This chapter begins with a discussion of the anaerobic and aerobic energy continuum during exercise. The discussion then focuses on the concept of alactic and lactic anaerobic energy utilization that predominates in high-intensity exercise lasting less than 30 seconds. Included are the debates revolving around lactate threshold terminology, determination and the meaning and concepts of oxygen deficit and excess postexercise oxygen consumption (EPOC). The chapter ends with a discussion of lactate removal and how these concepts apply to children and older adults, as well as the genetic influence of anaerobic characteristics.
ANAEROBIC METABOLISM DURING EXERCISE

MEDIA FOR INSTRUCTORS

To view the chapter resources and activities listed below, please visit The Physiology Place located at www.physiologyplace.com.

Chapter Features
- Objectives
- Passport to the Internet

Instructor Resources
- Chapter 4 Test

Student Resources
- Quiz 1 & 2
- Activity: The Three Major Phases of Glycolysis (LA: HAP 25.2)

IP InterActive Physiology®

Muscular – Muscle Metabolism (pages 3-12; 15-18)
Chapter 4

Anaerobic Metabolism During Exercise

Outline

I. The Energy Continuum
   A. Alactic Anaerobic PC Production
   B. Lactic Acid/Lactate Production
   C. Lactate Clearance

II. Measurement of Anaerobic Metabolism
   A. Laboratory Procedures
      1. ATP-PC and Lactate
      2. Tests of Anaerobic Power and Capacity
         a. The Wingate Anaerobic Test
         b. The Margaria-Kalamen Stair Climb
         c. Field Tests

III. The Anaerobic Exercise Response
    A. Oxygen Deficit and Excess Postexercise Oxygen Consumption

IV. Anaerobic Exercise Responses
    A. ATP-PC Changes
    B. Lactate Changes
       1. High Intensity, Short Duration Dynamic Exercise
       2. Low Intensity, Short- and Long-Term Dynamic Aerobic Exercise
       3. Long-Term, Moderate to Heavy, Submaximal Aerobic Exercise
       4. Incremental Exercise to Maximum
       5. Dynamic Resistance Exercise
       6. Why is Lactic Acid a Problem?
       7. Time Frame for Lactate Removal Postexercise

V. Male Versus Female anaerobic Characteristics
   A. The availability and Utilization of ATP-PC
   B. The Accumulation of Lactate
   C. Mechanical Power and Capacity

VI. Anaerobic Exercise Characteristics of Children
    A. The Availability and Utilization of ATP-PC
    B. The Accumulation of Lactate
       1. The Muscle Enzyme Theory
       2. Sexual Maturation Theory
       3. Neurohormonal Regulation Theory
    C. The Lactate Threshold(s)
    D. Mechanical Power and Capacity

VII. Anaerobic Exercise Characteristics of Older Adults
    A. The Availability and Utilization of ATP-PC
    B. The Accumulation of Lactate
    C. Mechanical Power and Capacity

VIII. Heritability of Anaerobic Characteristics
ANAEROBIC METABOLISM DURING EXERCISE

Suggested Laboratory Activities

1. Time each student as she/he performs three of the following runs (comparable distance can of course be used if other modalities are selected):
   - 100 m dash
   - 200 m dash
   - 400 m dash
   - 800 m dash
   - 1500 or 1600 m run
   - 3 mile run
   On the basis of the performance times, determine the approximate percent contribution of aerobic and anaerobic metabolism using Figure 4.2.

2. Compare and contrast lactate accumulation ([La¹]) from the following activities:
   - 10 second Wingate Anaerobic Test (arms or legs)
   - 30 second Wingate Anaerobic Test (arms of legs)
   - 20 minute cycle ergometer ride (heart rate not to exceed 120 b·min⁻¹)

3. Calculate the peak power, mean power, and Fatigue Index for contrasting individuals such as:
   - untrained male versus untrained female
   - aerobically trained versus anaerobically trained (same sex)
   - anaerobically trained athlete versus untrained individual (same sex)

4. Complete a single load submaximal aerobic workout. Measure oxygen consumption at rest (5 minutes), during exercise (20 minutes), and during recovery (15 minutes). Graph the results showing oxygen deficit and EPOC (Figure 4.5).

5. Determine [La¹] every 5 minutes for 30 minutes during recovery from an interval training session. Use three recovery variations:
   - rest
   - walking
   - jogging at a self-selected pace
   Compare and contrast the results.


1. Responses to Different Categories of Exercise, page 29
1. Describe the energy continuum. For each of the following sports or events, determine the percentage contribution from the ATP-PC, LA, and \( O_2 \) systems.

**Figure 4.2; Pgs. 86-89**
The energy continuum indicates the relative contribution of each energy system (alactic anaerobic or ATP-PC; lactic anaerobic or LA; and aerobic or \( O_2 \)) to the total energy requirements of an activity based on the time of the activity. This assumes that the intensity of all-out effort decreases from 100% to 80% as the duration of the activity increases from 10 seconds to 120 minutes.

<table>
<thead>
<tr>
<th>Event</th>
<th>% ATP-PC</th>
<th>%LA</th>
<th>%( O_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-m dash</td>
<td>75</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>800-m dash</td>
<td>30</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>Soccer</td>
<td>20</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>Triathlon</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>98</td>
</tr>
<tr>
<td>Volleyball spike</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>100-m swim</td>
<td>17</td>
<td>58</td>
<td>25</td>
</tr>
<tr>
<td>mile run</td>
<td>2</td>
<td>8</td>
<td>80</td>
</tr>
<tr>
<td>stealing a base</td>
<td>65</td>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>

2. List the major variables that are typically measured to describe the anaerobic response to exercise. Where possible, provide an example of an exercise test from which the variable could be determined.

**Figure 4.8; Table 4.2; Pgs. 92-96**

<table>
<thead>
<tr>
<th>Major Anaerobic Variables</th>
<th>Exercise Test Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical</td>
<td></td>
</tr>
<tr>
<td>• ATP-PPC</td>
<td>• must be measured directly after high intensity exercise</td>
</tr>
<tr>
<td>• lactate concentration</td>
<td>• must be measured directly after high intensity exercise</td>
</tr>
<tr>
<td>• lactate thresholds</td>
<td>• Incremental test to maximum (cycle ergometer)</td>
</tr>
<tr>
<td>(LT1 &amp; LT2)</td>
<td></td>
</tr>
<tr>
<td>Mechanical work/ performance</td>
<td></td>
</tr>
<tr>
<td>• mean power</td>
<td>• Wingate Anaerobic Test (WAT)</td>
</tr>
<tr>
<td>• peak power</td>
<td>• WAT/ Margaria-Kalamem Stair Climb/ vertical jump</td>
</tr>
<tr>
<td>• fatigue index</td>
<td>• Wingate Anaerobic Test (WAT)</td>
</tr>
<tr>
<td>• lactic anaerobic power &amp; capacity</td>
<td>• sprint and middle distance run times</td>
</tr>
<tr>
<td>• alactic anaerobic power</td>
<td>• short (40-100-m) dash times</td>
</tr>
</tbody>
</table>
3. Explain the five physiological reasons for the production of lactic acid. What determines whether or not lactate accumulates in the blood? How is lactate cleared?

**Pg. 90-92, Figure 4.4**
The five physiological reasons for the production of lactate are:

a) Muscle contraction- during muscle contractions there is a release of Ca\(^{++}\), this causes glycogenolysis by activating the enzyme glycogen phosphorylase.;

b) Enzyme activity- the activity of lactate dehydrogenase is higher than that of the enzymes that provide alternate pathways for pyruvate;

c) Sympathetic nervous system activation- hormonal changes during exercise increase the breakdown of glycogen leading to increased G6P levels. In turn, glycolysis and the production of pyruvate are increased. High levels of pyruvate lead to high levels of lactate as noted in b;

d) Insufficient oxygen (anaerobiosis, onset of anaerobic metabolism) during high intensity exercise, the delivery of oxygen to the mitochondria to become the final electron acceptor can become deficient.;

e) Muscle fiber type- the recruitment of fast twitch muscle fibers, especially FG fibers.

Lactate clearance occurs primarily by three processes: oxidation, gluconeogenesis/glyconeogenesis, and transamination. Lactate moves between lactate-producing and lactate-consuming sites by means of intracellular and extracellular lactate shuttles. As of 1998, seven monocarboxylate transporters have been reported in the literature.

4. Arrange the ATP-PC, LA, and \(O_2\) systems from highest to lowest in terms of (a) power and (b) capacity. What is the difference between power and capacity?

<table>
<thead>
<tr>
<th></th>
<th>Power</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>high</td>
<td>ATP-PC</td>
<td>(O_2)</td>
</tr>
<tr>
<td>medium</td>
<td>LA</td>
<td>LA</td>
</tr>
<tr>
<td>low</td>
<td>(O_2)</td>
<td>ATP-PC</td>
</tr>
</tbody>
</table>

Power in terms of the energy system is defined as the maximum amount of energy that can be produced per unit of time, and is expressed in kcal-min\(^{-1}\) (kJ-min\(^{-1}\)). Capacity is defined as the total amount of energy that can be produced by the energy system. It is expressed in kcal (kJ).

5. Diagram the oxygen deficit and excess postexercise oxygen consumption for an activity that requires 110% \(VO_2\)max in an individual whose \(VO_2\) max equals 4 L·min\(^{-1}\). Explain how energy is provided during the oxygen deficit time period and why oxygen remains elevated during recovery.

**Figure 4.7; Pgs. 96-98**
Energy is provided during the oxygen deficit by four sources: (1) \(O_2\) transport and utilization; (2) utilization of oxygen stores in capillary blood and on myoglobin; (3) splitting of stored ATP-PC; (4) anaerobic glycolysis with the concomitant production of lactic acid. Energy remains elevated during the excess post exercise oxygen consumption (EPOC) phase because: (1) restoration of ATP-PC stores which has a half-life of 30 sec, so full storage takes about 2 min; (2) restoration of \(O_2\) stores which takes about 2-3 min; (3) elevated cardiovascular-respiratory function but only accounts for 1-2% of excess \(O_2\); (4) elevated hormonal levels (catecholamines, thyroxine, and cortisol); (5) elevated body temperature, which is the major factor; and (6) lactate removal.
6. Diagram and explain the changes that take place in ATP, PC, and [LA\textsuperscript{-}] during constant-load, heavy exercise lasting 3 minutes or less.

**Figure 4.8; Table 4.3; Pgs. 98-100**

ATP, PC and Lactate changes in heavy exercise in <3 minutes are as follows: ATP level in the muscle decreases only slightly (30-40%). The greatest depletion of PC occurs in the first 20 seconds of exercise, after which the decline in both ATP and PC is gradual. PC is nearly depleted (decreased by 60-70%). Lactate level depends on intensity of exercise but in short duration high intensity exercise, lactate levels rise immediately at onset and continue throughout exercise, reading levels from 2-12 mmol\cdot L\textsuperscript{-1}.

7. Explain the concept of maximal lactate steady state and why MLSS is important in endurance performance.

**Pg. 101**

MLSS is the highest workload that can be maintained over time without a continual rise in blood lactate. MLSS indicates an exercise intensity above which lactate production exceeds clearance. Performances at the MLSS intensity will result in a steady state for lactate, while performances below this intensity will show declining lactate values and performance above this level will exhibit increasing levels of lactate.
8. Diagram the lactate response to incremental work to maximum. The ventilatory and lactate thresholds often occur at approximately the same time. Debate whether this is a result of cause and effect or coincidence. Can either the lactate thresholds or the ventilatory thresholds be accurately described as anaerobic thresholds? Why or why not?

**Figures 4.13, 4.14; Pgs. 101-105**

![Graph](image)

In order for the accumulation of lactate (indicated by the lactate thresholds) to be causally related to the breakpoints seen in minute ventilation (ventilatory thresholds) the following conditions must be met:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Evidence</th>
</tr>
</thead>
</table>
| Lactic acid or some by-product of it’s buffering must be capable of stimulating respiration almost simultaneous to it’s production | **Pro-** Carbon dioxide is produced as a result of the buffering of lactic acid 
(NaHCO₃ + HLa ⇄ NaLa + H₂CO₃; H₂CO₃ ⇄ H₂O + CO₂)  
CO₂ is a potent stimulant of respiration  
**Con-** The presence of lactic acid is not the only mechanism that can account for an increase in CO₂ or Vₑ. For example, M’Ardle’s syndrome patients cannot produce lactic acid due to an enzyme deficiency yet they show VT points. |
| Anything which affects the lactate threshold should affect the ventilatory thresholds equally | **Con-** The LT and VT points do not change to the same extent in the same individuals as a result of training, glycogen depletion, and varying pedaling rates. |

Neither the lactate thresholds nor the ventilatory thresholds can be accurately described as anaerobic thresholds.

- the presence of lactate does not automatically mean that there is a lack of oxygen (anaerobiosis). The presence of lactate instead reflects the use of the anaerobic glycolytic pathway (by fast twitch fibers and from the utilization of glycogen) and, the balance between glycolytic and mitochondrial activity (the balance between lactate production, removal and clearance, as well as the rate of pyruvate oxidation). Most especially lactate accumulation does not occur at the time of increased production.
- the pattern of lactate accumulation is more likely a positive exponential curve than any sharp breakpoints or thresholds.
9. What are the physiological effects of lactate accumulation?

**Pgs. 105-106**
The physiological effects of lactic acid are more related to the concentration of H⁺ ions than the concentration of La⁻. The effects of an increased concentration of H⁺ on the decrease in pH include: pain, performance decrement, reduced production of ATP (rate-limiting enzymes can be inactivated, and substrate availability is inhibited); reduced force and velocity of muscle contraction by [1] inhibition of actomyosin ATPase which is the enzyme responsible for the breakdown of ATP for muscle contraction, and [2] interference with the actions and uptake of calcium ions that is necessary for excitation-coupling and relaxation of protein cross-bridges within muscle fibers. High levels of lactate ions may also interfere with cross bridging.

10. What is the best way to clear lactate quickly during recovery?

**Pgs. 106-108**
Active recovery is the best way to clear lactate quickly during recovery. Continuous activity is best at intensity levels below the lactate threshold (~29-45% VO₂ max for cycling and 55-70% VO₂ max for running).
11. What are the effects of sex and age on anaerobic metabolism during exercise?

**Figures 4.19, 4.21, 4.23; Pgs. 108-113**

**The Influence of Age on Anaerobic Metabolism**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Children</th>
<th>Young Adults</th>
<th>Elderly</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATP-PC</td>
<td></td>
<td></td>
<td>stores are reduced an unable to be used quickly</td>
</tr>
<tr>
<td>[La-]max</td>
<td>lower</td>
<td>baseline for comparison</td>
<td>lower</td>
</tr>
<tr>
<td>LT2</td>
<td>lower absolute workload but higher %VO₂ max</td>
<td>baseline for comparison</td>
<td>unknown</td>
</tr>
<tr>
<td>Mechanical Power &amp; Capacity</td>
<td>lower</td>
<td>baseline for comparison</td>
<td>lower</td>
</tr>
</tbody>
</table>

**The Influence of Sex on Anaerobic Metabolism**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Female</th>
<th>Male</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATP-PC</td>
<td></td>
<td>baseline for comparison</td>
</tr>
<tr>
<td>[La-]max</td>
<td>lower</td>
<td>baseline for comparison</td>
</tr>
<tr>
<td>LT1 &amp; LT2</td>
<td>same %VO₂ max lower absolute workload</td>
<td>baseline for comparison</td>
</tr>
<tr>
<td>Mechanical Power &amp; Capacity</td>
<td>lower peak power &amp; mean power</td>
<td>baseline for comparison</td>
</tr>
<tr>
<td></td>
<td>equal fatigue index</td>
<td></td>
</tr>
</tbody>
</table>

12. Approximately how much of an individual’s anaerobic ability is due to genetics? Are sprinters made or born?

**Pgs. 113-114**

Approximately 44-76% of an individual’s anaerobic ability is due to genetics, the exact amount is unknown. At least to a certain extent, sprinters are born.