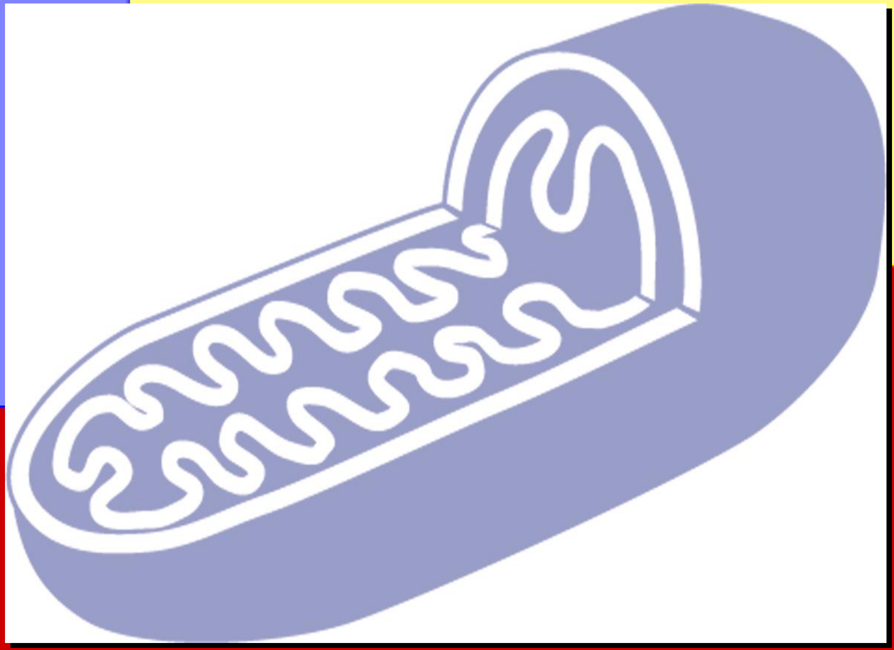
METABOLISM, ENERGY, AND THE BASIC ENERGY SYSTEMS



Learning Objectives

- Learn how our bodies change the food we eat into ATP to provide our muscles with the energy they need to move.
- Examine three systems that generate energy for muscles.
- Explore how energy production and availability can limit performance.

(continued)

Learning Objectives

- Learn how exercise affects metabolism and how metabolism can be monitored to determine energy expenditure.
- Discover the underlying causes and sites of fatigue in muscles.

Calorie and Kilocalorie

- Energy in biological systems is measured in calories (cal).
- 1 cal is the amount of heat energy needed to raise 1 g of water 1°C from 14.5°C to 15.5°C.
- In humans, energy is expressed in kilocalories (kcal), where 1 kcal equals 1,000 cal.
- People often mistakenly say “calories” when they mean more accurately kilocalories. When we speak of someone expending 3,000 cal per day, we really mean that person is expending 3,000 kcal per day.

Energy for Cellular Activity

- Food sources are processed via catabolism—the process of “breaking down.”
- Energy is transferred from food sources to our cells to be stored as ATP.
- ATP is a high-energy compound stored in our cells and is the source of all energy used at rest and during exercise.

Energy Sources

- At rest, the body uses carbohydrates and fats for energy.
- Protein provides little energy for cellular activity, but serves as building blocks for the body's tissues.
- During moderate to severe muscular effort, the body relies mostly on carbohydrate for fuel.

Carbohydrate

- Readily available (if included in diet) and easily metabolized by muscles
- Once ingested, it is transported as glucose and taken up by muscles and liver and converted to glycogen
- Glycogen stored in the liver is converted back to glucose as needed and transported by the blood to the muscles where it is used to form ATP
- Glycogen stores are limited, which can affect performance

Fat

- Provides substantial energy at rest and during prolonged, low-intensity activity
- Body stores of fat are larger than carbohydrate reserves
- Less accessible for metabolism because it must be reduced to glycerol and free fatty acids (FFA)
- Only FFAs are used to form ATP
- Fat is limited as an energy source by its rate of energy release

Body Stores of Fuels and Energy

	g	kcal
Carbohydrates		
Liver glycogen	110	451
Muscle glycogen	500	2,050
Glucose in body fluids	15	62
Total	**625**	**2,563**
Fat		
Subcutaneous and visceral	7,800	73,320
Intramuscular	161	1,513
Total	**7,961**	**74,833**

Note. These estimates are based on an average body weight of 65 kg (143 lb) with 12% body fat.

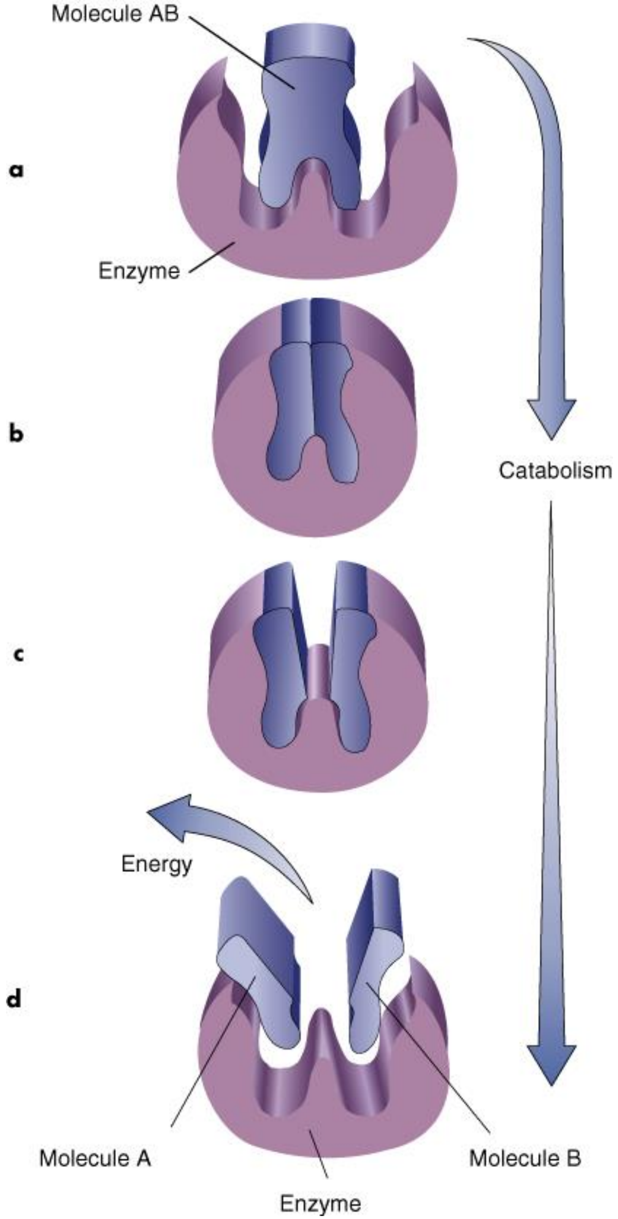
Protein

- Can be used as an energy source if converted to glucose via **gluconeogenesis**
- Can generate FFAs in times of starvation through **lipogenesis**
- Only basic units of protein—amino acids—can be used for energy: ~4.1 kcal of energy per g of protein

Enzymes

- Specific protein molecules that control the breakdown of chemical compounds
- Names are often complex, but always end in “ase”
- Work at different rates and can limit a reaction
- Glycolytic enzymes act in the cytoplasm, while oxidative enzymes act in the mitochondria

ACTION OF ENZYMES



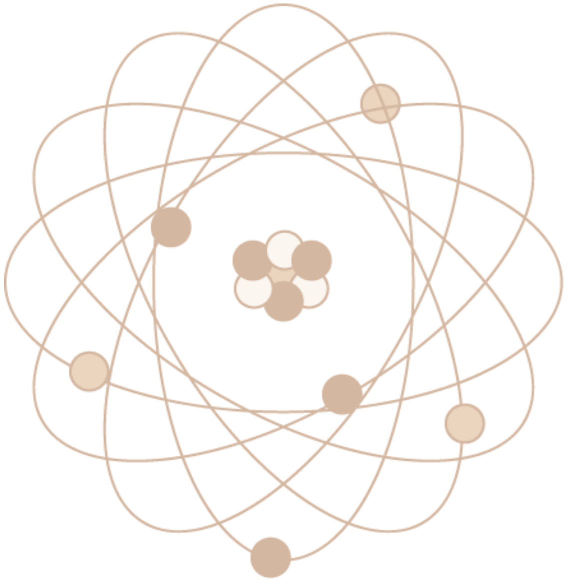
Key Points

Energy for Cellular Metabolism

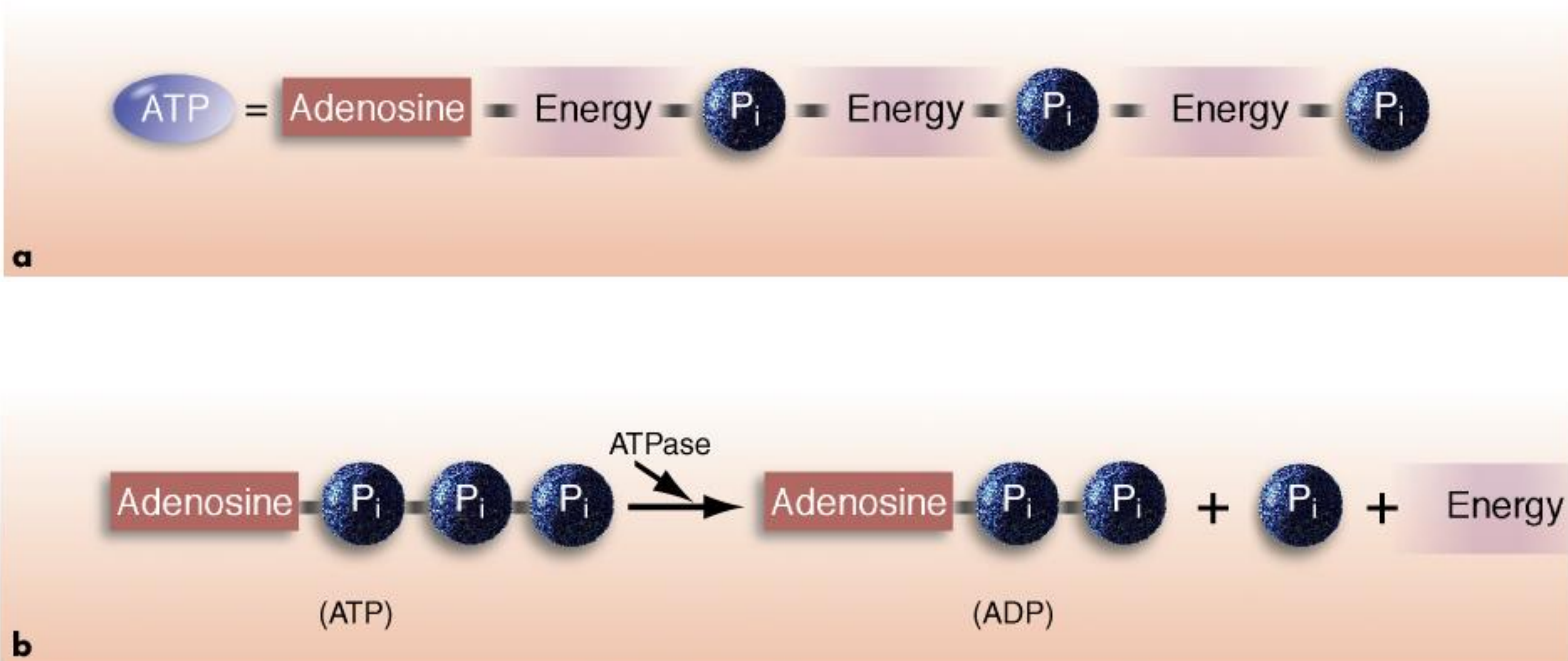
- Carbohydrate, fats, and protein provide us with fuel that our bodies convert to ATP.
- ATP is the high-energy compound released and stored within our cells.
- Carbohydrate and protein provide about 4.1 kcal/g while fat provides about 9.4 kcal/g.
- Carbohydrate energy is more accessible to the muscles than protein or fat.

Basic Energy Systems

1. ATP-PCr system (phosphagen system)—cytoplasm
2. Glycolytic system—cytoplasm
3. Oxidative system—mitochondria or powerhouses of cell



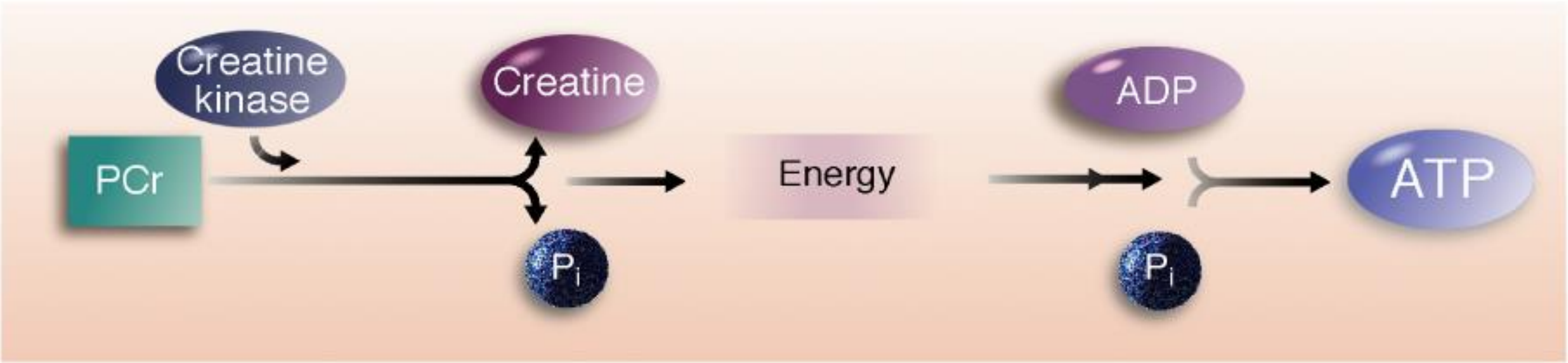
ATP MOLECULE



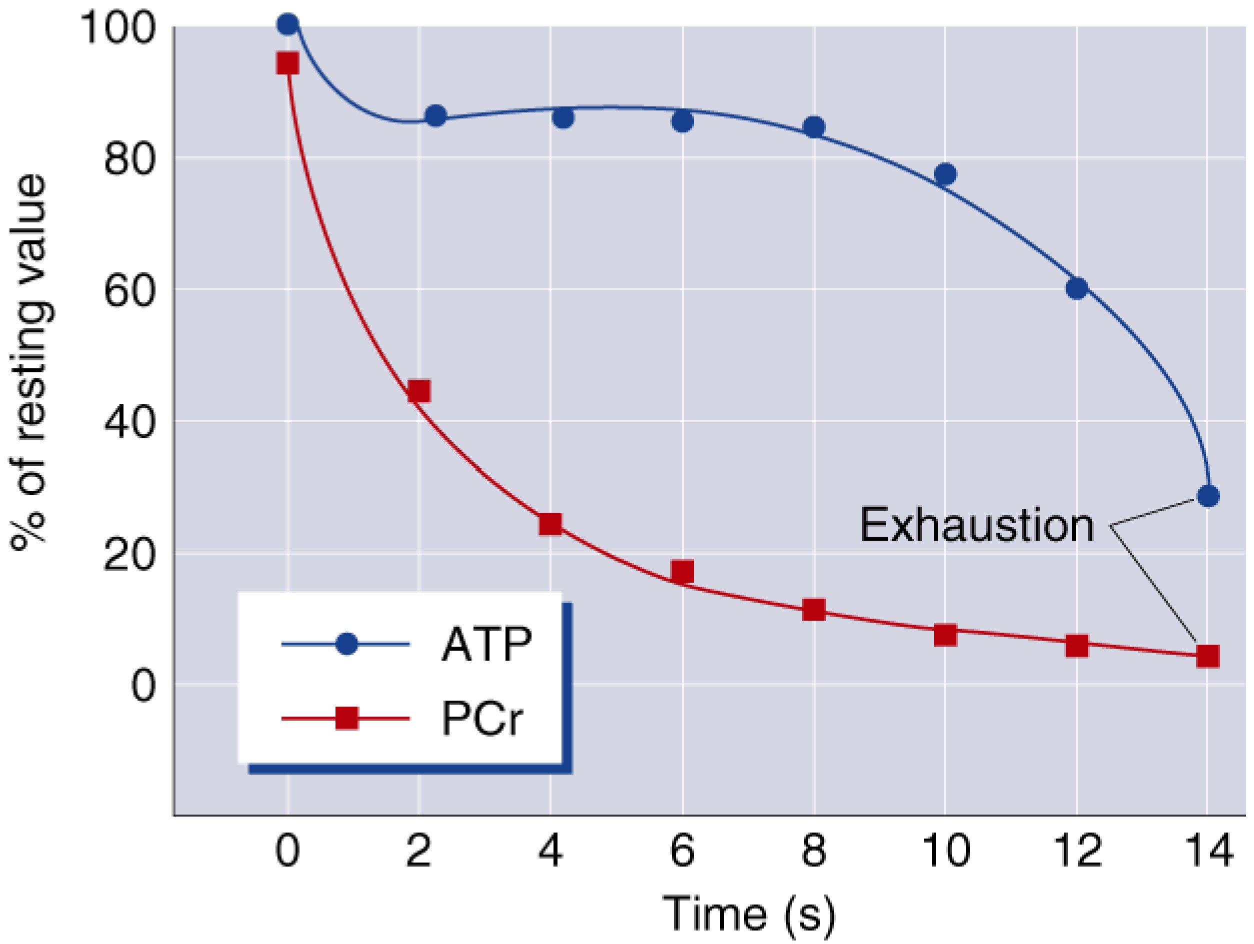
ATP-PCr System

- This system can prevent energy depletion by quickly reforming ATP from ADP and P_i.
- This process is anaerobic—it occurs without oxygen.
- 1 mole of ATP is produced per 1 mole of phosphocreatine (PCr). The energy from the breakdown of PCr is not used for cellular work but solely for regenerating ATP.

RECREATING ATP WITH PCr



ATP AND PCr DURING SPRINTING



Glycogen Breakdown and Synthesis

Glycolysis—Breakdown of glucose; may be anaerobic or aerobic

Glycogenesis—Process by which glycogen is synthesized from glucose to be stored in the liver

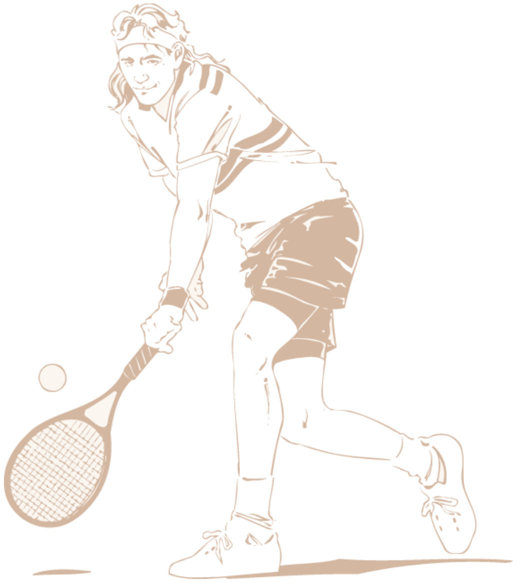
Glycogenolysis—Process by which glycogen is broken into glucose-1-phosphate to be used by muscles

Glycolytic System

- Requires 12 enzymatic reactions to breakdown glucose and glycogen into ATP
- Glycolysis that occurs in glycolytic system is generally anaerobic (without oxygen)
- The pyruvic acid produced by anaerobic glycolysis becomes lactic acid
- 1 mole of glycogen produces 3 mole ATP; 1 mole of glucose produces 2 mole of ATP. The difference is due to the fact that it takes 1 mole of ATP to convert glucose to glucose-6-phosphate, where glycogen is converted to glucose-1-phosphate and then to glucose-6-phosphate without the loss of 1 ATP.

Did You Know…?

The combined actions of the ATP-PCr and glycolytic systems allow muscles to generate force in the absence of oxygen; thus these two energy systems are the major energy contributors during the early minutes of high-intensity exercise.



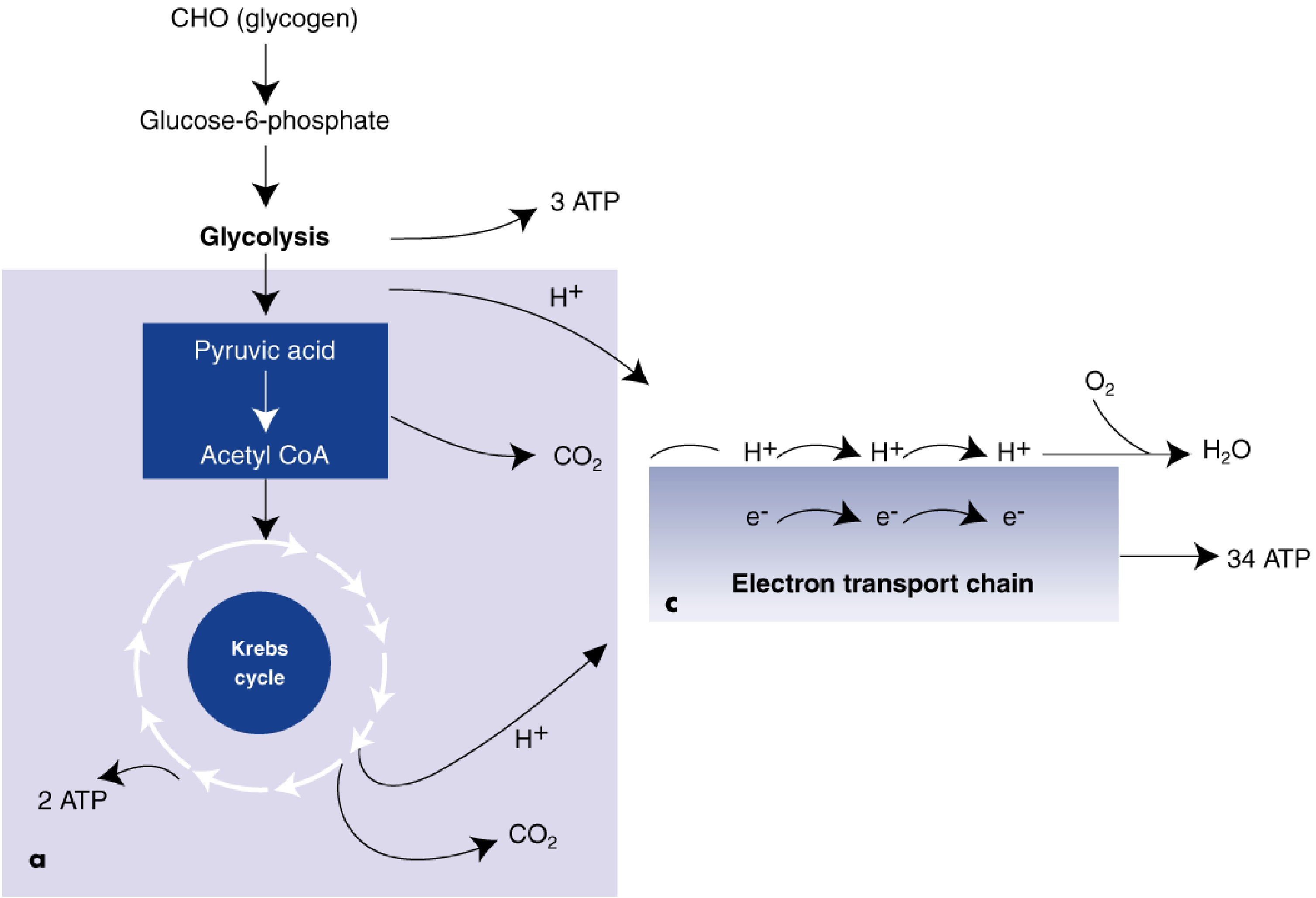
Oxidative System

- Relies on oxygen to breakdown fuels for energy
- Produces ATP in mitochondria of cells
- Can yield much more energy (ATP) than anaerobic systems
- Is the primary method of energy production during endurance events

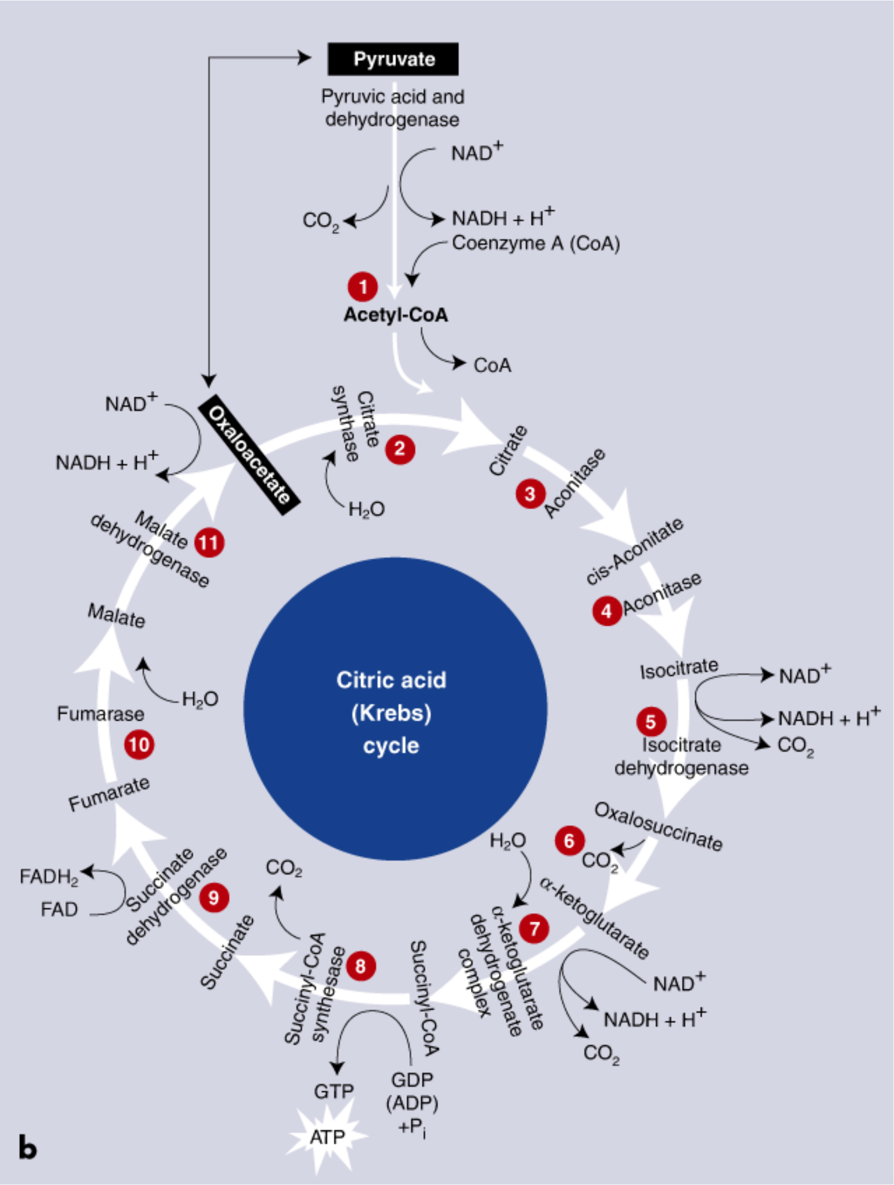
Oxidative Production of ATP

1. Aerobic glycolysis—cytoplasm
2. Krebs cycle—mitochondria
3. Electron transport chain—mitochondria

AEROBIC GLYCOLYSIS AND THE ELECTRON TRANSPORT CHAIN



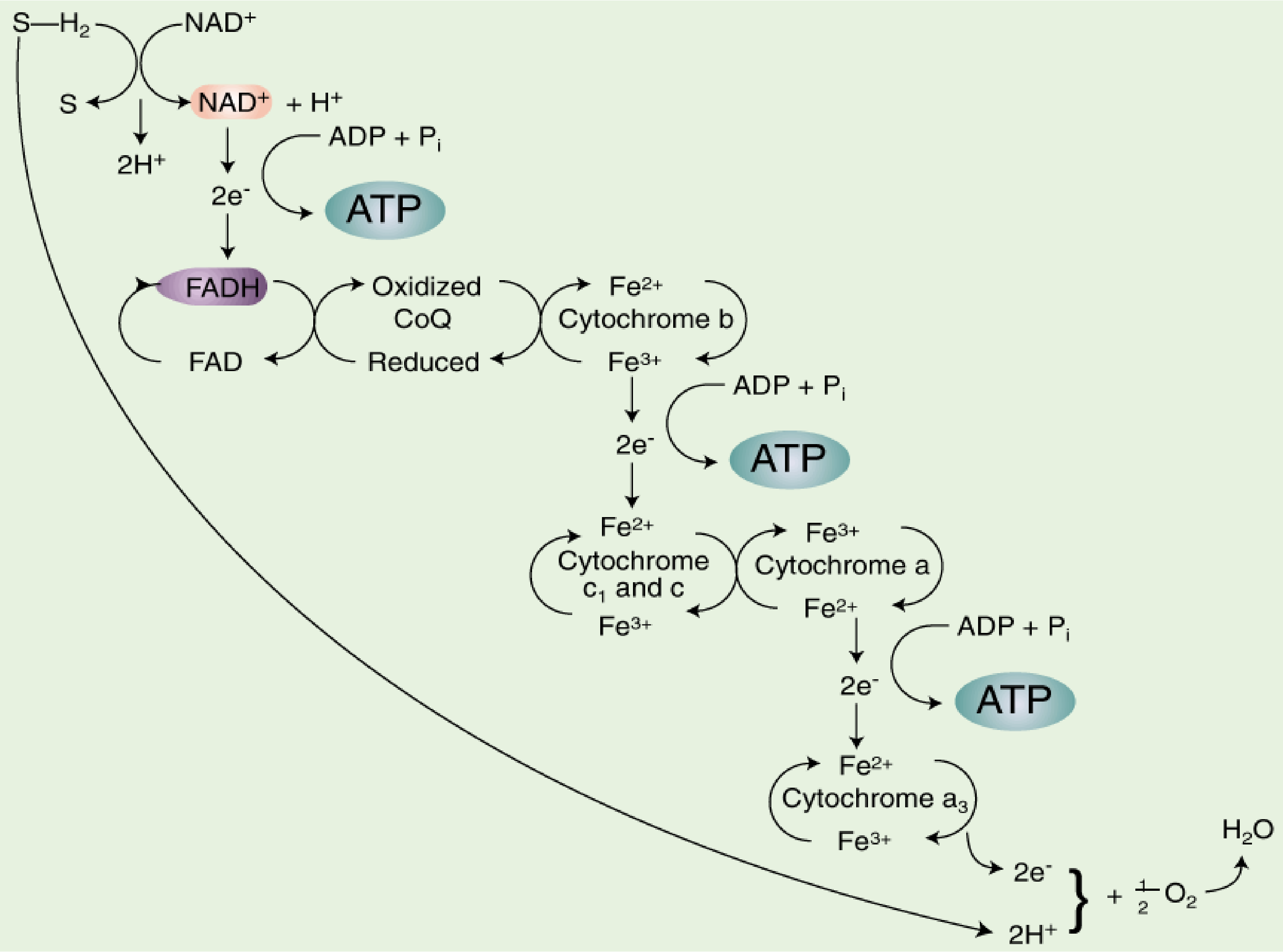
KREBS CYCLE


Pyruvate
Pyruvic acid and dehydrogenase
NAD+
NADH + H+
CO2
Coenzyme A (CoA)
1
Acetyl-CoA
CoA
Citrate synthase
2
H2O
Oxaloacetate
NAD+
NADH + H+
Citrate
3
Aconitase
cis-Aconitate
4
Aconitase
Isocitrate
NAD+
NADH + H+
CO2
5
Isocitrate dehydrogenase
Oxalosuccinate
6
CO2
H2O
α-ketoglutarate
7
α-ketoglutarate dehydrogenate complex
NAD+
NADH + H+
CO2
Succinyl-CoA
8
Succinyl-CoA synthesase
GTP
GDP (ADP) +Pi
ATP
CO2
Succinate
9
Succinate dehydrogenase
FADH2
FAD
Fumarate
10
Fumarase
H2O
Malate
11
Malate dehydrogenase
Citric acid (Krebs) cycle
b

Oxidation of Carbohydrate

1. Pyruvic acid from glycolysis is converted to acetyl coenzyme A (acetyl CoA).
2. Acetyl CoA enters the Krebs cycle and forms 2 ATP, carbon dioxide, and hydrogen.
3. Hydrogen in the cell combines with two coenzymes that carry it to the electron transport chain.
4. Electron transport chain recombines hydrogen atoms to produce ATP and water.
5. One molecule of glycogen can generate up to 39 molecules of ATP.

OXIDATIVE PHOSPHORYLATION



Oxidation of Fat

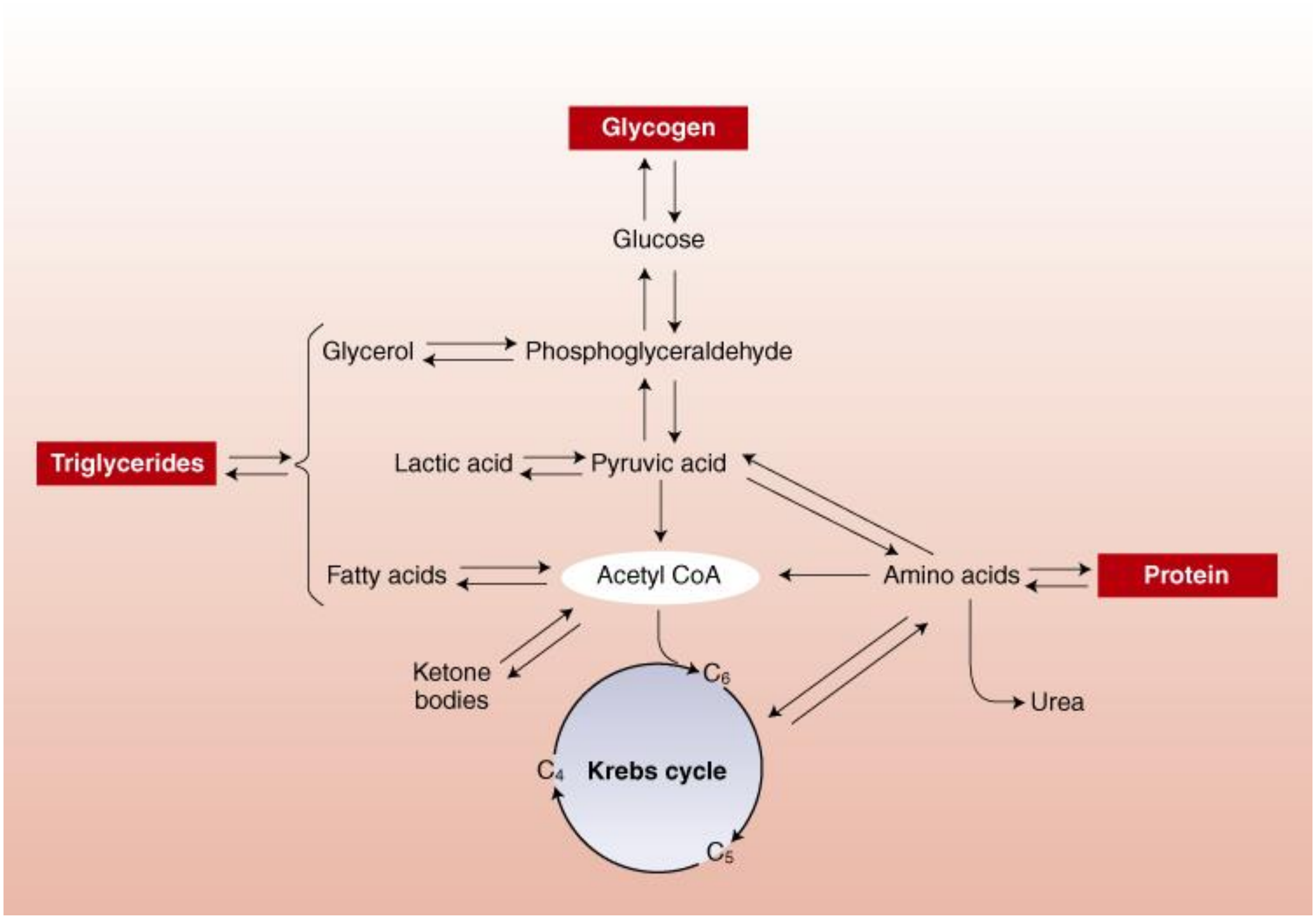
- Lypolysis—breakdown of triglycerides into glycerol and free fatty acids (FFAs).
- FFAs travel via blood to muscle fibers and are broken down by enzymes in the mitochondria into acetic acid which is converted to acetyl CoA.
- Aceytl CoA enters the Krebs cycle and the electron transport chain.
- Fat oxidation requires more oxygen and generates more energy than carbohydrate oxidation.

Energy Production From the Oxidation of Liver Glycogen

Stage of process	Direct	By oxidative phosphorylation[a]
Glycolysis (glucose to pyruvic acid)	3	4-6[b]
Pyruvic acid to acetyl coenzyme A	0	6
Krebs cycle	2	22
Subtotal	5	32-34
Total	37-39	

[a]Refers to adenosine triphosphate (ATP) produced by transferring H^+ and electrons to the electron transport chain. [b]The energy yield differs depending on whether reduced nicotinamide adenine dinucleotide (NADH) or reduced flavin adenine dinucleotide (FADH) is the carrier molecule to transport the electron through the mitochondrial membrane and the electron transport chain, with NADH yielding up to 39 molecules of a ATP and FADH yielding 37 molecules of ATP.

METABOLISM OF FAT



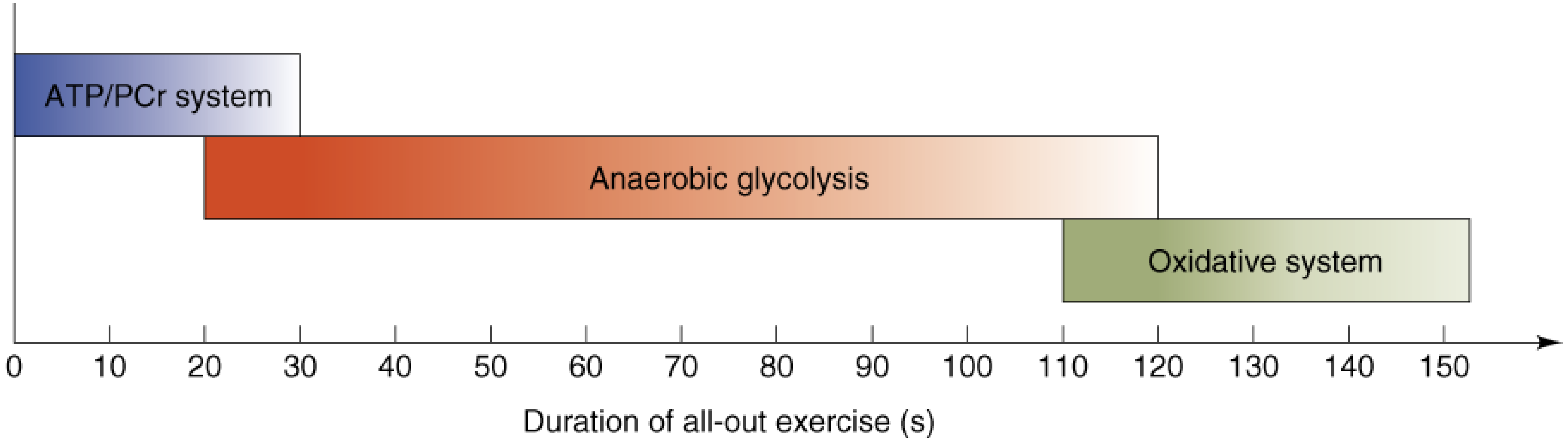
Energy Production From the Oxidation of Palmitic Acid ($C_{16}H_{32}O_2$)

	Adenosine triphosphate produced from 1 molecule of palmitic acid	
Stage of process	**Direct**	**By oxidative phosphorylation**
Fatty acid activation	0	–2
β-oxidation	0	35
Krebs cycle	8	88
Subtotal	8	121
Total	129	

Protein Metabolism

- Body uses little protein during rest and exercise (less than 5% to 10%).
- Some amino acids that form proteins can be converted into glucose.
- The nitrogen in amino acids (which cannot be oxidized) makes the energy yield of protein difficult to determine.

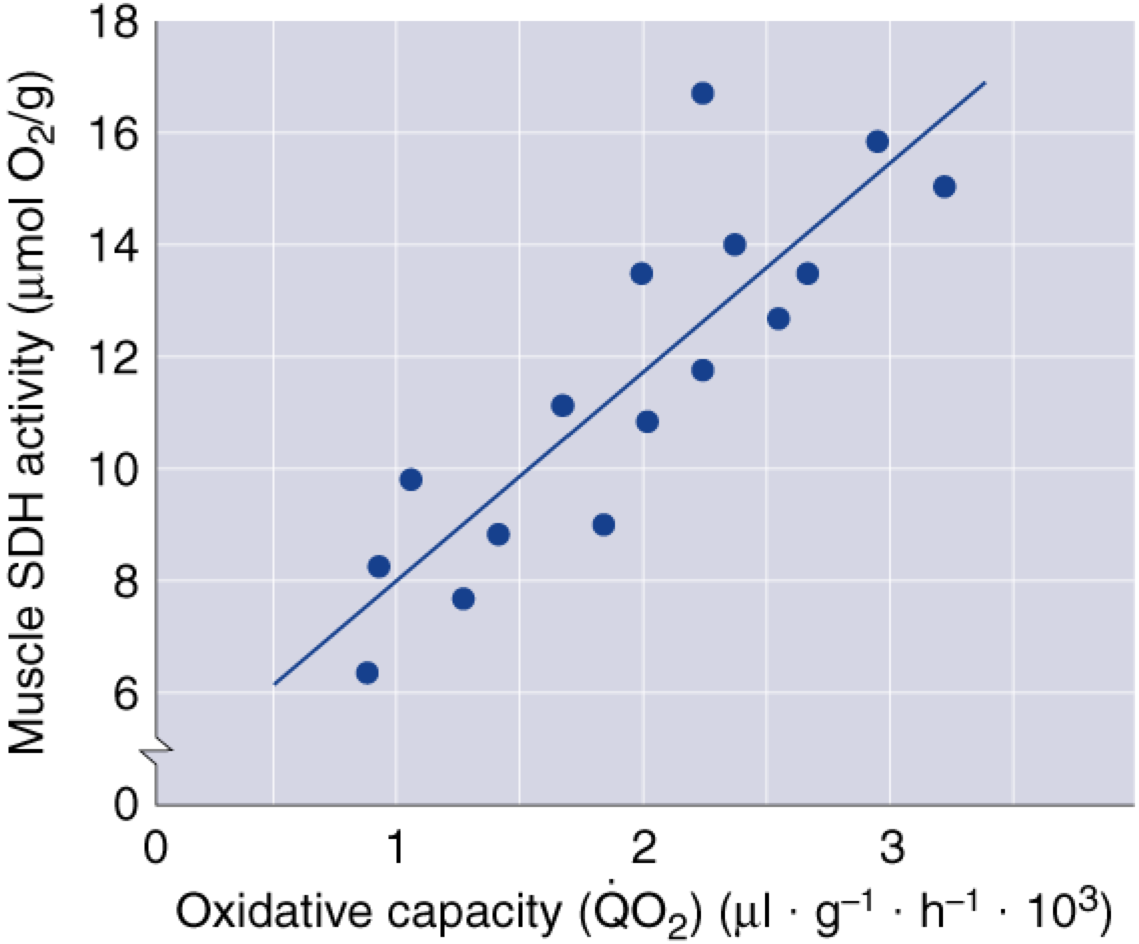
INTERACTION OF ENERGY SYSTEMS ILLUSTRATING THE PREDOMINANT ENERGY SYSTEM



What Determines Oxidative Capacity?

- Oxidative enzyme activity within the muscle
- Fiber-type composition and number of mitochondria
- Endurance training
- Oxygen availability and uptake in the lungs

OXIDATIVE ENZYME ACTIVITY AND OXIDATIVE CAPACITY



Key Points

Bioenergetics: ATP Production

- The ATP-PCr and glycolytic systems produce small amounts of ATP anaerobically and are the major energy contributors in the early minutes of high-intensity exercise.
- The oxidative system uses oxygen and produces more energy than the anaerobic systems.
- Carbohydrate oxidation involves glycolysis, the Krebs cycle, and the electron transport chain to produce up to 39 ATP per molecule of glycogen aerobically.

(continued)

Key Points

Bioenergetics: ATP Production

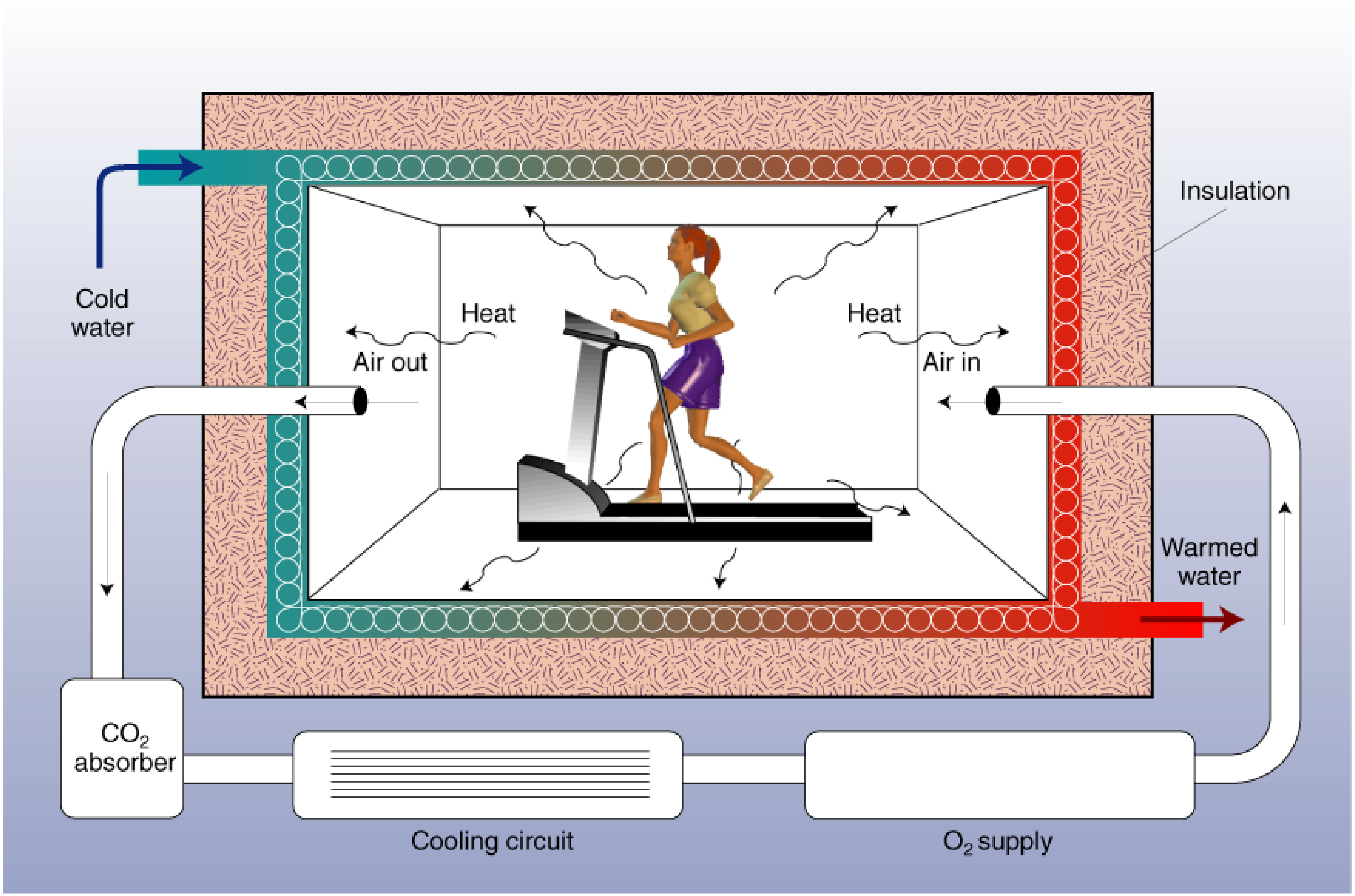
- Fat oxidation involves β oxidation of free fatty acids, the Krebs cycle, and the electron transport chain to produce more ATP than carbohydrate, but it is O_2-limited.
- Protein generally contributes little to energy production (less than 5%), and its oxidation is complex because amino acids contain nitrogen, which cannot be oxidized.
- The oxidative capacity of muscle fibers depends on their oxidative enzyme levels, fiber-type composition, how they have been trained, and oxygen availability.

Measuring Energy Costs of Exercise

Direct calorimetry—measures the body's heat production to calculate energy expenditure.

Indirect calorimetry—calculates energy expenditure from the respiratory exchange ratio (RER) of $\dot{V}CO_2$ and $\dot{V}O_2$.

CALORIMETRIC CHAMBER



MEASURING RESPIRATORY GAS EXCHANGE

Measuring Energy Costs of Exercise

$\dot{V}O_2$—volume of O_2 consumed per minute (L/min).

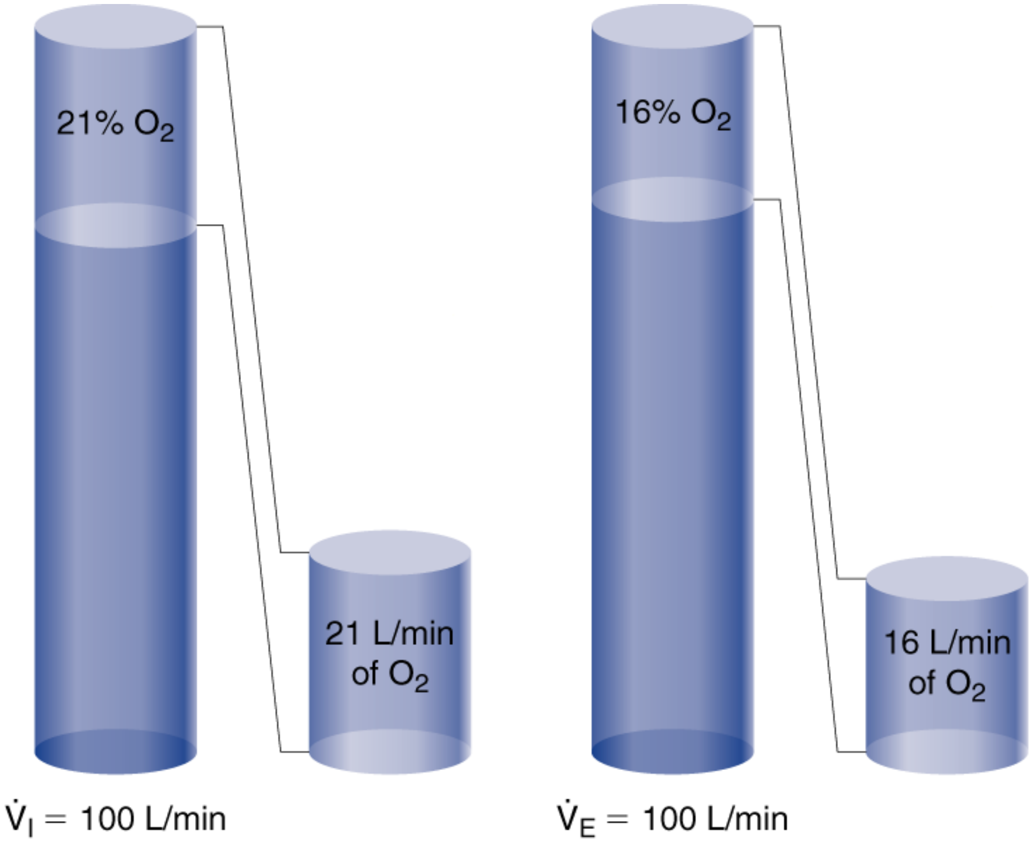
$\dot{V}CO_2$—volume of CO_2 produced per minute (L/min).

$$\dot{V}O_2 = (\dot{V}_I \times F_IO_2) - (\dot{V}_E \times F_EO_2)$$

$$\dot{V}CO_2 = (\dot{V}_E \times F_ECO_2) - (\dot{V}_I \times F_ICO_2)$$

Where $\dot{V}_E$ = expired ventilation; $\dot{V}_I$ = inspired ventilation; F_IO_2 = fraction of oxygen inspired; F_ICO_2 = fraction of carbon dioxide inspired; F_EO_2 = fraction of oxygen expired; and F_ECO_2 = fraction of carbon dioxide expired.

CALCULATING OXYGEN CONSUMPTION



$$\dot{V}O_2 = \dot{V}_I \times F_IO_2 - \dot{V}_E \times F_EO_2$$

$$\dot{V}O_2 = 100\ \text{L/min} \times 0.21 - 100\ \text{L/min} \times 0.16$$

$$\dot{V}O_2 = 21\ \text{L/min} - 16\ \text{L/min} = 5\ \text{L/min}$$

Haldane Transformation

You can use $\dot{V}_E$ to calculate $\dot{V}_I$ knowing that the volume of nitrogen expired is constant:

$$\dot{V}_I = (\dot{V}_E \times F_EN_2)/F_IN_2 \text{ and } F_EN_2 = 1 - (F_EO_2 + F_ECO_2)$$

$$\dot{V}O_2 = (\dot{V}_I \times F_IO_2) - (\dot{V}_E \times F_EO_2)$$

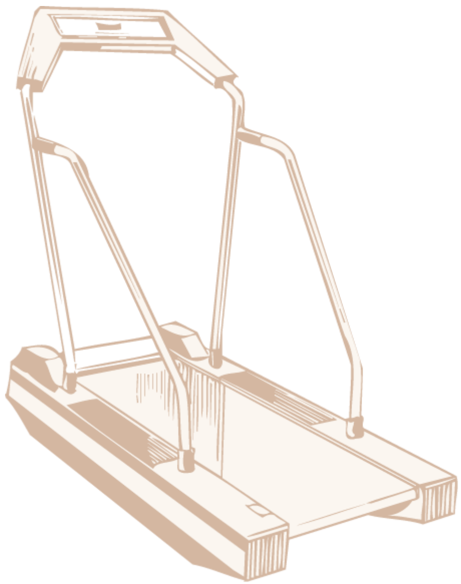
$$\dot{V}O_2 = [(\dot{V}_E \times F_EN_2)/(F_IN_2 \times F_IO_2)] – (\dot{V}_{E)} \times F_EO_2)$$

Then substitute known values for F_IO_2 of 0.2093 and F_IN_2 of 0.7903:

$$\dot{V}O_2 = (\dot{V}_E \times \{[(1 – (F_EO_2 + F_ECO_2)) \times 0.265] – F_EO_2\}$$

Respiratory Exchange Ratio

- The ratio between CO_2 released ($\dot{V}CO_2$) and oxygen consumed ($\dot{V}O_2$)
- RER = $\dot{V}CO_2/\dot{V}O_2$
- The RER value at rest is usually 0.78 to 0.80
- The RER value can be used to determine energy substrate used at rest and during exercise, with a value of 1.00 indicating CHO and 0.70 indicating fat.



Caloric Equivalence of the Respiratory Exchange Ratio (RER) and % kcal From Carbohydrates and Fats

	Energy	% kcal	
RER	**kcal/L O_2**	**Carbohydrates**	**Fats**
0.71	4.69	0.0	100.0
0.75	4.74	15.6	84.4
0.80	4.80	33.4	66.6
0.85	4.86	50.7	49.3
0.90	4.92	67.5	32.5
0.95	4.99	84.0	16.0
1.00	5.05	100.0	0.0

Measurements of Energy Expenditure

Carbon-13—Infused and selectively traced to determine its movement and distribution

Doubly labeled water—$^{2}H_2{}^{18}O$ is ingested and the rate at which ^{2}H and ^{18}O diffuses throughout the body’s water and bicarbonate stores and leaves the body is monitored and used to calculate how much energy is expended

Key Points

Measuring Energy Use During Exercise

- Direct calorimetry measures the heat produced by the body while indirect calorimetry estimates caloric expenditure by measuring O_2 consumption.
- The RER value can be used to determine what fuels are being oxidized and is used in the calculation of the energy expended per liter of O_2 consumed.
- Tracking ingested or injected isotopes in the body can also be used to calculate caloric expenditure.

Metabolic Rate

- Rate at which the body expends energy at rest and during exercise
- Measured as whole-body oxygen consumption and its caloric equivalent
- Basal or resting metabolic rate (BMR) is the minimum energy required for essential physiological function (varies between 1,200 and 2,400 kcal/24 hr)
- The minimum energy required for normal daily activity is about 1,800 to 3,000 kcal/24 hr

Factors Affecting BMR/RMR

- The more **fat-free mass**, the higher the BMR
- The more **body surface area**, the higher the BMR
- BMR gradually decreases with increasing **age**
- BMR increases with increasing **body temperature**
- The more **stress**, the higher the BMR
- The higher the levels of **thyroxine** and **epinephrine**, the higher the BMR

Caloric Equivalents

- Food energy equivalents

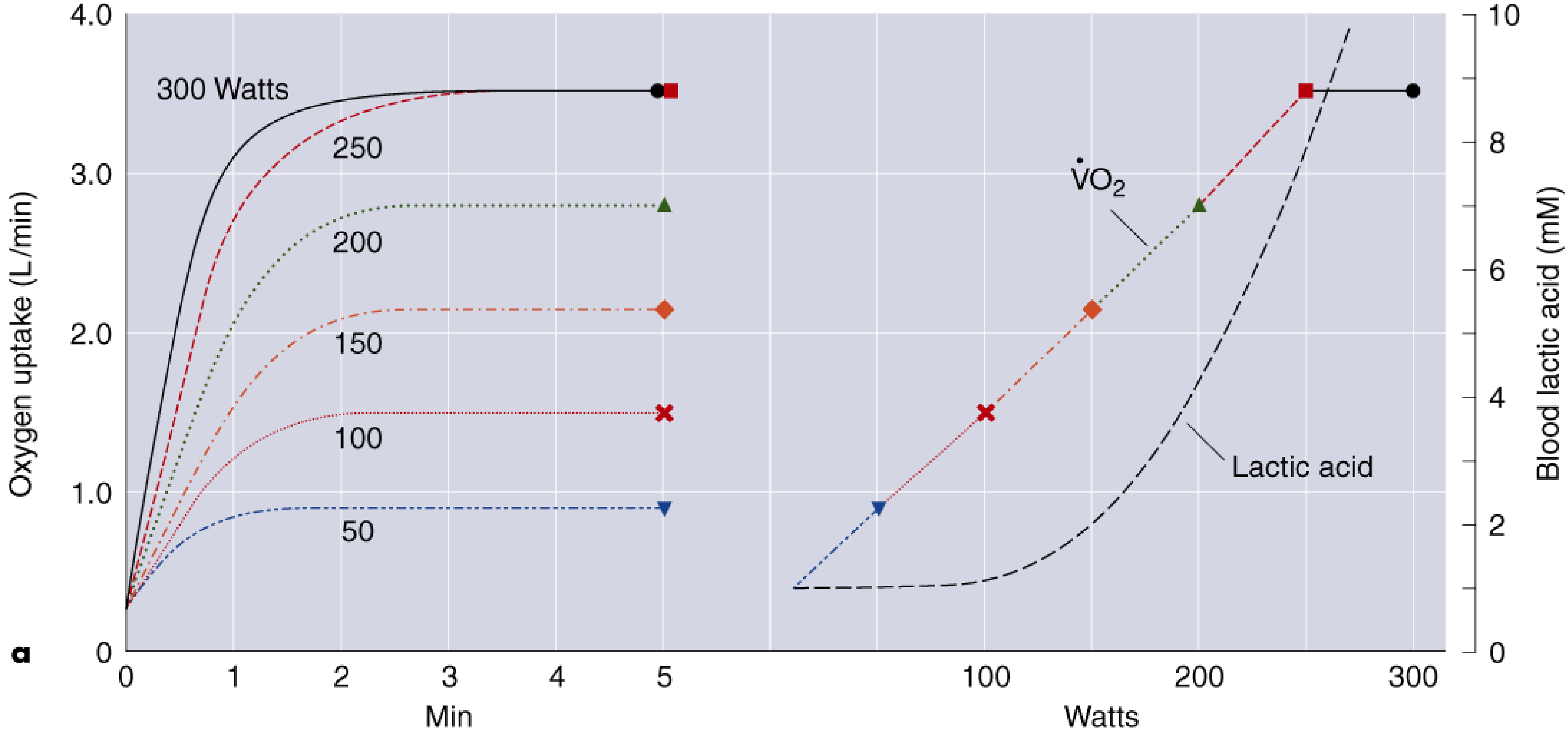
CHO:	4.1 kcal/g
Fat:	9.4 kcal/g
Protein:	4.1 kcal/g

- Energy per liter of oxygen consumed

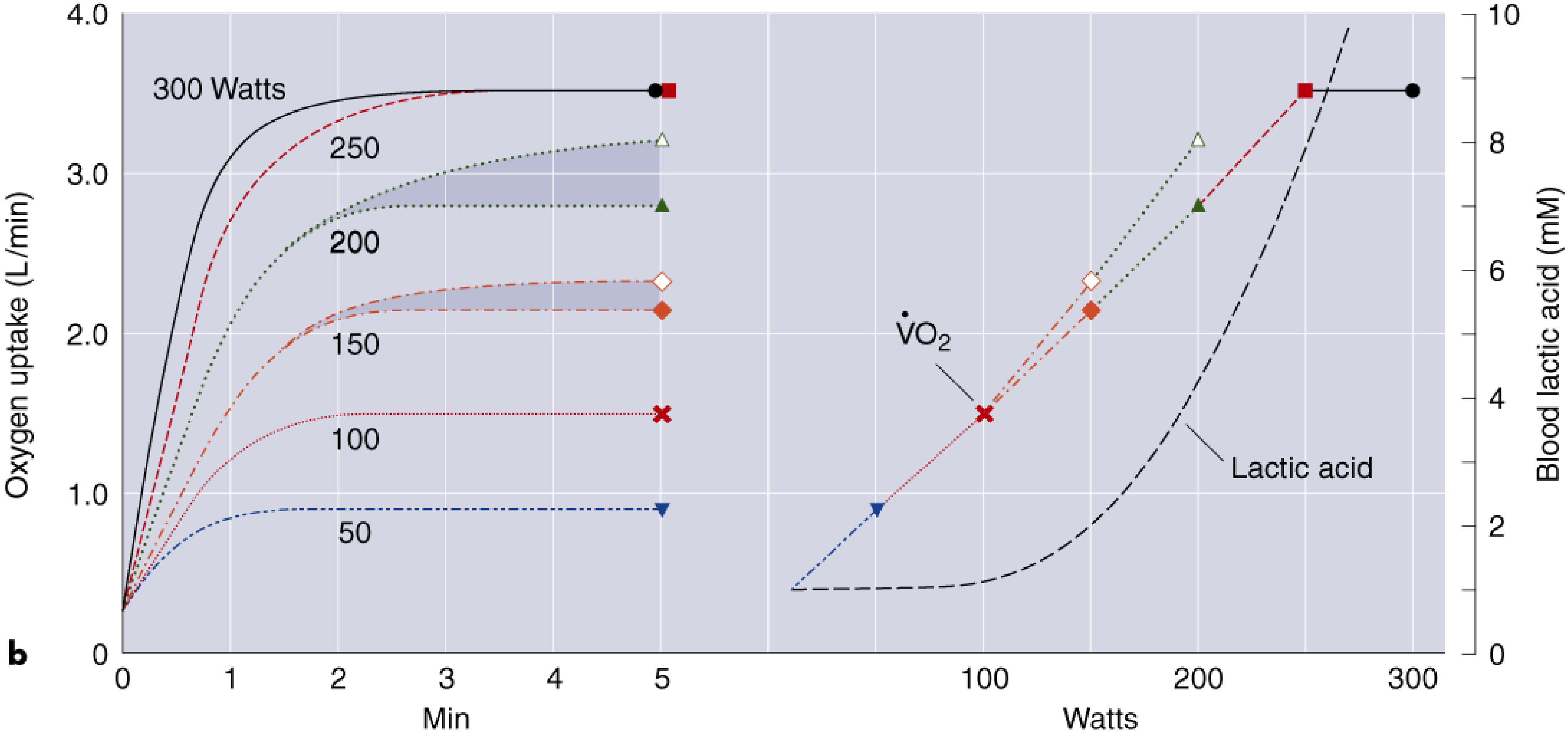
CHO:	5.0 kcal/L
Fat:	4.7 kcal/L
Protein:	4.5 kcal/L

Example: $\dot{V}O_2$ rest = 0.300 L/min $\times$ 60 min/hr $\times$ 24 hr/day = 432 L/day $\times$ 4.8 kcal/L = 2,074 kcal/day

O_2 UPTAKE vs POWER OUTPUT (1986)



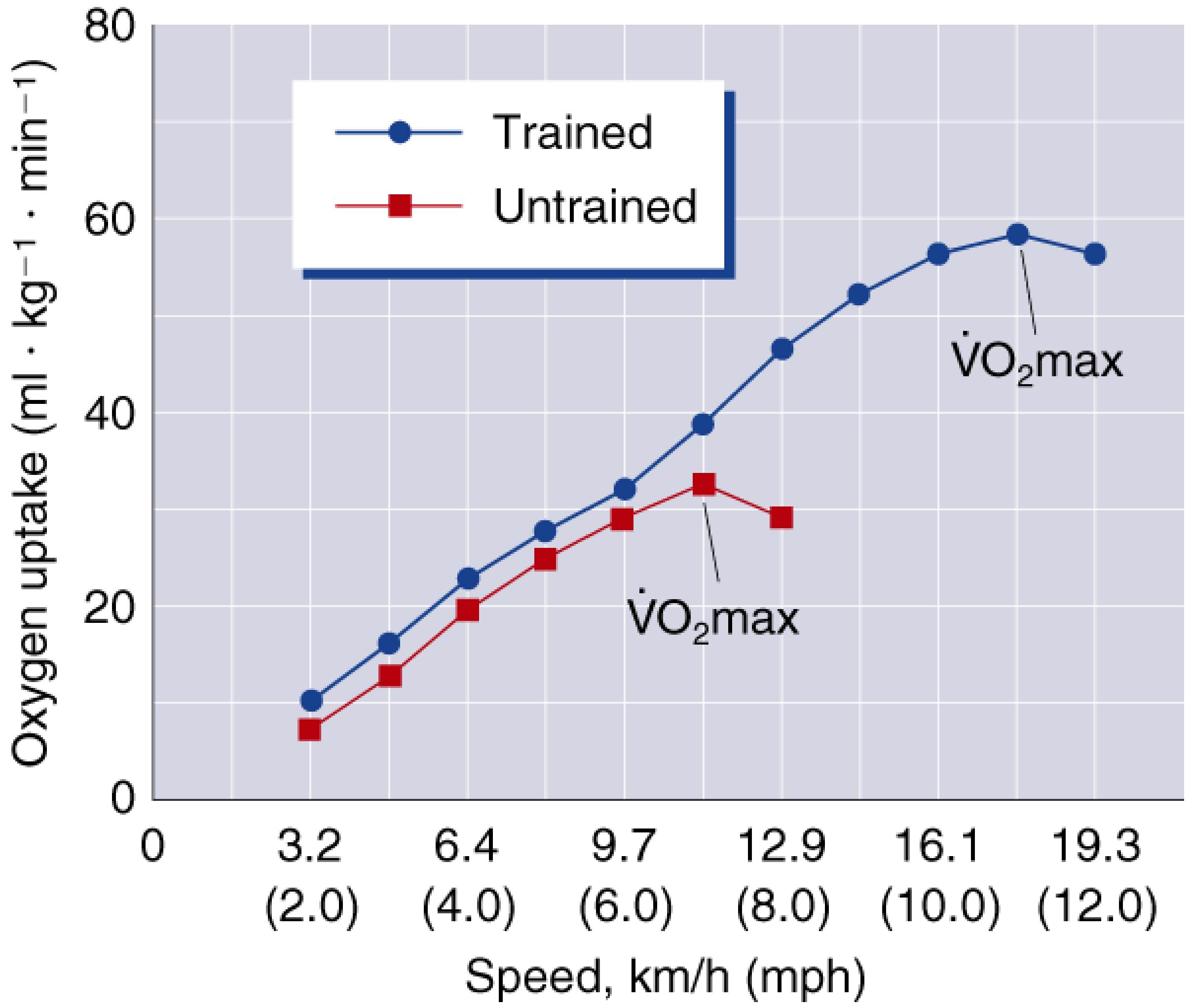
O_2 UPTAKE vs POWER OUTPUT (1996)



Maximal Oxygen Uptake ($\dot{V}O_2max$)

- Upper limit of a person's ability to increase oxygen uptake.
- Good indicator of cardiorespiratory endurance and aerobic fitness.
- Can differ according to sex, body size, age, and is greatly influenced by the level of aerobic training.
- Expressed relative to body weight in ml of O_2 consumed per kg body weight per min ($ml \cdot kg^{-1} \cdot min^{-1}$).

EXERCISE INTENSITY AND OXYGEN UPTAKE

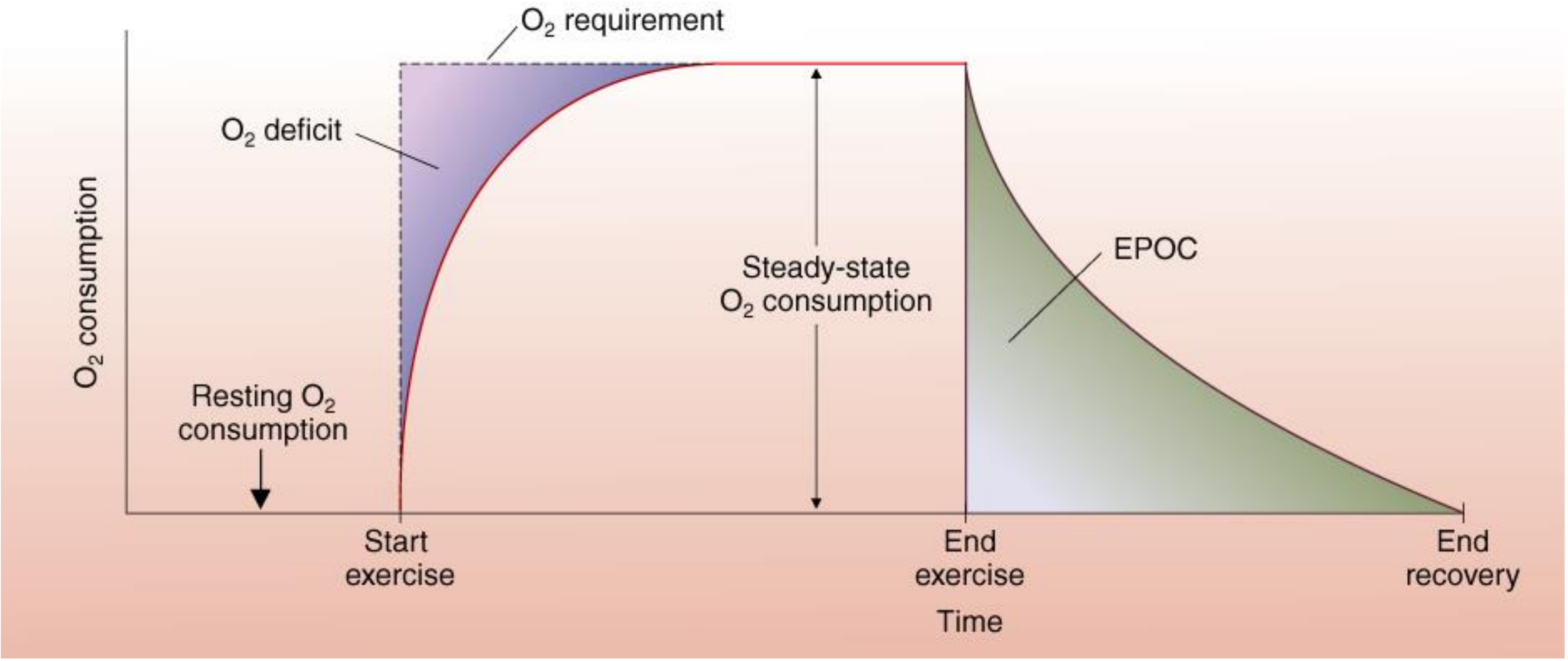


Estimating Anaerobic Effort

There is not yet available a method that definitively measures anaerobic capacity, however there are ways to estimate it:

- Examine excess postexercise oxygen consumption (EPOC)—the mismatch between O_2 consumption and energy requirements during recovery from exercise
- Estimate lactate accumulation in muscles through blood analysis; estimate lactate threshold (LT)
- Use the maximal accumulated oxygen deficit test, the critical power test, or the Wingate anaerobic test which also show good promise for estimating the metabolic potential of anaerobic capacity

OXYGEN DEFICIT AND EPOC



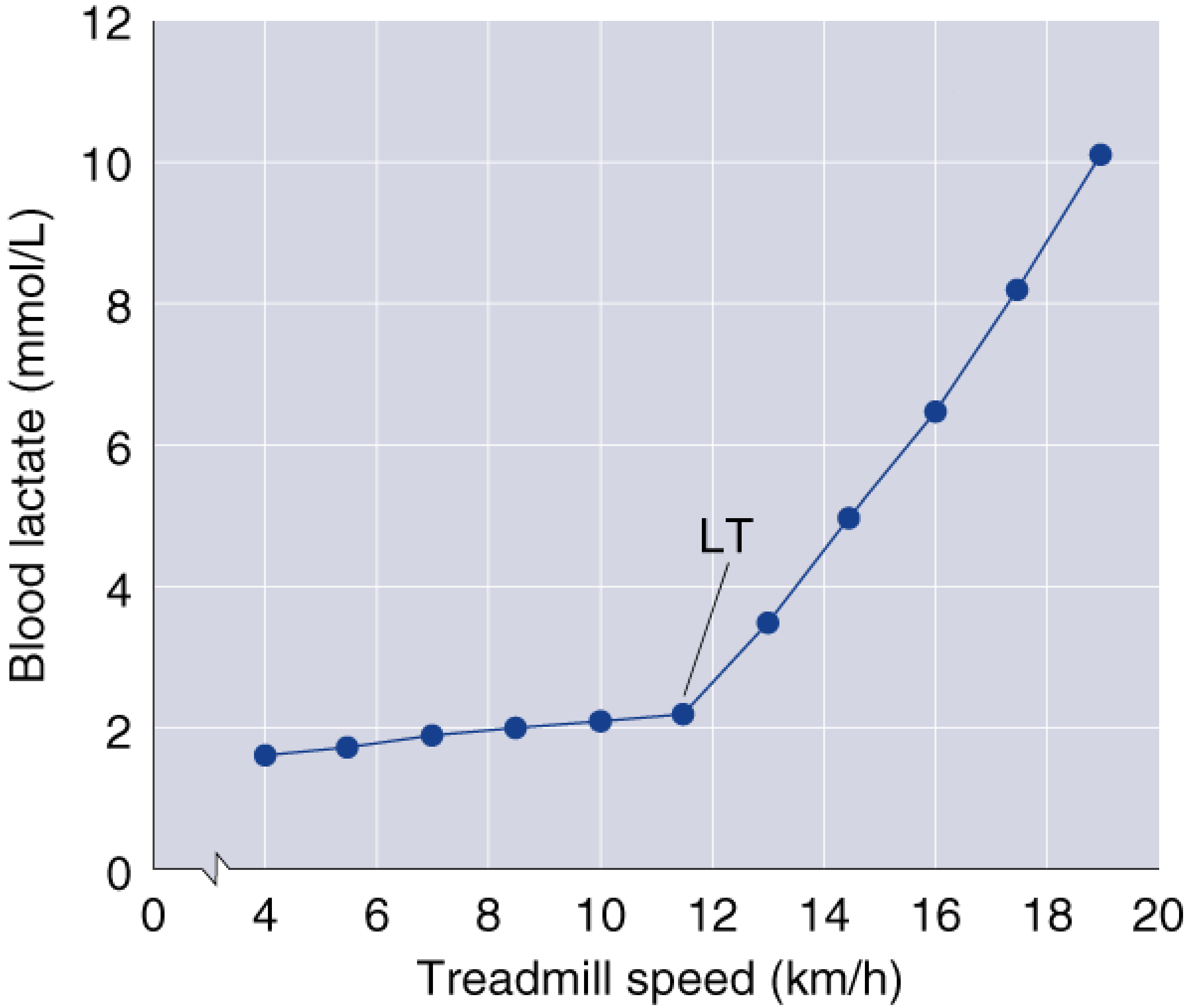
Factors Responsible for EPOC

- Rebuilding depleted ATP supplies
- Clearing lactate produced by anaerobic metabolism
- Replenishing O_2 supplies borrowed from hemoglobin and myoglobin
- Removing CO_2 that has accumulated in body tissues
- Increased metabolic and respiratory rates due to increased body temperature and norepinephrine and epinephrine levels

Lactate Threshold

- The point at which blood lactate begins to accumulate above resting levels during exercise of increasing intensity, where lactate production exceeds lactate clearance
- Sudden increase in blood lactate with increasing effort can be the result of an increase in the production of lactate or a decrease in the removal of lactate from the blood
- Can indicate potential for endurance exercise; lactate formation contributes to fatigue

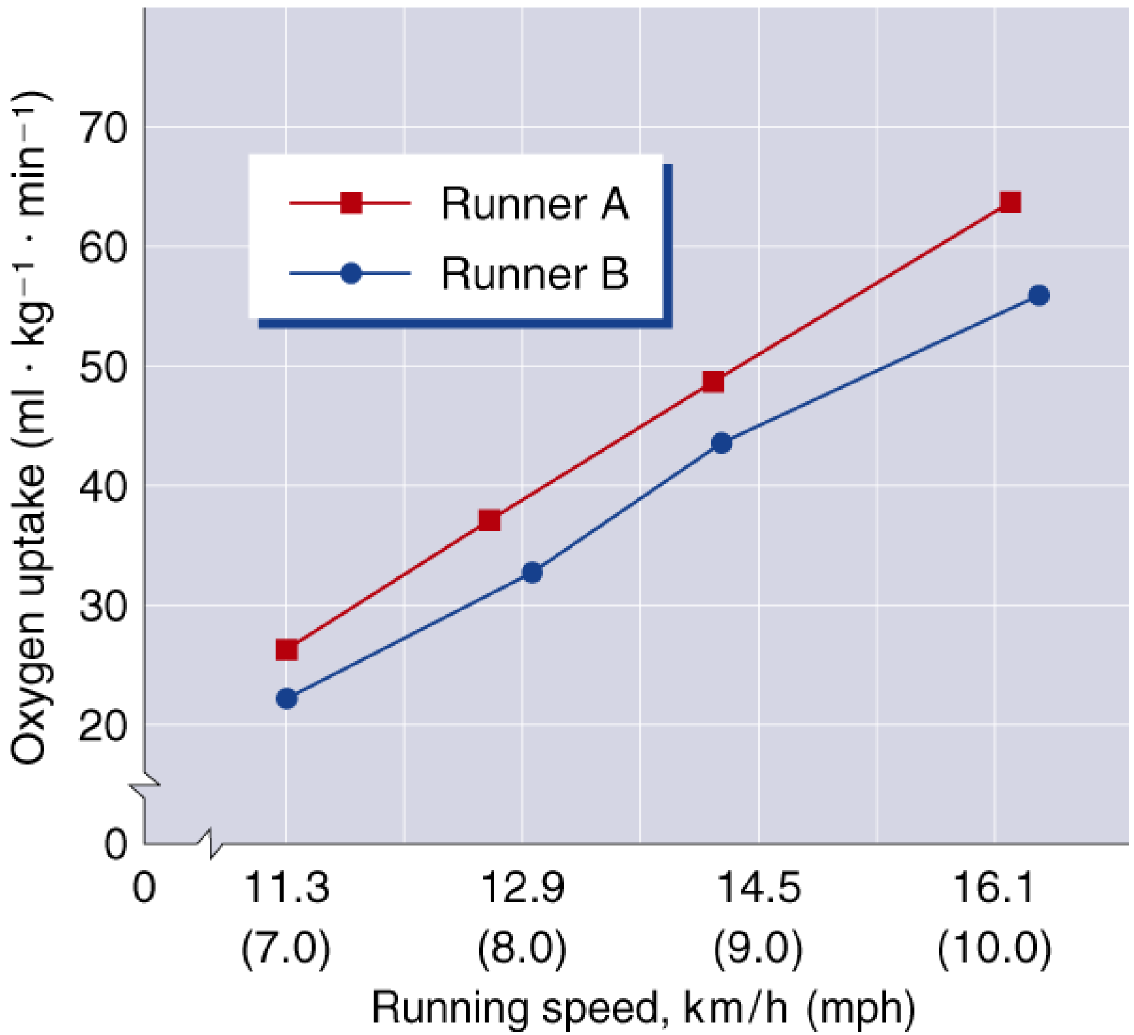
EXERCISE INTENSITY AND BLOOD LACTATE ACCUMULATION



Did You Know…?

Lactate threshold (LT), when expressed as a percentage of $\dot{V}O_2$max, is one of the best determinants of an athlete's pace in endurance events such as running and cycling. While untrained people typically have LT around 50% to 60% of their $\dot{V}O_2$max, elite athletes may not reach LT until around 70% or 80% $\dot{V}O_2$max.

OXYGEN REQUIREMENTS OF TWO RUNNERS



Determining Endurance Performance Success

- High maximal oxygen uptake ($\dot{V}O_2max$)
- High lactate threshold
- High economy of effort
- High percentage of slow-twitch muscle fibers

Factors Influencing Energy Costs

- Type of activity
- Activity level
- Age
- Sex
- Size, weight, and body composition
- Intensity of the activity
- Duration of the activity
- Efficiency of movement

Key Points

Energy Expenditure at Rest and During Exercise

- The basal metabolic rate (BMR) is the minimum amount of energy required by the body for basic physiological functions.
- The resting metabolic rate (RMR) is nearly identical to the BMR.
- Your metabolism increases with increased exercise intensity.
- Oxygen consumption increases during exercise to its upper limit ($\dot{V}O_2max$).

(continued)

Key Points

Energy Expenditure at Rest and During Exercise

- Excess postexercise oxygen consumption (EPOC) is the elevation of O_2 consumption above resting levels after exercise; it is caused by a combination of several factors.
- Lactate threshold is the point at which blood lactate begins to accumulate above resting levels during exercise, where lactate production exceeds lactate clearance.

(continued)

Key Points

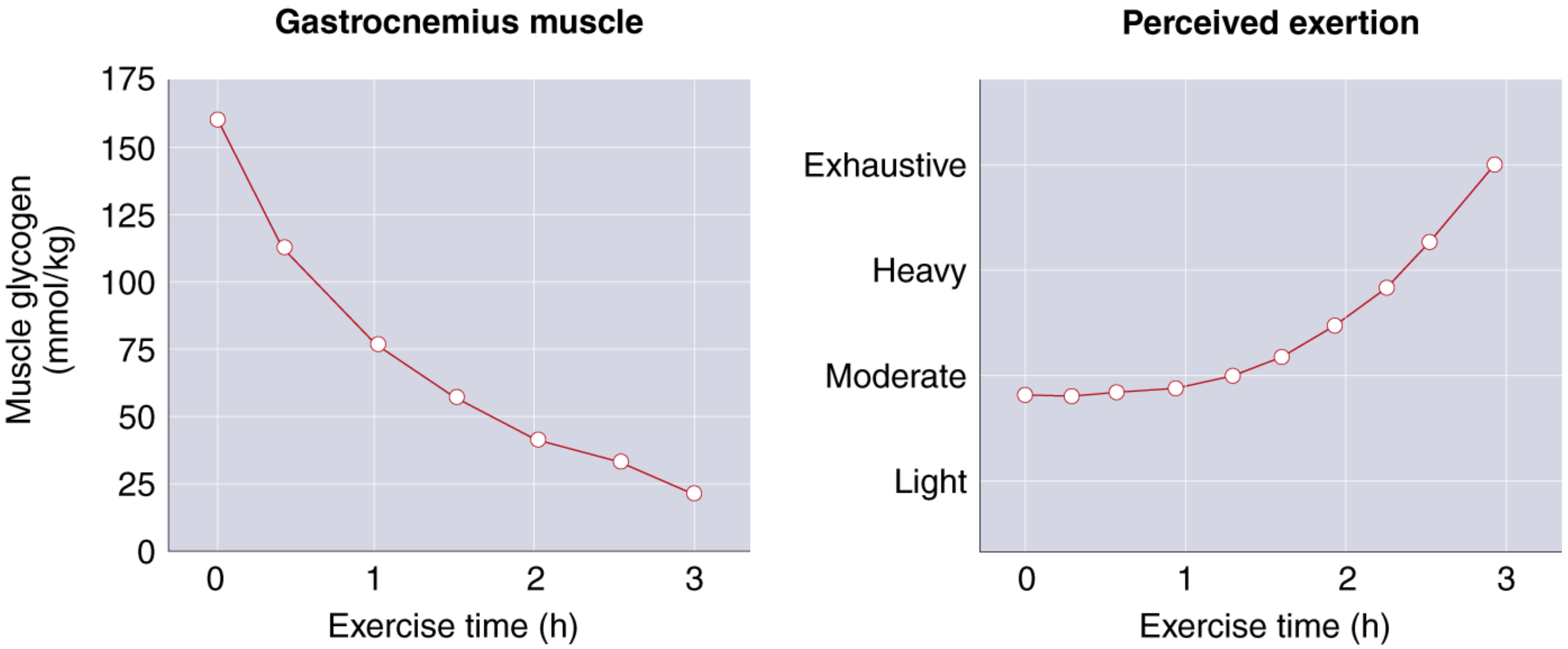
Energy Expenditure at Rest and During Exercise

- Individuals with higher lactate thresholds, expressed as a percentage of $\dot{V}O_2max$, are capable of the best endurance performance.
- Performance improvements often mean that an individual can perform for longer periods at a higher percentage of his or her $\dot{V}O_2max$.
- Performance capacity can be improved by increasing one's economy of effort.

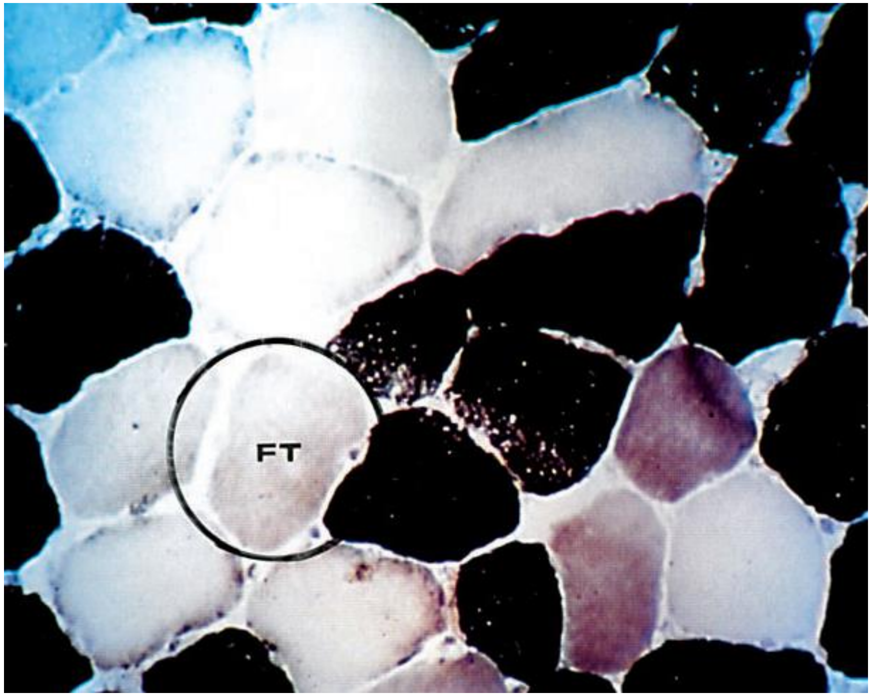
Fatigue and Its Causes

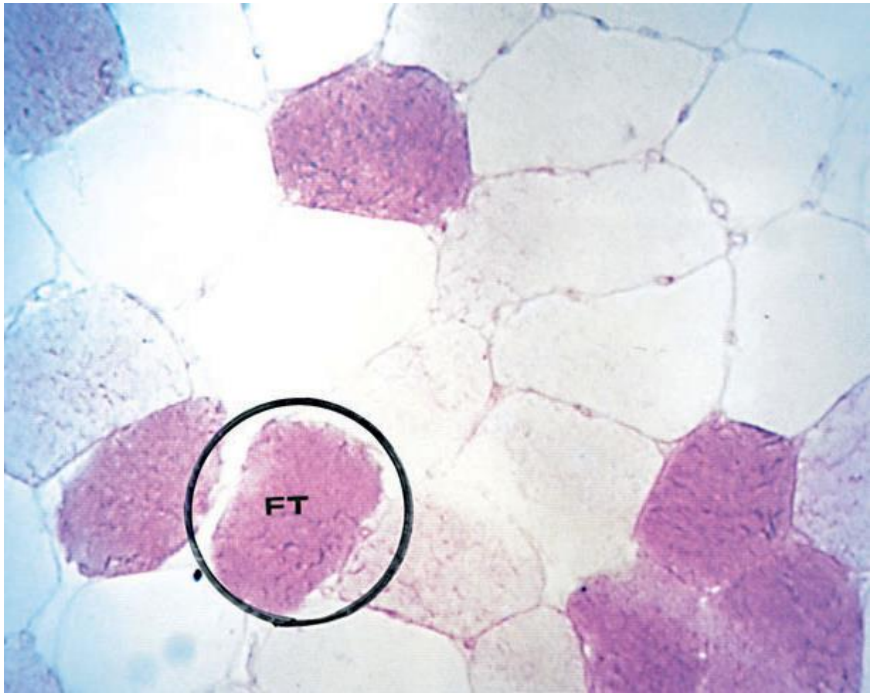
- Phosphocreatine (PCr) depletion
- Glycogen depletion (especially in activities lasting longer than 30 minutes)
- Accumulation of lactate and H^+ (especially in events shorter than 30 minutes)
- Neuromuscular fatigue

USE OF MUSCLE GLYCOGEN DURING EXERCISE

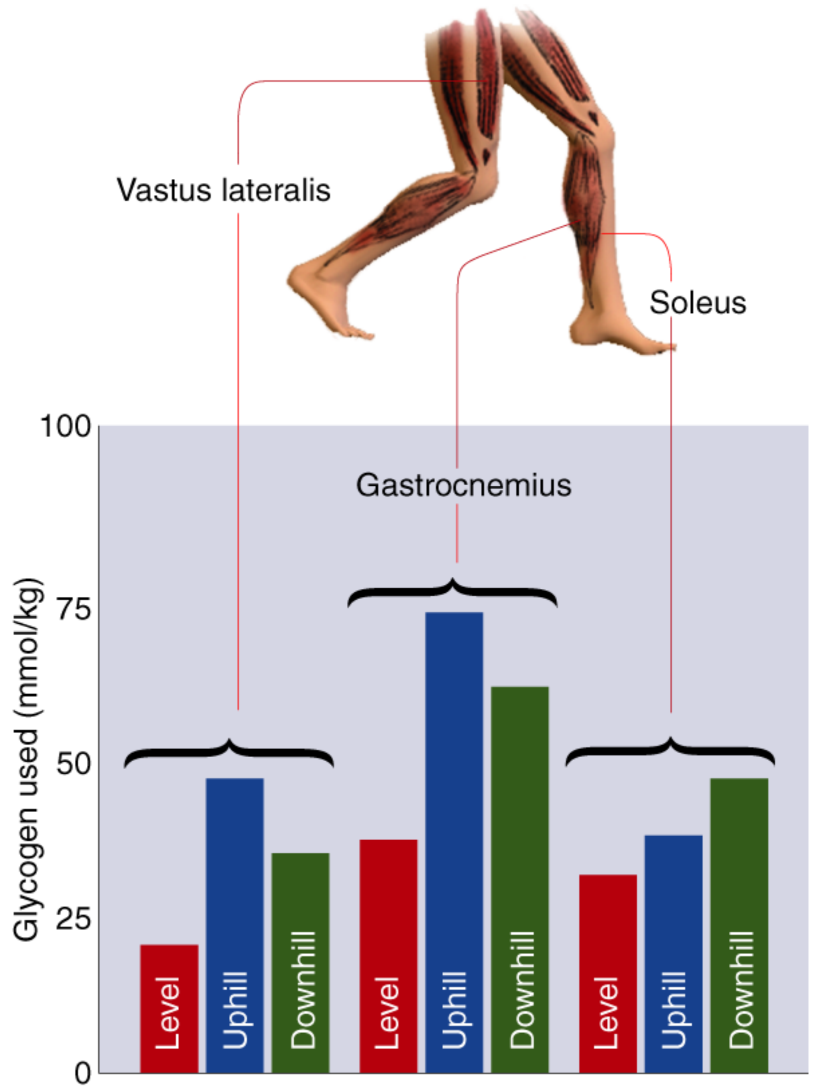


MUSCLE FIBERS STAINED TO SHOW GLYCOGEN



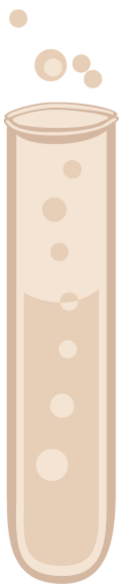


GLYCOGEN USE DURING RUNNING

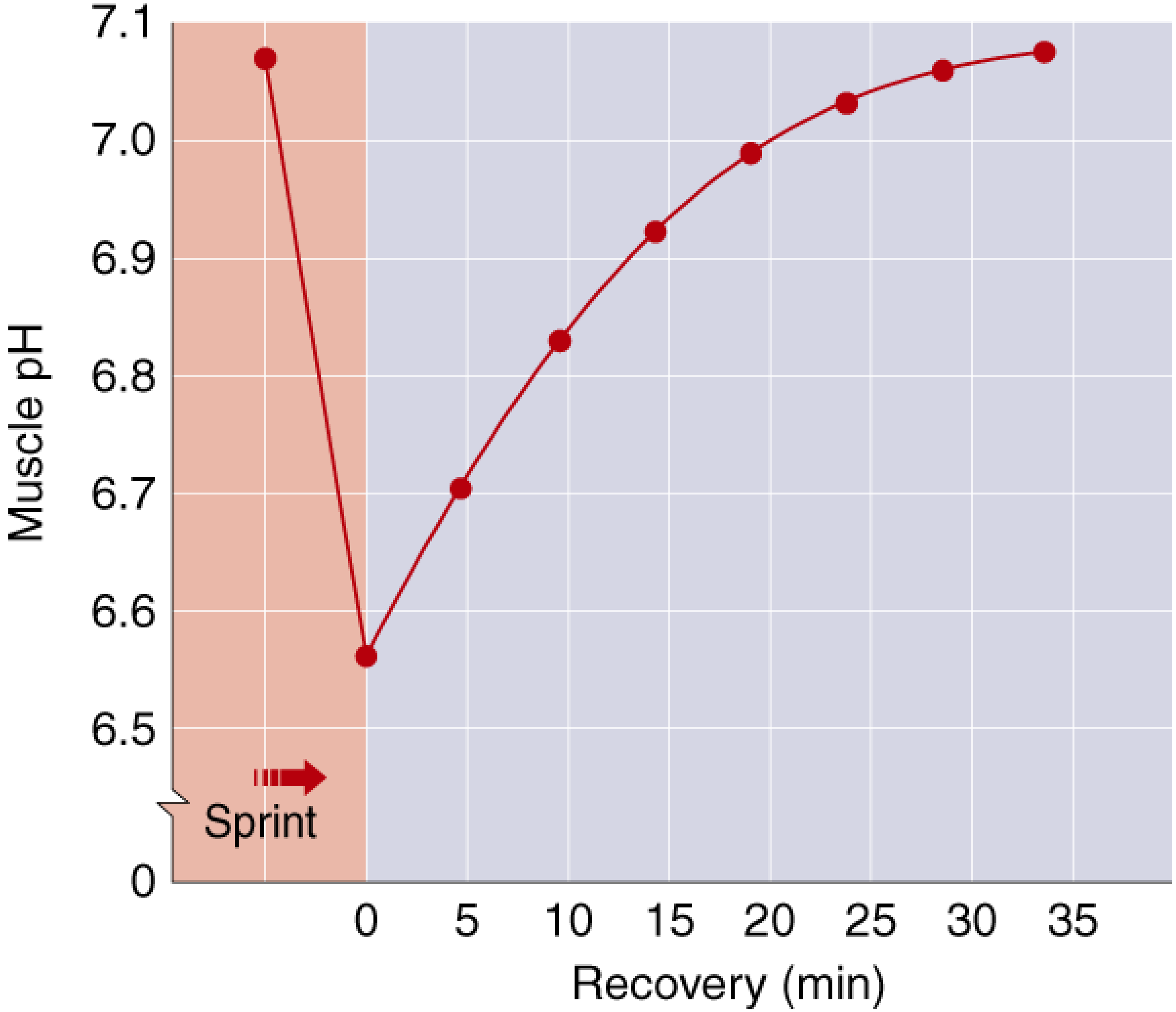


Metabolic By-Products and Fatigue

- Short duration activities depend on anaerobic glycolysis and produce lactate and H^+.
- Cells buffer H^+ with bicarbonate (HCO_3) to keep cell pH between 6.4 and 7.1.
- Intercellular pH lower than 6.9, however, slows glycolysis and ATP production.
- When pH reaches 6.4, H^+ levels stop any further glycolysis and result in exhaustion.



CHANGES IN MUSCLE pH



Key Points

Fatigue and Its Causes

- Fatigue may result from a depletion of PCr or glycogen, which then impairs ATP production.
- The H^+ generated by lactic acid causes fatigue in that it decreases muscle pH and impairs the cellular processes of energy production and muscle contraction.
- Failure of neural transmission may cause some fatigue.
- The central nervous system may also perceive fatigue as a protective mechanism.