameters also reach a non-steady state like blood lactate. Various non-invasive surrogate parameters were developed to determine the LT and were used for training intensity prescriptions. A close link has been established in various studies with respect to ventilatory gas parameters and blood lactate, though the exact physiological mechanisms are still unclear.[96] Meyer et al had developed the non-invasive gas parameters ventilatory threshold (VT) model that coincides with the LT. They had named the two break points as in the Kindermann blood lactate framework as VT_1/ $AerT_{GE}$ and VT_2/ AnT_{GE} corresponding with LT_{Aer} and $LT_{An.}$[31] VT_1 is usually done graphically by V-slope method with VCO_2 on y-axis and VO_2 on x-axis.[97] The gas exchange parameters have been widely used in endurance sports like cycling for competition intensity quantification as training intensity zones namely low intensity (intensity of workload below VT_1), moderate intensity (workload intensity between VT_1 and VT_2) and high intensity (workload intensity beyond VT_2).[98]

Similarly other non-invasive surrogate parameters for LT that have been commonly studied are heart rate threshold,[99-101] electromyography threshold,[102] rating of perceived exertion[103,104] and recently using the near infrared spectroscopy garments based on the oxygenation and blood flow at the active muscles.[105]

Repeatability and predictive value of LT concepts

In a recent study done in 2018 on endurance cyclists by Heuberger at al, all the LT concepts have been studied for repeatability as well as predictive value of the LT concepts in endurance performance in cycling[106] The LT concepts were categorized and about 08 LT concepts, each representing one of the categorized groups of LT concept were used. Repeatability was studied using Cronbach's alpha and intra- subject correlation of variance. Predictive value was assessed with 45 minutes' time trial tests and a road race to the top of Mont Ventoux, France using Pearson correlations. The result showed that all the LT concepts had good to excellent repeatability (Cronbach's alpha of 0.89 – 0.96) and predictive value of time trial tests and road race showed significant correlations ranging from 0.65 - 0.94 and 0.53 - 0.76. However, D_{max} modified method by Bishop et al had both highest repeatability and predictive value and hence it was recommended to be used in cyclists to evaluate aerobic endurance. Also, OBLA at 4mmol/L had similar repeatability and predictive value of endurance performance.[106]

In a study done in soccer players, there was no agreement in analysis between four LT concepts that they studied namely Visual method, D_{max}, D_{max} mod and logarithmic log-log method. The researchers recommended that the LT concepts should not be interchangeably used.[107]

CONCLUSION

Despite over 200 years of scientific research had passed by in the field of lactate metabolism and its role in endurance performance, there has been new perspectives added day by day.[2,31] LT still being considered one of the key tool in endurance performance prediction as well as training intensity prescription, has moved onto more than 25 LT concepts.[24,106] Surrogate markers of LT fraction of maximal oxygen uptake have gained popularity due to reduced cost of evaluation and non-invasive nature of the procedure.[100,102,104] Various newer technologies like wearable garments using these surrogate parameters and artificial neural networks have been recent addition to the field of LT concept application in endurance sports.[101,105,108]

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