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optimize endurance training

One of your clients, a recreational runner, tells you that she has just registered for a 10K road race and would appreciate your input in designing a training program. Wanting to optimize her endurance training, you do some background research and discover that *lactate threshold* is the best predictor of endurance performance. However, in your reading, *ventilatory threshold, anaerobic threshold* and other obscure terms are cited as the same physiological event. Intrigued but confused, you wonder what all of these terms mean.

If this scenario sounds familiar, you're not alone. Deciphering the inconsistent terminology regarding this most essential component of endurance performance can be tricky. This article not only clearly explains the physiological mechanisms of lactate threshold, ventilatory threshold and anaerobic threshold but also discusses *heart rate threshold.* You can use this knowledge to outline training principles to improve the lactate thresholds of your clients.

Understanding the science behind and differences between the lactate, ventilatory, anaerobic and heart rate thresholds can help you customize endurance training programs for your athletic clients.

Lactate Threshold

Both at rest and under steady-state exercise conditions, there is a balance between blood lactate production and blood lactate removal (Brooks 2000). **Lactate threshold** is the exercise intensity at which blood lactate level increases abruptly (Robergs & Roberts 1997).

Maximal oxygen uptake (VO_2max) has traditionally been viewed as the key to success in prolonged exercise activities (Bassett & Howley 2000). However, researchers have recently proposed that lactate threshold is really the best and most consistent predictor of performance in endurance events. Indeed, studies have repeatedly found high correlations between performance in endurance events (such as running, cycling and race-walking) and maximal steady-state workload at lactate threshold (McArdle, Katch & Katch 1996).

Before we discuss the key physiological mechanisms of lactate threshold, a brief overview of metabolic pathways is necessary. **Metabolism** is all of the energy transformations that occur in the body. Therefore, a **metabolic pathway**

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is a series of chemical reactions that result in the formation of adenosine triphosphate (ATP, the universal energy-providing compound in the body) and waste products such as carbon dioxide. The body has three such energy systems, but it is a misconception to think that they work independently. They work together to produce ATP.

The **ATP-PC** (often called **phosphagen**) system is the simplest energy system. It has the shortest capacity to maintain ATP production (a maximum of 15 seconds) but is the most rapid and available source of ATP during intense exercise such as sprinting.

During submaximal-endurance exercise, the energy for muscle contraction comes from ATP regenerated almost exclusively through **mitochondrial respiration,** the second energy system. Mitochondrial respiration is the production of ATP within the mitochondria of cells.

Initially, mitochondrial respiration has the same pathway that **glycolysis,** the third energy system, has. In glycolysis, either blood glucose or muscle glycogen is converted into pyruvate. At exercise intensities below lactate threshold, pyruvate enters the mitochondria for mitochondrial respiration. At exercise intensities above lactate threshold, the capacity for mitochondrial respiration is exceeded, and pyruvate is converted into lactate. At this point, high-intensity exercise is compromised because, although the glycolytic and phosphagen systems sustaining muscle contraction above lactate threshold produce ATP at a high rate, they do so only for short durations of time (Bassett & Howley 2000).

Clearly, the energy for exercise requires all of these energy systems. However, the involvement of a particular system depends greatly on exercise intensity.

Understanding metabolic pathways helps in understanding the physiological mechanisms of lactate threshold. The exact physiological factors of lactate threshold are still being resolved, but it is thought to involve four key mechanisms (Robergs & Roberts 1997):

- **Decrease in Lactate Removal.** Even at rest, a small amount of lactate is produced. Therefore, lactate must also be removed; otherwise, it would accumulate at rest. The primary means of lactate removal is the uptake of lactate by the heart, liver and kidneys as a metabolic fuel (Brooks 1985). Within the liver, lactate functions as a chemical building block in **gluconeogenesis,** the production of glucose. Glucose is then released back into the bloodstream to be used as fuel or substrate elsewhere. Nonexercising or less active muscles are also capable of lactate uptake and consumption.

  The increase in lactate production that occurs exclusively during high-intensity exercise was once considered a negative metabolic event (see "Lactate Does Not Cause Fatigue" sidebar) but is definitely natural (Robergs & Roberts 1997). At exercise intensities above lactate threshold, there is simply a mismatch. The rate of lactate removal apparently lags behind the rate of lactate production (Katz & Sahlin 1988).
- **Increase in Fast-Twitch Motor Unit Recruitment.** To support the exercise workload at low intensities, slow-twitch muscles, characterized by a high aerobic endurance capacity that enhances mitochondrial respiration, are primarily recruited. Conversely, with increasing exercise intensity, more fast-twitch muscles, which have metabolic characteristics geared toward glycolysis, are recruited. The recruitment of these muscles shifts metabolism from mitochondrial respiration to glycolysis, eventually increasing lactate production (Anderson & Rhodes 1989).
- **Imbalance Between Glycolysis and Mitochondrial Respiration.** At higher exercise intensities, **glycolytic flux,** an increase in the rate of the conversion of glucose into pyruvate through the reactions of glycolysis, occurs. As

GLOSSARY

TERM	DEFINITION
Acidosis	a decrease in pH
Anaerobic threshold	an original concept describing increased lactate production during ischemia and hypoxia
Gluconeogenesis	the synthesis of glucose from noncarbohydrate sources
Glycolysis	a series of chemical reactions that break glucose down into pyruvate
Glycolytic flux	an increase in the rate of transformation of glucose into pyruvate through glycolysis
Hypoxia	diminished blood oxygen content
Ischemia	diminished blood flow
Lactate	a compound created from pyruvate during high-intensity exercise
Lactate threshold	the exercise intensity at which blood lactate level increases abruptly
Metabolic pathway	a series of chemical reactions that produce adenosine triphosphate (ATP) and waste products
Metabolism	all energy transformations within the body
Mitochondrial respiration	reactions within the mitochondria of cells that ultimately produce ATP and consume oxygen
Phosphagen system	the production of energy from coupled reactions of ATP and PC
Pyruvate	a compound derived from the metabolism of carbohydrates
Substrate	a substance, such as a foodstuff, acted upon and changed by an enzyme
Ventilatory threshold	the point of progressive increase in exercise intensity at which ventilation increases nonlinearly

described earlier, the pyruvate produced at the end of glycolysis can either enter mitochondria for mitochondrial respiration or be converted into lactate. Some researchers believe that, at high rates of glycolysis, pyruvate is produced faster than it can enter mitochondria (Wasserman, Beaver & Whipp 1986). Pyruvate that cannot enter mitochondria is converted into lactate, which can be used as fuel elsewhere in the body (such as the liver or other muscles).

- **Ischemia or Hypoxia.** For years, **ischemia** (diminished blood flow to exercising muscles) and **hypoxia** (low blood levels of oxygen in exercising muscles) were thought to be two primary causes of lactate production (Robergs & Roberts 1997). However, no experimental data indicate ischemia or hypoxia in exercising muscles, even at very high exercise intensities (Brooks 1985).

Confusingly, researchers have described lactate threshold with various terminology, including *maximal steady-state, anaerobic threshold, aerobic threshold, individual anaerobic threshold, lactate breaking point* and *onset of blood lactate accumulation.* Whenever studying lactate threshold, remember that all of these terms describe essentially the same physiological event (Weltman 1995).

Ventilatory Threshold

As exercise intensity progressively increases, ventilation, the flow of air into and out of the respiratory tract, increases linearly. However, with increasing exercise intensity, there eventually comes a point at which ventilation increases nonlinearly: the **ventilatory threshold.** Ventilatory threshold coincides with but is not identical to the development of muscle and blood acidosis (Brooks 1985). Blood buffers, compounds that help neutralize acidosis, work to reduce acidosis in muscle fibers, increasing levels of carbon dioxide, which the body attempts to eliminate by increasing ventilation (Neary et al. 1985).

Because ventilation increases with acidosis and increasing blood lactate levels, scientists originally believed that the ventilatory and lactate thresholds might occur at similar exercise intensities. This interpretation is appealing because, unlike lactate threshold, ventilatory threshold is measured noninvasively. Nonetheless, although numerous studies have shown a close correlation between the thresholds, other studies have demonstrated that different factors, including training status and carbohydrate supplementation, can cause them to differ substantially within an individual (Neary et al. 1985).

Anaerobic Threshold

The term **anaerobic threshold** was introduced in the 1960s. It is based on the concept that hypoxia exists in muscles at high exercise intensities (Robergs & Roberts 1997). At this point, if exercise were to be continued, the source of energy would have to shift from mitochondrial respiration (the aerobic energy system) to glycolysis and the phosphagen system (the anaerobic energy systems).

Many researchers find the term *anaerobic threshold* misleading because it suggests that the oxygen supply to muscles is limited at specific exercise intensities. As mentioned, no evidence indicates that muscles become deprived of oxygen, even at maximal exercise intensities (Brooks 1985).

The second main argument against the term is that it suggests that metabolism shifts *completely* from aerobic to anaerobic energy systems. This interpretation oversimplifies the regulation of metabolism. At higher exercise intensities, glycolysis and the phosphagen system do augment the energy supply provided by mitochondrial respiration but do not take over ATP regeneration completely (Robergs & Roberts 1997).

Heart Rate Threshold

In the early 1980s, Italian researchers developed a methodology to detect lactate threshold by determining **heart rate threshold,** the heart rate deflection point during a running test (Conconi et al. 1982). This easy and noninvasive approach to indirect lactate threshold measurement has been used extensively to design training programs and recommend exercise intensities (Hofmann et al. 1997; Janssen 2001).

However, research has shown that heart rate threshold is visible in only about half of all individuals and commonly overestimates lactate threshold (Vachon, Bassett & Clarke 1999). Because of these findings and the grave errors associated with use of the heart rate threshold method, fitness professionals are discouraged from recommending it when designing endurance-training programs for clients.

The Effect of Endurance Training on Lactate Threshold

Although similar, the ventilatory and lactate thresholds do not occur at exactly the same exercise workloads. The term *anaerobic threshold* oversimplifies the body's energy systems and has led to much confusion among fitness professionals. So many errors presently exist with the heart rate threshold technique that further research is needed before it can be used with confidence. Clearly, the key to designing a successful endurance-training program is the physiological understanding of lactate threshold alone.

It has been suggested that training intensity should be based on the running velocity (mph) or cycling workload (mph or watts) corresponding to lactate threshold. However, Arthur Weltman (1995), a leading researcher on the topic, says that more research is needed to identify not only the minimal training intensity for improving lactate threshold but also the optimal training intensity for improving lactate threshold. It is well known that, after endurance training, lactate threshold occurs at a relatively higher percentage of an individual's VO_2max than before training. This physiological training adaptation enables an individual to maintain higher steady-state running velocities or cycling workloads while maintaining a balance between lactate production and lactate removal. Endurance training influences both the rate of lactate production and the capacity for lactate removal.

The decrease in lactate production at the same given workload after endurance training can be attributed to an increase in the size and quantity of mitochondria and to mitochondrial enzymes (Holloszy & Coyle 1984; Honig, Connett & Gayeski 1992). These training adaptations enhance the body's ability to generate energy through mitochondrial respiration to decrease lactate production at a given workload.

In addition, endurance training appears to increase muscles' lactate utilization (Gladden 2000). Consequently, despite the heightened lactate production at high exercise intensities, blood lactate levels are lower. It should be noted that endurance training may also improve capillary density around muscles, especially slow-twitch muscles. This adaptation improves blood flow to and from exercising muscles to enhance the clearance of lactate and acidosis (Robergs & Roberts 1997).

LACTATE DOES NOT CAUSE FATIGUE

The classical explanation for fatigue, denoted by sensations of pain and the muscle "burn" experienced during intense exercise, is lactic acid buildup. Coaches, athletes, personal trainers and scientists alike have traditionally linked lactic acidosis to the inability to continue exercising at a given intensity. However, although lactate threshold indicates that conditions within muscle cells have shifted to a state favorable for the development of acidosis, lactate production itself does not directly contribute to the fatigue experienced at high intensities of exercise.

In actuality, the proton (H^+) accumulation coinciding with but not caused by lactate production decreases cellular pH (metabolic acidosis), impairing muscle contraction and ultimately leading to fatigue (Robergs 2001). During intense exercise, this increased H^+ accumulation occurs in a few different biochemical reactions, most notably the splitting of adenosine triphosphate (ATP) within myofilaments for sustained muscle contraction.

Training Programs for Lactate Threshold Improvement

Although researchers have yet to determine the *optimal* training program for lactate threshold improvement, you can follow some excellent guidelines to create workouts to enhance the lactate thresholds of your clients. Research has indicated that programs that combine high-volume, steady-state and interval workouts have the most pronounced effect on lactate threshold (Robergs & Roberts 1997; Weltman 1995).

Training Volume

Initially, whether the endurance activity is cycling, running or swimming, the best way to improve lactate threshold is simply to increase training volume. The premier benefit of increased training volume is increased capacity for mitochondrial respiration, essential to improving lactate threshold.

Volume should be increased gradually, by approximately 10 to 20 percent per week (Bompa 1999). For example, if an individual runs 20 miles per week, increase the training volume by 2 to 4 miles per week. Furthermore, intensity during this phase should be kept low. This approach may appear conservative but helps prevent overtraining and injuries.

The maximum training volume that an individual can attain depends on numerous factors and can best be gauged by determining the overall physical capacity and motivation of your client. Factors such as training status, training time, age and body weight determine the training volume that your client is realistically capable of achieving.

Steady-State and Interval Training

After an adequate buildup in training volume, steady-state and interval training should be addressed. Correct training intensity during this phase, which focuses on lactate threshold, is key to the continued success of the client's training program. Methods used to monitor steady-state and interval training must ensure that intensity is neither under- nor overestimated.

Most individuals do not have access to scientific laboratories where lactate threshold can be accurately determined from blood sampled during an incremental VO_2max test. Fortunately, alternative methods for the noninvasive estimation of lactate threshold have been recommended. For example, research has shown that lactate threshold occurs at 80 to 90 percent of the heart rate reserve (HRR) in trained individuals and 50 to 60 percent of HRR in untrained individuals (Weltman 1995).

The rating of perceived exertion (RPE) scale may be the most accurate way to determine training intensity during steady-state and interval training. Research has shown that RPE is strongly related to the blood lactate response to exercise, regardless of gender, training status and intensity, or the type of exercise performed (Weltman 1995). Studies have indicated that lactate threshold occurs between 13 and 15 on the RPE scale, which correspond to feelings of "somewhat hard" and "hard" (Weltman 1995).

Steady-State Training. Steady-state workouts should be performed as close to lactate threshold as possible. The length of these sessions can vary, depending on training status, the type of endurance activity performed and the distance of the endurance activity. Whereas novice runners training for a 5K road race and performing their first steady-state run may do only a 10-minute steady-state workout, a semiprofessional cyclist training for multiple days of racing 80-to-100-mile distances may do a 1-hour steady-state workout.

Interval Training. Interval training workouts are high-intensity training sessions performed for short durations of time at velocities or workloads above lactate threshold. As in steady-state workouts, the times and distances for interval workouts depend on training status, the type of endurance activity performed and the distance of the endurance activity. A novice runner training for a 5K road race may complete three 1-mile intervals at or faster than race pace with adequate recovery time between repetitions. A semiprofessional cyclist training for multiple days of racing 80-to-100-mile distances may perform several 5-to-10-mile intervals at or faster than race pace with appropriate recovery periods between repetitions.

The key to successful steady-state and interval training is careful monitoring of training intensity. Although it is necessary to perform these sessions at an elevated intensity, trainers should ensure that their clients avoid the pitfalls of racing through these workouts; that eventually results in overtraining. Moreover, it has been suggested that steady-state and interval workouts not exceed 10 to 20 percent of the client's total weekly training volume (Foran 2001).

The Bottom Line

After reading this, you should better understand the terminology and physiological mechanisms of lactate, ventilatory, anaerobic and heart rate thresholds. Designing the optimal endurance-training program for your client in preparation for her 10K road race should now be a less formidable task.

Because lactate threshold is the most important determinant of success in endurance-related activities, the main goal of endurance-training programs should be its improvement. You can improve your clients' lactate thresholds by first increasing training volume and then incorporating steady-state workouts (at lactate threshold) and interval workouts (above lactate threshold).

Finally, remember that correct training intensity is essential to any endurance-training program. Both the relative percentage of HRR and the RPE scale are proven methods for monitoring the training intensity of your clients during their workouts.

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