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WARM-UP

Leuven, July 2025

I had the urge to write this book – not to prove myself (not to someone else nor to myself), nor to prove my right. At least, I hope my ego doesn't need it.

The idea to write something about lactate testing originated some 10 years ago, when I actually wrote a new syllabus for one of my first workshops. I spent two entire summer months writing, not knowing if there would be enough interest in my new course. Hence, I prepared the syllabus in such a way that it could serve as a basis for a book, in case nobody would be interested in my classes. In that way, my industrious summer wouldn't have been a complete waste of time.

My classes turned out to be a huge success. People almost fought for a place. I organized new editions of my courses, tweaking my syllabus as many times. When some colleagues started to offer their own classes, interest in my own classes diminished. I also had to deal with 'not-always-very-constructive' criticisms. The comments sometimes paralyzed me. I doubted a dozen times whether I would go on. I couldn't hear the word 'lactate' anymore. But the idea of writing down my view on lactate testing never left me. Even if no one was interested or agreed, I wanted to be able to get my point across before I could move on. That's also why I decided to publish it independently, instead of working with a publisher that uses peer review - I've received enough comments along the way. My approach is undoubtedly imperfect, but I believe it's also too effective and too lived-through to simply discard.

If this final writing product leads to anything, my ego hopes it's one or more of the following.

First of all, I hope this work inspires you to think critically. I do NOT encourage you to follow my advice blindly - never ever do that! Listen with an open mind, listen truly, but always stay skeptical and critical to yourself, as I keep on trying. "Stay hungry, stay foolish" (Steve Jobs) – because "all convictions are prisons" (Friedrich Nietzsche).

Secondly, and more specifically, I hope this work broadens your view on lactate testing.

Third, exercise testing is the most beautiful métier of the world. I hope this manual contributes to the satisfaction you experience by guiding your clients to a healthier lifestyle and better performances.

Last but not least, and maybe the greatest satisfaction an author may wish for, is to get in touch with his readers: never hesitate to reach out to me! I am looking forward to your feedback, questions, or even meeting you in person for a coffee chat about 'exercise philosophy'.

Karel

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I. BACKGROUND



1. LACTATE TESTING: WHAT'S IN A NAME?

1.1. What is lactate?

It is not the aim of the present work to be exhaustive regarding biochemistry and to go into very ‘molecular’ details. However, for a better understanding of what follows, it is indispensable to summarize what is lactate and what it is not, where it comes from and what it presently means to exercise physiologists. For the reader who wants to achieve a more profound insight into this matter, some interesting extensive reviews have been written (Gladden 2008, Brooks 2009, van Hall 2010, Cabo, Martinez-Cambor et al. 2011, Hall, Rajasekaran et al. 2016, Brooks 2020).

1.1.1. The difference between lactate and lactic acid

‘Lactic acid’ and ‘lactate’ are often used interchangeably but they are not really the same. From a biochemical point of view, the difference is small and rather semantic: lactate is the conjugate base of lactic acid (Figure 1). Currently, most scientists agree that the muscle produces only lactate, not lactic acid (Robergs, Ghiasvand et al. 2004, Hall, Rajasekaran et al. 2016, Robergs 2019). At physiological pH levels, less than 0.5% of the total lactic acid and lactate is in the undissociated lactic acid form (Goodwin, Harris et al. 2007).

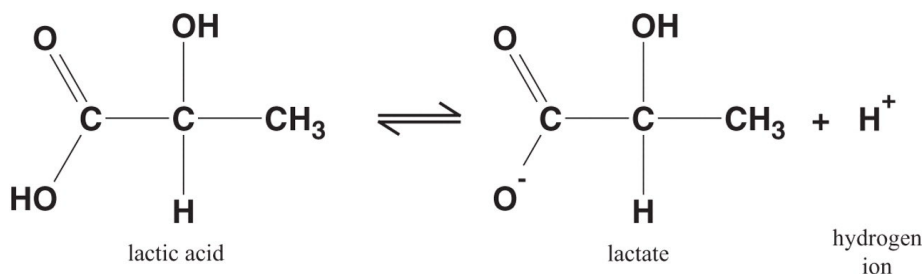


Figure 1. Lactic acid and the lactate anion.

However, the notion that *lactate* – actually L-lactate, the L-enantiomer of the lactate anion (Robergs, Ghiasvand et al. 2004, Brooks 2020) – and not *lactic acid* is produced by the body is rather new. This is in contrast to the belief that reigned for almost two centuries, since the discovery of ‘lactic’ acid in 1780 in sour milk (hence the trivial name for this molecule) (Robergs, Ghiasvand et al. 2004, Gladden 2008). However, lactic acid is a naturally occurring molecule. The fact that it was originally detected in food products led to its use in the food industry, e.g. as a preservative. Lactic acid has been used to acidify foods and beverages, assist in the fermentation of cabbage to sauerkraut, to preserve cucumbers, as an ingredient in the brewing and flavoring of beer, an ingredient to make cheese, as a source

of calcium (calcium lactate) in baby food, and an ingredient in bread (Robergs, Ghiasvand et al. 2004, Gladden 2008).

1.1.2. Lactic acidosis is (probably) a myth

For a very long time it was thought that glucose was converted to *lactic acid* in case of insufficient oxygen availability and/or when the energetic demands of the muscle exceeded the rate of ATP that could be delivered by aerobic metabolism. Nowadays we know that none of both is true: (1) *lactate* rather than *lactic acid* is being produced in the muscle, and (2) also under fully *aerobic* conditions (Robergs, Ghiasvand et al. 2004, Hall, Rajasekaran et al. 2016, Ferguson, Rogatzki et al. 2018, Robergs 2019, Brooks 2020, Poole, Rossiter et al. 2020). However, that belief was based on nothing less than the work of Otto Meyerhoff and Archibald V. Hill, which was rewarded with a Nobel prize in 1922.

This largely explains the persistent belief in *lactic acid* and its role in the origin of *metabolic acidosis*. It was thought that the production of lactic acid led to the release of protons, hence 'lactic acidosis' and ensuing fatigue. However, the latter reasoning has rather recently been questioned by Robergs (Robergs, Ghiasvand et al. 2004, Robergs 2019). He argues that the formation of lactate *consumes* rather than it *produces* protons (Figure 2). Rather than the formation has to be buffered, the formation of lactate acts as a buffer. The increase in blood and muscle lactate during intense exercise coincides with a decrease in pH in both tissues, but there is no causal relationship.

The exercise-induced metabolic acidosis is still debated, but probably can be explained by non-mitochondrial energy catabolism (i.e. ATP production in the cytosol, by the phosphagen and glycolytic systems) (Robergs, Ghiasvand et al. 2004, Hall, Rajasekaran et al. 2016, Ferguson, Rogatzki et al. 2018, Robergs 2019, Brooks 2020).

1.1.3. The origin and fate of lactate

Knowledge of energy delivery during exercise is crucial to understand lactate kinetics during exercise, and to design efficient and effective training programs.

Muscle contractions and, hence, all types of movements require the energy molecule ATP. Because its intramuscular stores are very small (hardly enough for 15 seconds of effort at even moderate intensity), the body continuously needs to regenerate ATP for efforts of longer duration. The shorter and/or the more intense the effort, the more important the anaerobic metabolic pathways ('substrate level phosphorylation') in energy supply. In contrast, the longer and/or the less intense the activity, the more the body will rely on aerobic energy metabolism (oxidative phosphorylation) (Hall, Rajasekaran et al. 2016, Hargreaves and Spriet 2020).

Hargreaves and Spriet (Hargreaves and Spriet 2020) provide us with an excellent up-to-date summary of the metabolic events during exercise:

*During very intense efforts lasting seconds (such as throws, jumps or 100- to 400-m sprints) or during intermittent game activities and field sports, most ATP is derived from the breakdown of phosphocreatine (PCr) and [intramuscular] glycogen to **lactate**.*

During events lasting several minutes to hours, the oxidative metabolism of carbohydrate and fat provides almost all the ATP for contracting skeletal muscle. Even during marathon and triathlon events lasting 2–2.5 h, there is a primary reliance on carbohydrate oxidation.

The major intramuscular and extramuscular substrates are muscle glycogen, blood glucose (derived from liver glycogenolysis and gluconeogenesis, and from the gut when carbohydrate is ingested) and fatty acids derived from both muscle (intramuscular triglyceride (IMTG)) and adipose tissue triglyceride stores.

Carbohydrate oxidation, particularly from muscle glycogen, dominates at higher exercise intensities, whereas fat oxidation is more important at lower intensities. Oxidation of muscle glycogen and fatty acids derived from IMTG is greatest during the early stages of exercise and declines as exercise duration is extended, coinciding with progressive increases in muscle glucose and fatty acid uptake and oxidation. Accompanying the increase in muscle glucose uptake is an increase in liver glucose output from both liver glycogenolysis and gluconeogenesis.

*Despite activation of the oxidative pathways in skeletal muscle during exercise, accelerated rates of glycolysis result in the production of **lactate**, which accumulates in muscle and blood, particularly at higher exercise intensities. (Hargreaves & Spriet, 2020: 1-2)*

Lactate is the inexorable product of glycolysis (Brooks, 2020). Glycolysis is nothing more or less than the breakdown of glucose into pyruvate. It consists of a series of 10 chemical reactions and takes place in the cytosol of the cell. The use of glycogen (the storage form of glucose) as the primary substrate, i.e. glycogenolysis, differs from glycolysis in bypassing the first reaction and thus shares the remaining nine reactions (Robergs, Ghiasvand et al. 2004, Hall, Rajasekaran et al. 2016). Both glycolysis and glycogenolysis produce the same amount of pyruvate.

Hall et al (Hall, Rajasekaran et al. 2016) briefly outline the fate of pyruvate and lactate:

[At lower exercise intensities] pyruvate will be ‘shuttled’ into the mitochondria, to undergo oxidative phosphorylation and to produce ATP for ongoing muscle contraction. At higher intensities of exercise, the mitochondria are unable to oxidize all the available pyruvate. The increasing

concentrations of pyruvate then trigger the conversion of pyruvate to lactate via the enzyme lactate dehydrogenase [Figure 2].

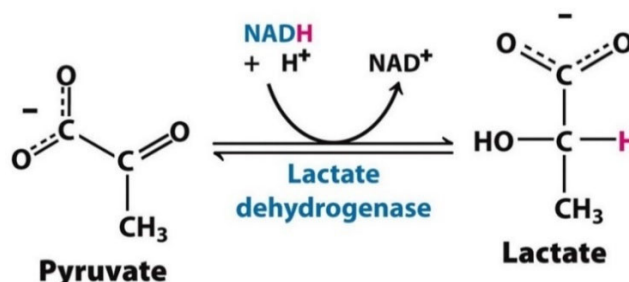


Figure 2. The lactate dehydrogenase reaction: rather than to produce protons, the formation of lactate consumes a proton and serves as a buffer.

At this point, several pathways can be taken, all of which are facilitated by the monocarboxylate transport proteins (MCTs). Lactate can be transported into the mitochondria (...) or it can be 'shuttled' out of the cell via an MCT, in conjunction with the extracellular transport of protons. This blood lactate can then be taken up and used as fuel by adjacent skeletal muscle, as well as the heart, brain, liver, and kidneys. During exercise, oxidation accounts for approximately 75% of lactate removal, with the remainder being used for gluconeogenesis in the liver and kidney.

Brooks introduced the concept of cell to cell [and intracellular] 'lactate shuttles' more than 30 years ago. (...) What has become clear is that lactate is not a waste product of anaerobic metabolism but rather an important fuel and potential signaling molecule that is continuously formed and utilized even under fully aerobic conditions.
(Hall et al., 2016: S9)

In a nutshell, lactate can be seen as a by-product of carbohydrate metabolism. When our muscles need energy during endurance exercise, they mainly use carbohydrates and fat to produce ATP. Oxygen is necessary for the oxidation of fat, and no lactate will be produced in this process. Carbohydrates can be 'burned' in the presence *or* in the absence of oxygen. More lactate will be produced in anaerobic than in aerobic conditions, i.e. when the demand for ATP is very high.

In fact, apart from brief and intense bursts of exercise, the human body can be compared to a car with three gears or types of fuel:

- ° gear 1 (low speed): (aerobic) oxidation of fat;
- ° gear 2 (intermediate speed): (aerobic) oxidation of carbohydrates;
- ° gear 3 (high speed): anaerobic glycolysis.

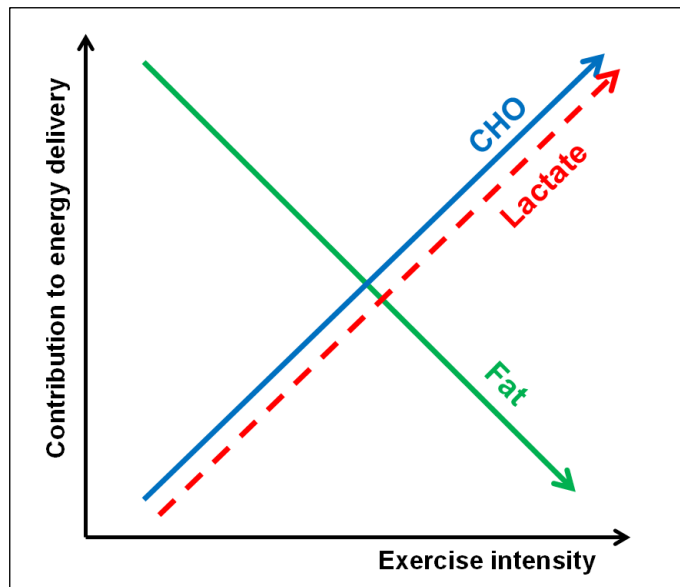


Figure 3. The simplified relationship between blood lactate concentration, fat oxidation and carbohydrate use as a function of exercise intensity. Carbohydrate and fat metabolism are largely complementary to each other. Therefore, lactate concentrations during exercise provide insight into the contribution of both carbohydrate and fat to energy delivery.

The body's ability to store carbohydrates is limited (~3000 kcal, liver and muscle combined), whereas fat resources are practically unlimited (~50.000-100.000 kcal, muscle and adipose tissue combined) (Hargreaves & Spriet, 2020). Hence, when an athlete wants to perform for many hours, reliance on fat is a *conditio sine qua non*. In other words, if it is the ambition of the athlete to possess an outstanding endurance, his or her ability to burn fat must be optimized.

Carbohydrate and fat metabolism are largely complementary to each other (Figure 3). This has also been very elegantly demonstrated in some studies on 'metabolic flexibility': endurance-trained athletes are able to use different types of fuel (such as carbohydrates and fats) depending on the body's needs (San-Millán and Brooks 2018). Other studies have shown that endurance training improves fat metabolism (Stisen, Stougaard et al. 2006).

The **cornerstone** of endurance training = training at a low intensity.

The **paradox** of endurance training = becoming faster by training slower (training mistake #1).



1.2. What is (physical) training?

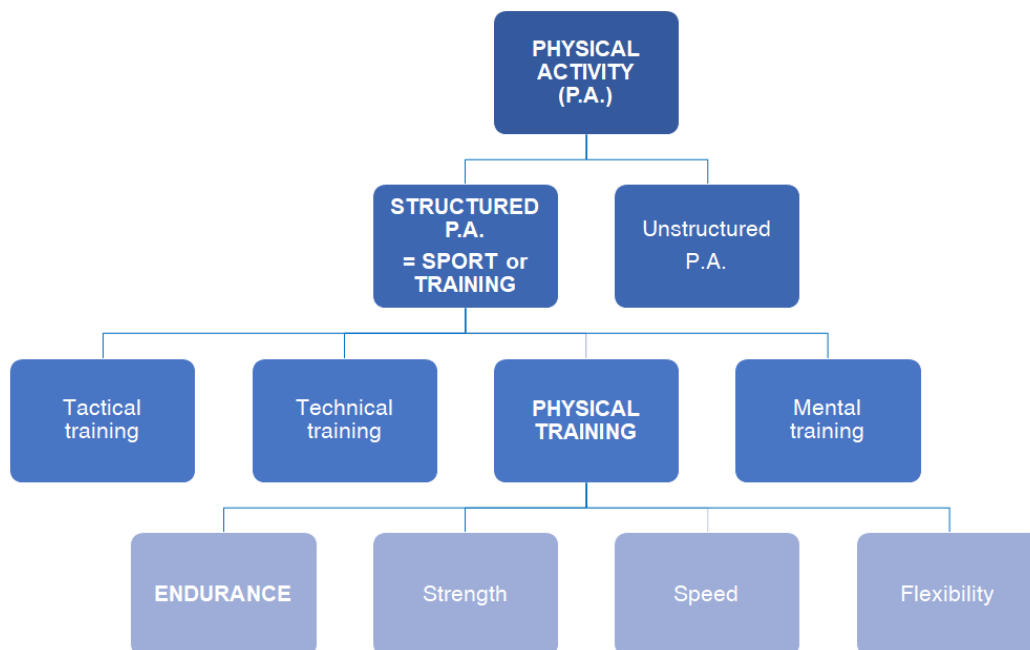


Figure 4. The different domains of structured physical activity, including endurance training.

Training of the physical characteristics is the domain of ‘training methodology’, which can be regarded as an applied science. Physical training consists mainly of improving the following four properties (Figure 4):

1. Endurance
2. Strength (incl. power)
3. Speed (incl. agility and ‘quickness’)
4. Flexibility

Sometimes the above list is extended with the properties *coordination* and/or *balance*.

Although coordination is frequently seen as subject to (and part of) ‘motor learning’ (training of technical skills), a certain overlap between motor learning and physical training will always exist (i.e. it is impossible to learn a technique (e.g. swimming) without being physically active).

Other classifications of physical training exist (ACSM 2006, Wormhoudt, Teunissen et al. 2013) but the question is whether they provide any added value compared to the traditional distinction, which works in the field (i.e. clear, distinctive, sufficiently mutually exclusive categories). In addition, the distinction is also acceptable on physiological grounds: e.g. training of speed is anaerobic, training of endurance is rather aerobic. Some training studies have also shown interference between endurance and strength training (i.e. ‘concurrent

training’)(Sedano, Marin et al. 2013, Ronnestad and Mujika 2014), or transfer between endurance sports (Millet, Candau et al. 2002).

1.3. What is endurance?

Endurance can be defined in several ways. Essentially, it reflects the duration that a certain effort can be sustained. From a physiological viewpoint, we can distinguish aerobic from anaerobic endurance, referring to the ‘capacity’ of respectively the aerobic and the anaerobic energy systems. Since the aerobic energy delivery is very much dependent on the cardiorespiratory system, it is also called ‘general endurance’. On the other hand, anaerobic performances are much less dependent on blood flow and they are the result of what we could describe as ‘local’ or ‘specific endurance’ (referring to a specific muscle or muscle group).

In the present work we will focus on general endurance, and, abbreviated, refer to it as endurance. Examples of sports in which cardiorespiratory fitness (i.e. the product of aerobic exercise) typically plays a pivotal role are swimming, cycling, (inline) skating, running, duathlon, triathlon, cross-country skiing, canoeing and kayaking.

It should be noted that, to be successful in ball sports such as tennis and soccer, it is necessary to possess so-called ‘repeated sprint ability’ (Chaouachi, Manzi et al. 2010) or ‘speed endurance’ (Vorup, Tybirk et al. 2016). The literature strongly suggests that a large overlap exists between (tests of) speed endurance and (tests of) general endurance (Krustrup, Mohr et al. 2003, Chaouachi, Manzi et al. 2010, Rampinini, Sassi et al. 2010, Ingebrigtsen, Brochmann et al. 2014, Vorup, Tybirk et al. 2016).

Watch your words !

In the context of endurance sports, terms like ‘capacity’, ‘power’, ‘performance’, or ‘fitness’ are never far away, e.g. ‘endurance capacity’, ‘aerobic power’, ‘cardiorespiratory fitness’. However, they should not be used interchangeably, as each of them has a different meaning.

Hence, **be careful and consistent with your vocabulary !**

This is where you distinguish the expert from the amateur.



1.4. Determinants of general endurance performance

In general and traditionally, three determinants of endurance performance are distinguished:

- (1) The *maximal exercise performance*, i.e. the size or magnitude of someone’s ‘engine’. It is reflected by the maximal workload, speed or oxygen uptake (Figure 5) that can be achieved during an exercise test.

LACTATE TESTING

For example, a man who is able to reach 300 Watt is likely to have a better endurance than a woman who only can push 150 Watt at the end of a gradual maximal bicycle ergometer test.

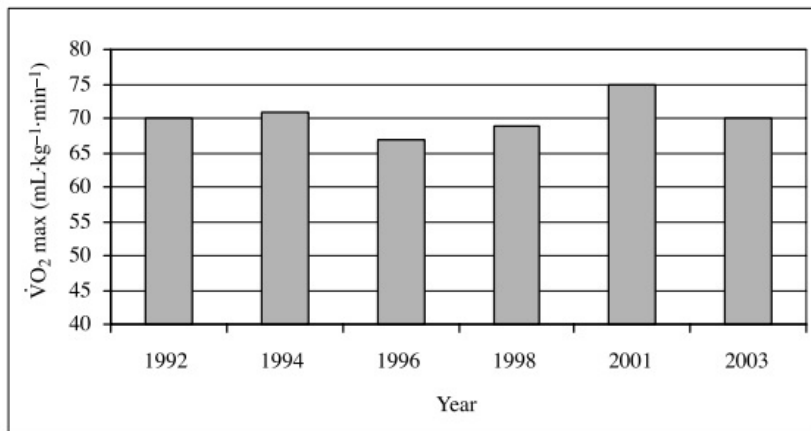


Figure 5. $\dot{V}O_2 \text{ max}$ values of Paula Radcliffe (≈ 1973), former world record holder for the women's marathon (Jones 2006).
[Reprinted by Permission of Sage Publications.]

- (2) The fraction of maximal exercise performance that can be sustained for a certain duration, i.e. 'the percentage of the engine' that can be used during an effort. It is reflected by 'thresholds', that can be determined during an exercise test (Figure 6).

For example, when two men are able to reach 300 Watt during a maximal exercise test, the one whose 'anaerobic threshold' (cf. infra) lies at a higher workload will perform better in an endurance event.

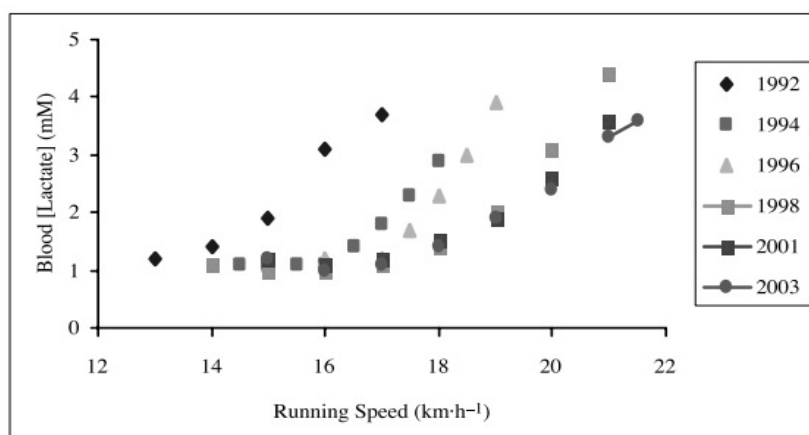


Figure 6. Lactate testing of Paula Radcliffe from age 19 to 30 (Jones 2006).
Note the exceptionally low maximal lactate values of the athlete.
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Recently, a lot of research has been dedicated to the determination of ‘critical power’ (cycling) or ‘critical speed’ (running), and whether it represents a better measure of the ‘maximal metabolic steady state’ than the lactate thresholds (Jones, Burnley et al. 2019, Galán-Rioja, González-Mohino et al. 2020).

- (3) The *economy of movement* or *work efficiency*, i.e. the amount of energy necessary to deliver a certain effort. It is reflected by the oxygen cost ($\dot{V}O_2$) for a given workload (Figure 7).

For example, when two men have the same maximal exercise performance and the same anaerobic threshold: in case of limited energy supplies (especially carbohydrate), the one who uses less oxygen for a given task (e.g. cycling at 30 km/h or 200 Watt) will win, when racing at that particular submaximal absolute exercise intensity.

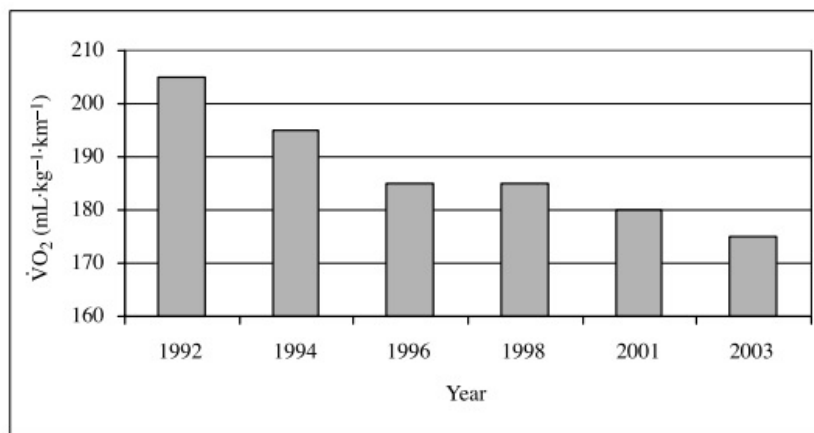


Figure 7. $\dot{V}O_2$ values when running at 16 kph of Paula Radcliffe, who established the women's world record for the marathon in London 2003 (Jones 2006).
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On the next pages we will focus on the first two determinants, i.e. maximal exercise performance and the fraction of maximal exercise performance that is usefully employable. In practice, economy of movement is relatively difficult to assess, and therefore less frequently considered (Coyle 2005, Jones 2006). This is rather unfortunate because it is very well acknowledged that this ‘third’ determinant of endurance performance even might be the most distinctive factor between high-level endurance athletes (who all have a large engine and are able to use that engine to a very great extent) (Lucia, Esteve-Lanao et al. 2006, Ronnestad and Mujika 2014). Not surprisingly, it played a crucial role in the selection of athletes attempting to break the 2-hour barrier in the marathon (Jones, Kirby et al. 2020).

It might be added that movement *economy* can not be deduced from someone's *style* of locomotion. Every coach recognizes his or her athletes by the characteristic way they move,

whether it is while swimming (i.e. a very ‘technical’ endurance sport) or during cycling (less ‘technical’). With the naked eye it is not always obvious to decide whether someone’s natural style has to be influenced to become more economical. The seemingly unpresentable style of some champion runners is famous (e.g. Paula Radcliffe, John Ngugi, Miel Puttemans), but nevertheless these athletes were very successful. Changes in technique must be accompanied by increased performance and/or reduced injury rate.

1.5. Lactate testing, definition & purpose

Any kind of exercise testing that is accompanied by lactate measurements at predefined points in time can be defined as a ‘lactate test’. However, the purpose of lactate testing is to evaluate the endurance of an athlete. Moreover, bearing the nature of lactate in mind, lactate testing will allow us to gain insight in both the aerobic and anaerobic abilities of the athlete. A lactate test therefore will generate a ‘metabolic profile’ of the athlete.

Several test protocols exist, but they roughly can be divided in two categories, i.e. graded and phased exercise testing.

In *graded* test protocols, the external load is gradually increased during the test: e.g. the running speed, the slope of the treadmill or the resistance on the bike. A typical example of a graded (or incremental or progressive) exercise test on the bike that you will frequently encounter in this work, consists of 10 minutes of warm-up at a load of 100 Watt, followed by increments of 40 Watt per 3 minutes.

During a *phased* test, efforts of varying intensity and duration are required. A typical example of a phased load test is depicted in Figure 8.

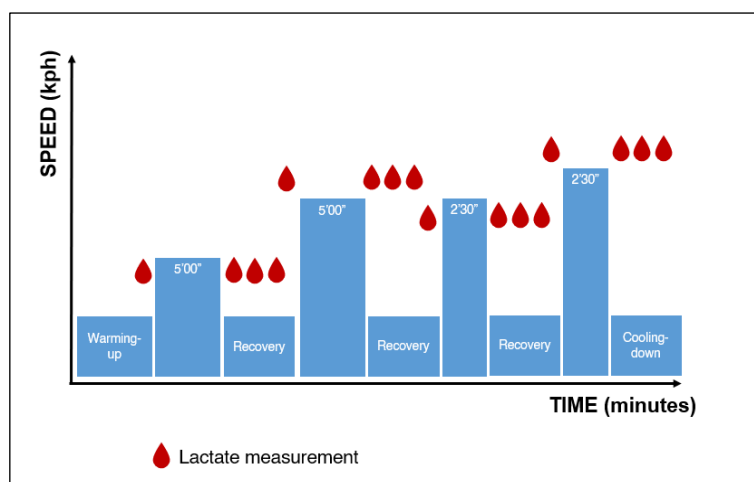


Figure 8. An example of a protocol of a phased exercise test. (source: Inscyd.com; adapted).

The collection of lactate measurements during phased tests happens in a completely different way than in graded tests: samples are taken immediately after the end of each

exercise phase, and several times during recovery. This allows to calculate other parameters and to make simulations of the behavior of the aerobic and the anaerobic systems.

Unlike the classical method of interpretation, where the assessment of the conditioning is directly based on the relation between lactate and speed, i.e. the position of the lactate curve in the lactate-speed diagram, this new evaluation technique uses the lactate values to determine the 2 decisive factors – the aerobic ($\dot{V}O_{2max}$) and the anaerobic capacities (vLA_{max}) – that generate the lactate-speed relation.

These capacities (...) can be used to simulate on computer the individual metabolic response that can be expected on different types of training exercises. According to the results of the simulation we then decide whether the metabolic reaction induced by a workout serves the purpose of the training objectives or not. (Olbrecht, 2000: 144)

To make a long story short, and in my opinion, both methods of testing have advantages and disadvantages, partly dependent on your target population (see Table 1).

In addition, experience (e.g. stories of trainers and athletes) has given me the impression that – in spite of the differences in methodology – the ensuing training advice is often very similar. In other words: the physiological basis for both kinds of testing is obviously the same; the ‘diagnosis’ of the energetic systems is made completely different; but the advice generally comes down to the same (Figure 9).

GRADED EXERCISE TESTING	PHASED EXERCISE TESTING
Generally less time consuming protocols	Generally more time consuming protocols
No calculation of movement economy	Calculation of economy generally possible
Generally cheaper (less measurements)	More expensive (more test strips needed, license for using software)
Determination of thresholds crucial but controversial	Less reliant upon thresholds
Interpretation very transparant	Underlying algorithms often not known
Limited software for analysis available	Software for analysis very well developed
A lot of scientific literature about test protocols and thresholds, but not about other parameters or practical applications	Little (English) scientific papers about the testing methodology

Table 1. Pros & cons of graded and phased exercise testing.

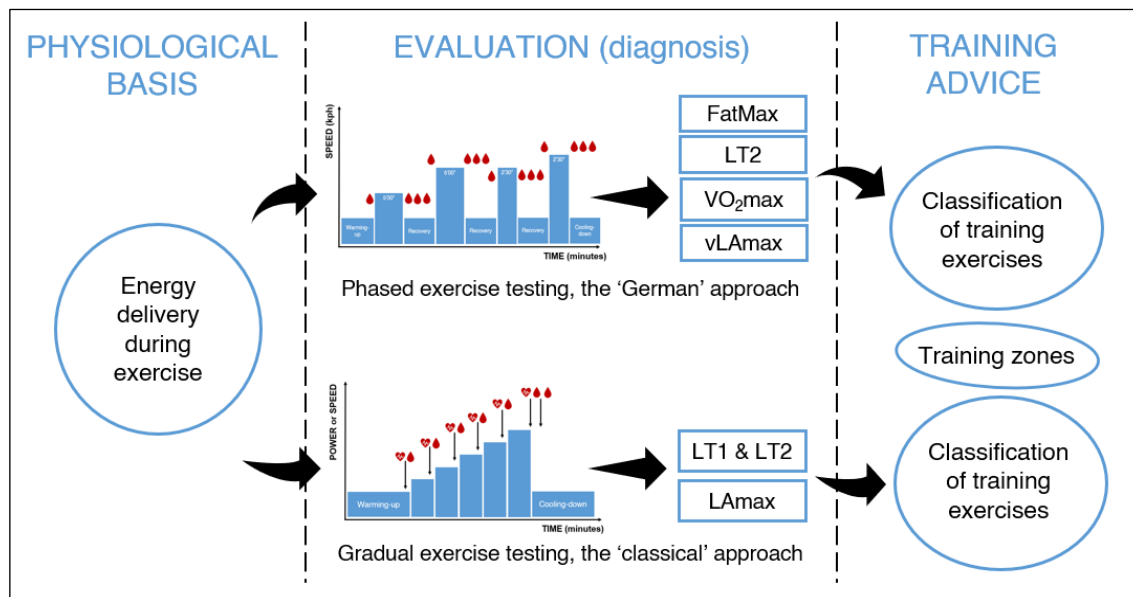


Figure 9. The differences and similarities between phased and gradual lactate testing.

In this manual we will focus on graded exercise testing. This kind of testing is usually performed until volitional exhaustion, i.e. 'maximal' exercise testing. This also applies to lactate testing: lactate measurements are usually collected during a maximal test.

Submaximal testing, e.g. until a predefined heart rate, workload or lactate concentration, sounds very appealing, e.g. to avoid untoward cardiovascular events. However, such events are very rare, especially in case of prior screening (see below), and a lot of valuable information is lost when testing submaximally: this will become clear in the following chapters.

Incremental and phased exercise testing: don't mix them up !

Sometimes, a stepwise – either submaximal or maximal – test protocol is followed by a single, shorter effort. The motivation to do so is usually to obtain 'maximal' values.

Suppose a test on an athletic track, with a protocol consisting of running 4 x 1200m (submaximal or not), followed by 5' jogging and 600m all-out:

- if the task is to run **the last 1200m all-out**, the 600m is very likely to generate higher values (speed, heart rate, lactate; cf. elsewhere); however, in my opinion, interpreting the test becomes very tricky, as you are comparing *apples and oranges*.
- if the task is to run **the last 1200m at an intensity corresponding with LT2**, then we probably have 'double trouble', especially when assuming that LT2 corresponds with 4,0 mmol/L.

Phased test protocols produce other results and other metrics (e.g. vLamax), that cannot be generated by means of an incremental exercise test. Don't mix them up. **It's one or the other.**