Significance of plasma lactate concentration during exercise

François Péronnet, Professeur émérite
Département de kinésiologie, Université de Montréal
fperonnet@gmail.com

1.INTRODUCTION

The significance of plasma lactate (LA) concentration ([LA]) is different in response to short duration high intensity exercise (SDHIE) and to prolonged endurance exercise.

2. HIGH INTENSITY SHORT DURATION EXERCISE

2.1. Anaerobic energy production

In response to SDHIE, LA production and accumulation is due to the fact that anaerobic glycolysis provides a substantial portion of the energy needed (Gastin 2001). The LA-space varies, and it is difficult to precisely estimate the amount of LA accumulated from plasma [LA]. Direct measures in animals (Bennett and Licht 1974) and indirect estimates in man (di Pamprero 1981) suggest that the amount of LA which can be accumulated is ~1-1.25 g/kg (~0.8 to 1 mole in a 70-kg subject: LA = 89 g/mole) in a minimum period of ~30 s. Since 47 kcal are released for 2 moles of LA accumulated (0.26 kcal/g of LA) this amount of LA corresponds to ~18.5-23 kcal and ~2600-3200 W. Consistent data indicate that plasma [LA] at the end of foot races ranging from 200 to 1500 m is slightly above 20 mmol/L (Kinderman and Keul 1977; Lacour et al. 1990) corresponding to a LA-space ranging between 50 and 60 % body mass.

2.2. LA production and efficiency of ATP synthesis

The maximal rate of plasma glucose entry into peripheral tissues is ~2 g/min (Hawley et al. 1994). Thus, the flux through glycolysis (at least ~70 g/30 s or 2 g/s) can only be sustained from muscle glycogen. In response to SDHIE a sharp decline in glycogen concentration in working muscles is indeed observed (Medbo et al. 2006). There are two advantages of using muscle glycogen to fuel glycolysis during SDHIE: 1) the small amount of plasma glucose is conserve to other organs; and 2) when compared to glycolysis from glucose, glycolysis from glycogen provides more ATP (3 vs 2 moles of ATP/mole of glucose) (Mayes 1988) (p. 160). With 47 kcal released/mole of glycosyl unit, the efficiency of ATP resynthesis (~12 kcal/mole) by glycolysis is much higher (36/47 = 0.77) than aerobic metabolism (~0.64 for an average P/O of 3).

2.3. LA distribution and clearance

The amount of LA accumulated during SDHIE is equal to the amount produced: there is essentially no LA clearance. The two major pathways of LA clearance during exercise are oxidation and gluconeogenesis (GNG) in the liver which both require oxygen: 0.750 L/g of LA oxidized; ~125-145 mL/g of LA in GNG. During SDHIE, the amount of oxygen consumed is low. Even under the assumption that all the oxygen available is used to oxidize LA, there is only enough oxygen to oxidize a few grams of LA (vs at least ~70 g produced). As for liver GNG, with a low oxygen consumption in the liver (~70 mL/min) (Nielsen et al. 2007), which cannot possibly be entirely devoted to fuel GNG, the amount of LA which can be converted into glucose in the liver during SDHIE is negligible.

2.4. LA production/accumulation during SDHIE

Since anaerobic glycolysis with LA accumulation provides a substantial portion of the energy needed during SDHIE, the highest the amount of LA accumulated the better the performance. This has been shown, for example, in a study by Lacour et al. (1990) conducted in 400- and 800-m runners: a high positive relationship was found between the average speed sustained and plasma [LA] at the end of the race.

3. PROLONGED ENDURANCE EXERCISE

3.1. Energy metabolism is entirely aerobic

In response to prolonged endurance exercise, plasma [LA] is much lower than in response to SDHIE : depending on the fractional utilization of VO2max sustained, training and nutritional states, and environmental conditions, the values range between 1.5 to 2 mmol/L (O'Brien et al. 1993) (i.e., only slightly above resting values) and ~10 mmol/L (Kenefick et al. 2002). In addition, plasma [LA] is stable or slowly drifts upwards or downwards. The slow changes in plasma [LA] over time, if any, suggests that the amount of LA present in the body remains fairly constant: the rate of plasma LA disappearance closely matching its rate of appearance. Energy and ATP provided by glycolysis are only anaerobic when electrons are accepted by pyruvate which is reduced in LA such as during SDHIE. When electrons which have been transiently accepted to pyruvate are removed from LA to be finally accepted by oxygen to produce water, the energy and ATP provided by glycolysis are aerobic. The stability or near stability of plasma [LA] during prolonged endurance exercise (whatever the total amount of LA present and the level of plasma [LA]) indicates that the energy needed for this type of exercise is entirely provided by aerobic metabolism.

3.2. Plasma [LA] and endurance performance

As shown for example by Coyle et al. (1988), for a given fractional utilization of VO2max, exercise time to exhaustion is longer (i.e., endurance capability is higher) in subjects with the lower plasma [LA]: the subjects with the lower plasma [LA] during a simulated bike race at 88%VO2max were able to sustained this workload almost twice longer than those with the highest plasma [LA]. When compared to the subjects with the lowest endurance capability, the LA curve (i.e., plasma [LA] plotted against %VO2max) during incremental exercise to VO2max, was shifted to the right in subjects with the highest endurance capability. The « LA threshold » (LT) defined in this particular study as the %VO2max when plasma [LA] was 1 mmol/L above the basal value, was observed at 65.8%VO2max in subjects with the lowest endurance capability vs 81.5%VO2max in subjects with the highest endurance capability.

3.3. LT and endurance performance

Based on this observation, which has been repeatedly confirmed, it is generally accepted that the LT identified during incremental exercise or during prolonged exercise at constant workload (maximal lactate steady state or MLSS), is a valid index of endurance capability (Faude et al. 2009). Although this observation can have practical applications, it should be recognized that the term LT is a misnomer since there is obviously no threshold in the LA curve. This is the reason why more than twenty different LTs have been suggested all of them based on purely geometric analysis of the LA curve without any physiological justification. In addition, in almost all the studies showing a correlation between performance and a particular LT, the LT was expressed in running speed, VO2 or power output (i.e., absolute LT). However, the absolute LT depends in a large extent on VO2max, which is itself a major determinant of performance for events lasting longer than about 60 seconds (Levine 2008) and is, thus, a confounding factor. This is probably why the absolute LTs are not selective determinants of performance in endurance events but also of performance for shorter distances such as the 800-m running and the 4-km cycling (Faude et al. 2009).

3.4. The LA shuttle

During prolonged endurance exercise, LA is continuously produced in some tissues and utilized in others, but the rate of plasma LA appearance and uptake are similar or very close. This phenomenon has been described as the cell-to-cell LA shuttle (Brooks 1986a, b; Gladden 2004, 2007). The sources of plasma LA are the working muscles but also the non-working muscles, and these tissues along with the heart, the brain and the liver are also the sites of plasma LA removal. In the liver, LA can be converted into glucose which can be released into the blood. In the heart and brain, the LA removed from the blood is oxidized and the LA shuttle, thus, could be seen as the way to fuel aerobic metabolism in these organs at the expense of the large stores of muscle glycogen in non-working muscles. The LA shuttle also sustain aerobic metabolism in working muscles at the expense of glycogen stores in non-working muscles in which glycogenolysis is stimulated by epinephrine (Gladden 2004).

3.5. Significance of plasma [LA] during prolonged exercise

During prolonged exercise the energy is entirely produced through aerobic metabolism but, plasma [LA], which is stable is higher than at rest. Also, for a given workload, plasma [LA] is stable but at a higher value in all situation where the availability of oxygen, oxygen transport, and oxygen utilization are impaired, and conversely (Wasserman and Koike 1992). Under the well entrenched theory of the anaerobic threshold, these observations indicate that above a certain workload, anaerobic metabolism has to be involved in ATP generation because aerobic energy supply becomes insufficient. This theory and explanation, however, cannot account for the facts 1) that there is actually no anaerobic energy provided when plasma [LA] is stable, whatever plasma [LA]; and 2) that a decrease in oxygen availability, or impairment in oxygen transport and utilization do not modify VO2 for a given submaximal workload.

The best (and simpler) explanation for these observations is that during prolonged exercise plasma [LA] is a marker of the error signals needed to stimulate mitochondrial respiration (Connett et al. 1990; Gladden 2004). The two factors which stimulate mitochondrial respiration are an increase in redox potential and a decrease in phosphate potential. In situations where aerobic ATP production is compromised (decrease in oxygen availability, or impairment in oxygen transport and utilization) but where there is room for compensation, mitochondrial VO2 and aerobic ATP production are maintained at the cost of a lower phosphate potential. In the cytosol, the lower phosphate potential stimulates glycolysis, increasing redox potential (NDH2/NAD) and, as consequence, the LA/pyruvate ratio, and muscle and, thus, plasma [LA].

REFERENCES

Baldwin KM, Campbell PJ, Cooke DA (1977) Glycogen, lactate, and alanine changes in muscle fiber types during graded exercise. J Appl Physiol 43: 288-291

Bennett AF, Licht P (1974) Anaerobic metabolism during activity in amphibians. Comparative Biochemistry and Physiology 48A: 8

Brooks GA (1986a) Lactate production under fully aerobic conditions: the lactate shuttle during rest and exercise. Fed Proc 45: 2924-2929

Brooks GA (1986b) The lactate shuttle during exercise and recovery. Med Sci Sports Exerc 18: 360-368

Brooks GA (2000) Intra- and extra-cellular lactate shuttles. Med Sci Sports Exerc 32: 790-799

Connett RJ, Honig CR, Gayeski TE, Brooks GA (1990) Defining hypoxia: a systems view of VO2, glycolysis, energetics, and intracellular PO2. J Appl Physiol 68: 833-842

Coyle EF, Coggan AR, Hopper MK, Walters TJ (1988) Determinants of endurance in well-trained cyclists. J Appl Physiol 64: 2622-2630

di Pamprero PE (1981) Energetics of muscular exercise. Rev Physiol Biochem Pharmacol 89: 144-222
Faude O, Kindermann W, Meyer T (2009) Lactate threshold concepts: how valid are they? Sports Med 39: 469-490
Gastin PB (2001) Energy system interaction and relative contribution during maximal exercise. Sports Med 31: 725-741
Gladden LB (2004) Lactate metabolism: a new paradigm for the third millennium. J Physiol 558: 5-30
Gladden LB (2007) Is there an intracellular lactate shuttle in skeletal muscle? J Physiol 582: 899
Hawley JA, Bosch AN, Weltan SM, Dennis SC, Noakes TD (1994) Glucose kinetics during prolonged exercise in euglycaemic and hyperglycaemic subjects. Pflugers Arch 426: 378-386
Kenefick RW, Mattern CO, Mahood NV, Quinn TJ (2002) Physiological variables at lactate threshold under-represent cycling time-trial intensity. J Sports Med Phys Fitness 42: 396-402
Kinderman, Keul (1977) Lactate acidosis with different forms of sports activity. Canadian Journal of Applied Sports Sciences 2: 177
Lacour JR, Bouvat E, Barthelemy JC (1990) Post-competition blood lactate concentrations as indicators of anaerobic energy expenditure during 400-m and 800-m races. Eur J Appl Physiol Occup Physiol 61: 172-176
Levine BD (2008) VO2max: what do we know, and what do we still need to know? J Physiol 586: 25-34
Mayes PA (1988) Glycolysis and the oxidation of pyruvate. In: Murray RK, Granner DK, Mayes PA, Rodwell VW (eds) Harper's biochemistry. Lange, Norwalk, Connecticut, pp. 158-164
Medbo JI, Jebens E, Noddeland H, Hanem S, Toska K (2006) Lactate elimination and glycogen resynthesis after intense bicycling. Scand J Clin Lab Invest 66: 211-226
Nielsen HB, Febbraio MA, Ott P, Krustrup P, Secher NH (2007) Hepatic lactate uptake versus leg lactate output during exercise in humans. J Appl Physiol 103: 1227-1233
O'Brien MJ, Viguie CA, Mazzeo RS, Brooks GA (1993) Carbohydrate dependence during marathon running. Med Sci Sports Exerc 25: 1009-1017
Stanley WC, Gertz EW, Wisneski JA, Neese RA, Morris DL, Brooks GA (1986) Lactate extraction during net lactate release in legs of humans during exercise. J Appl Physiol 60: 1116-1120
Wasserman K, Koike A (1992) Is the anaerobic threshold truly anaerobic? Chest 101: 211S-218S