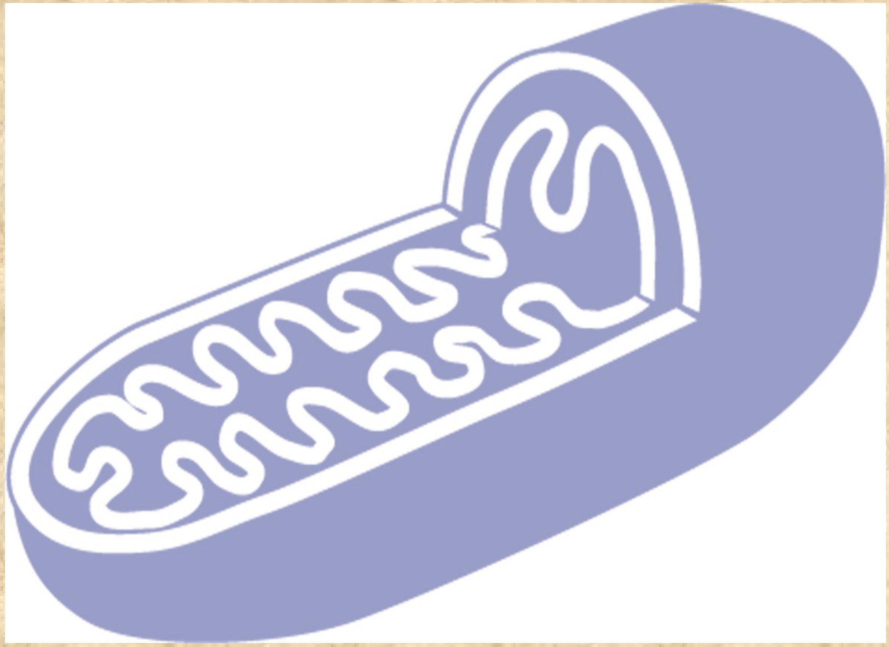
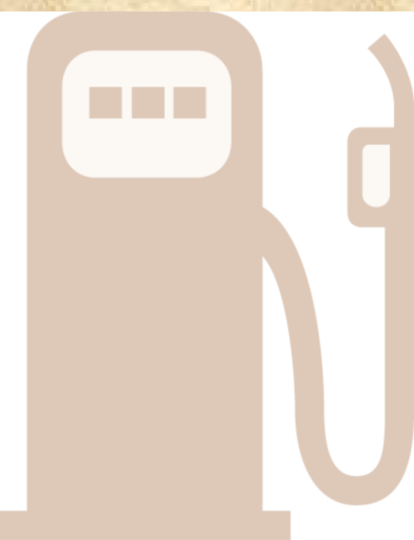
METABOLISM, ENERGY, AND THE BASIC ENERGY SYSTEMS



Energy for Cellular Activity

- What do we need energy for?

- 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

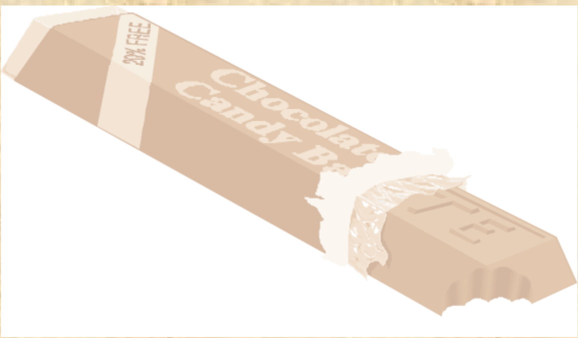
- At rest, the body uses carbohydrates and fats for energy.
- Protein provides little energy for cellular activity but serves as building blocks for the body's tissues.
- During moderate to severe muscular effort, the body relies mostly on carbohydrate for fuel.

Carbohydrate (saccharide)

- 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 (lipid)

- 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

Energy Content

1g Saccharide = 4.1 kcal (17 kJ)

1g Protein = 4.1 kcal (17 kJ)

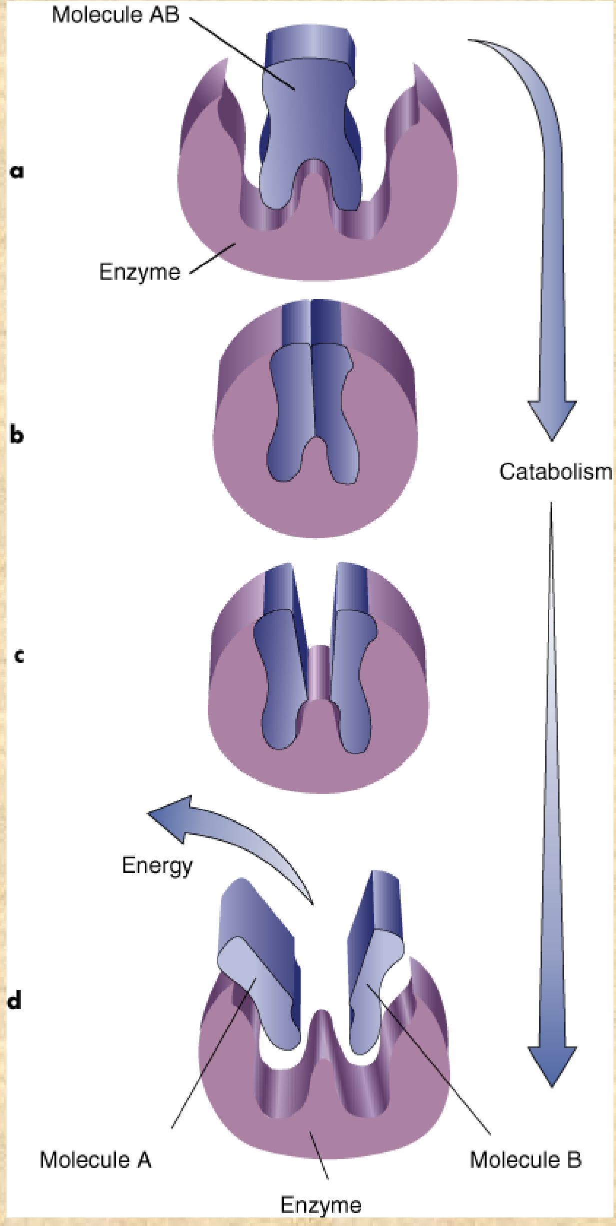
1g Lipid = 9.0 kcal (38 kJ)

(1 kcal = 4.2 kJ)

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



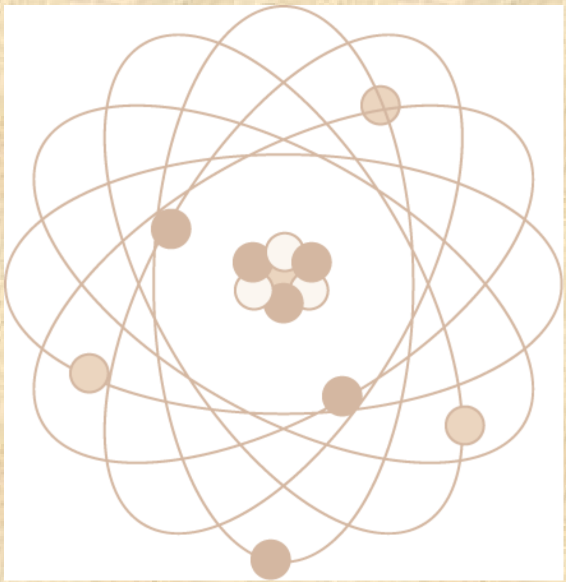
Key Points

Energy for Cellular Metabolism

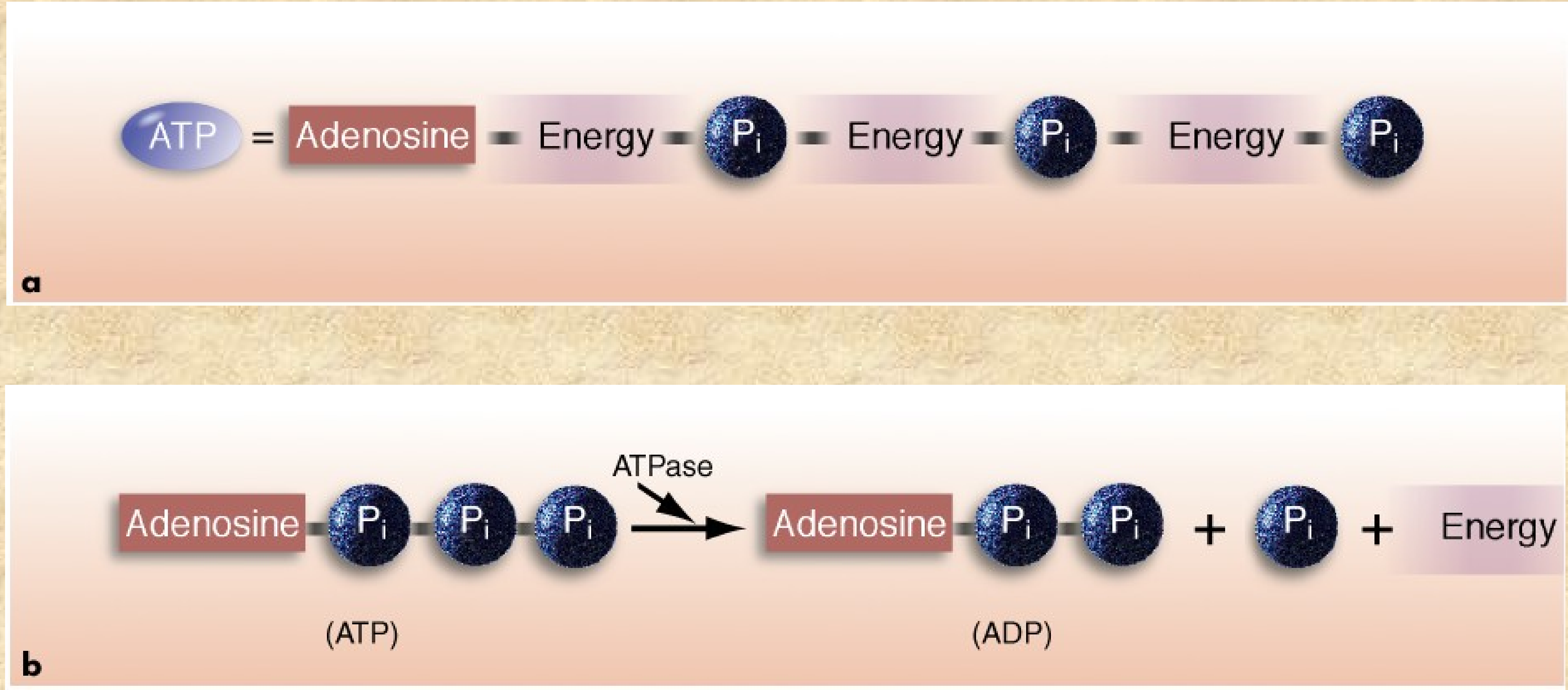
- Carbohydrate, fats, and protein provide us with fuel that our bodies convert to ATP.
- ATP is the high-energy compound released and stored within our cells.
- Carbohydrate and protein provide about 4.1 kcal/g while fat provides about 9 kcal/g.
- Carbohydrate energy is more accessible to the muscles than protein or fat.

Basic Energy Systems

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



ATP MOLECULE

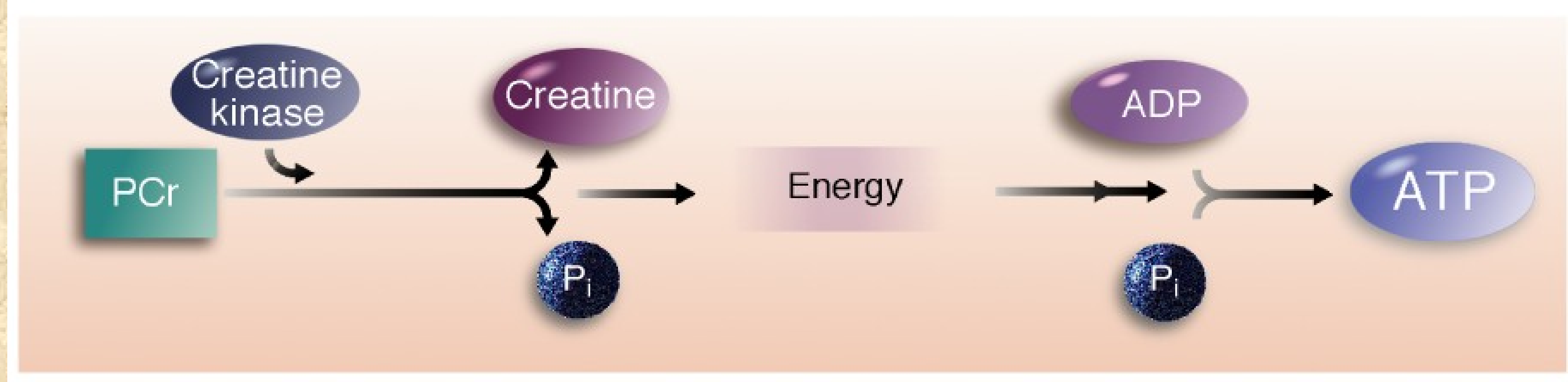


(Law of conservation of energy)

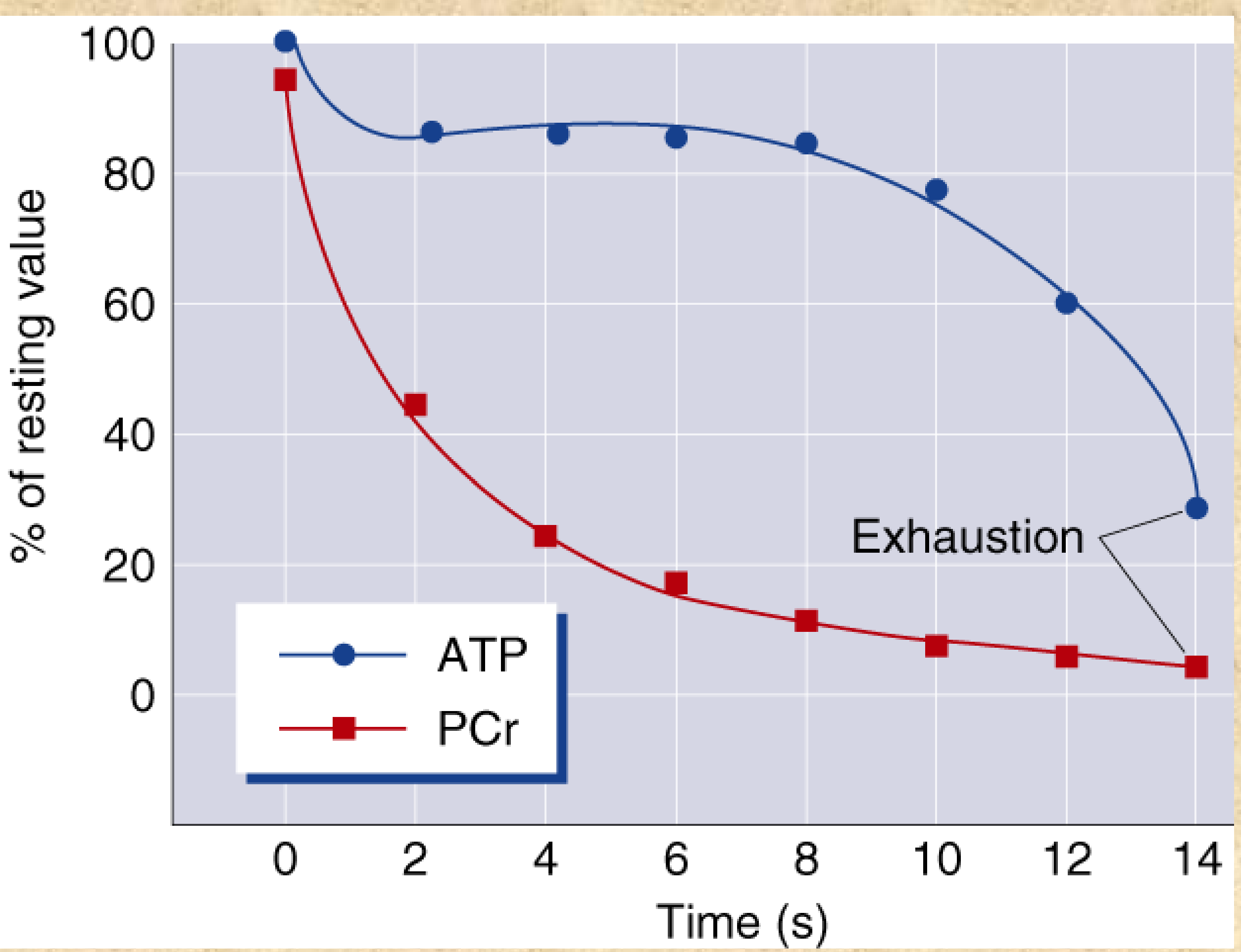
1) ATP-PCr System

- 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

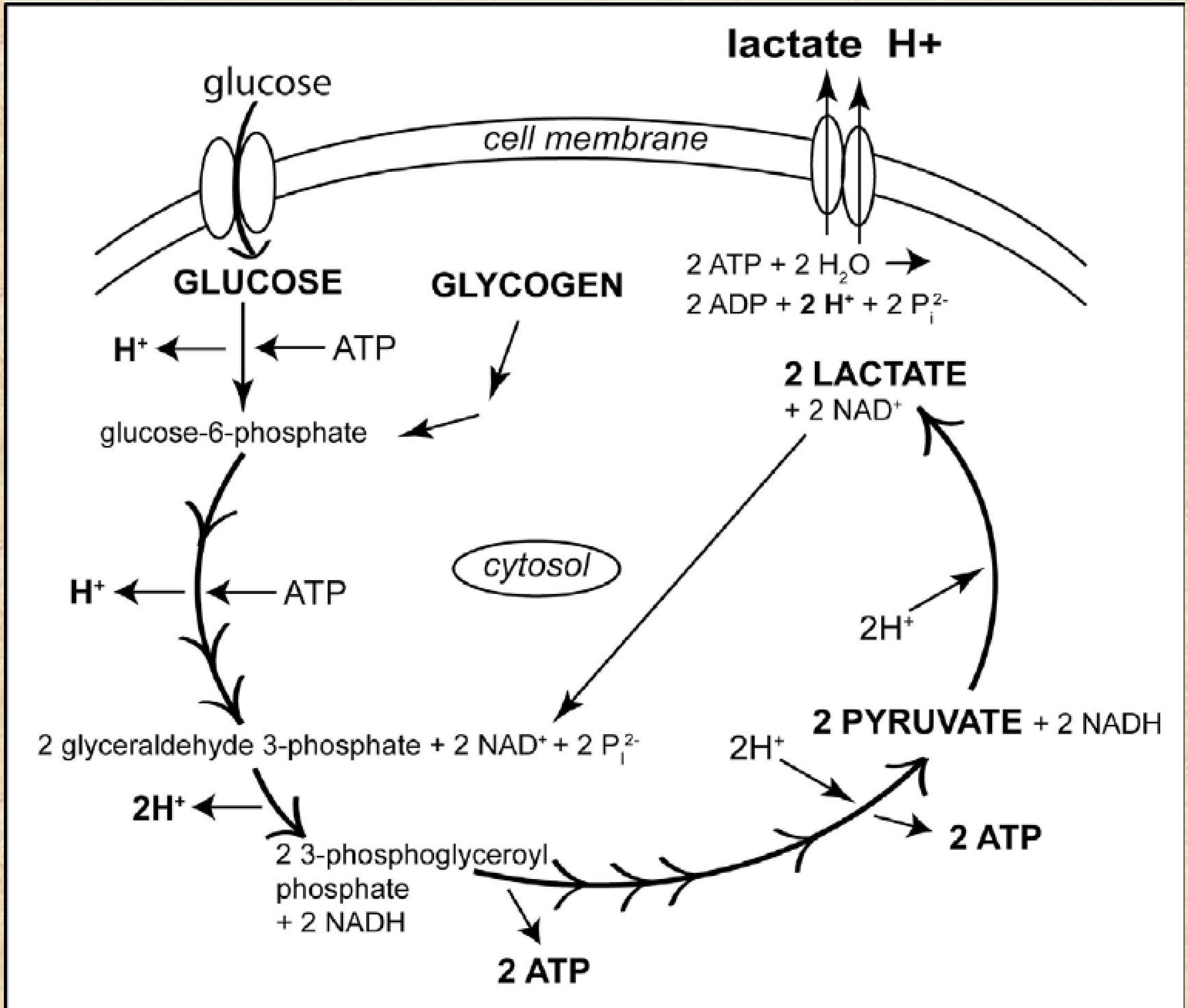
Glycolysis—Breakdown of glucose; may be anaerobic or aerobic

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

2) 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.



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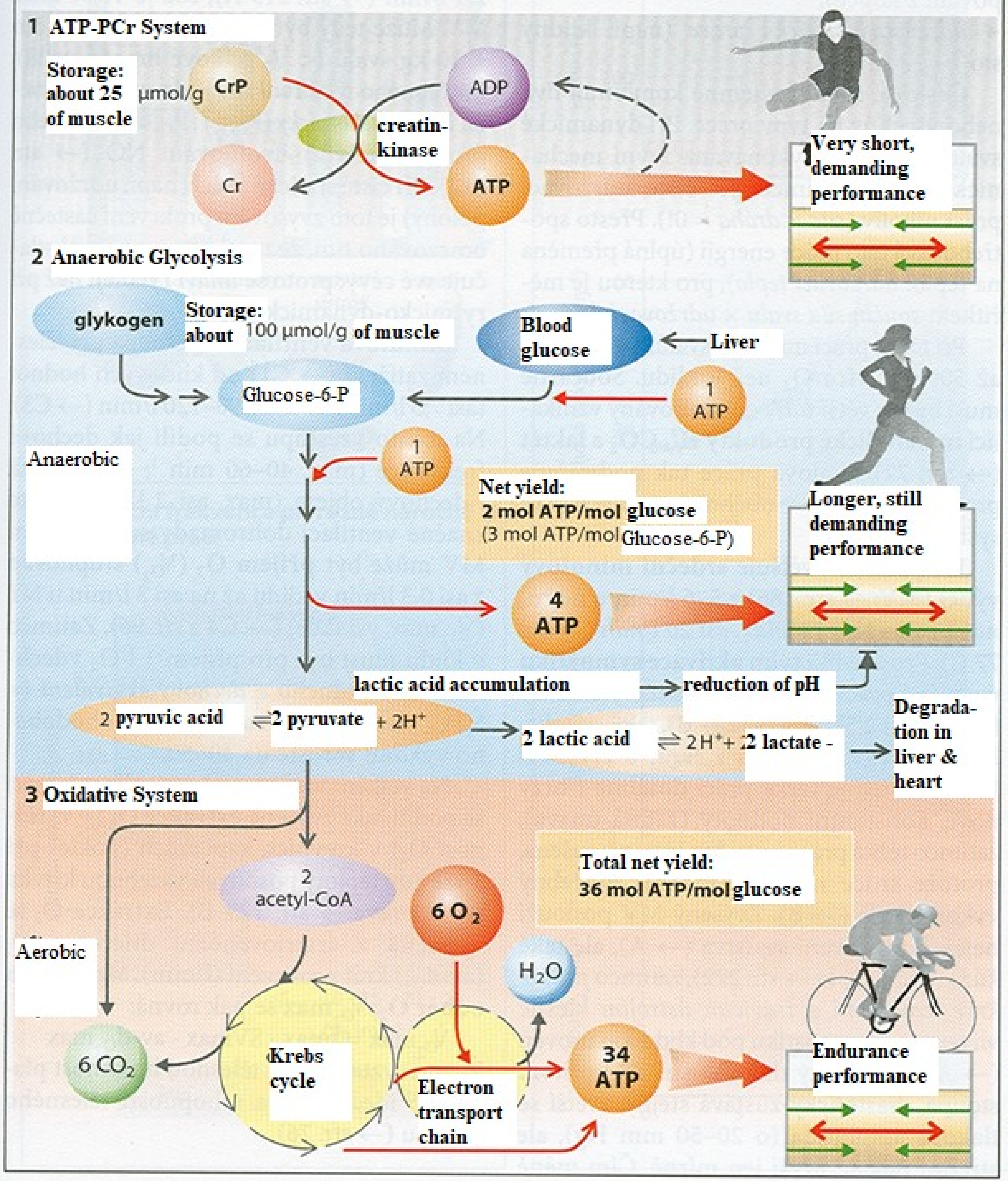
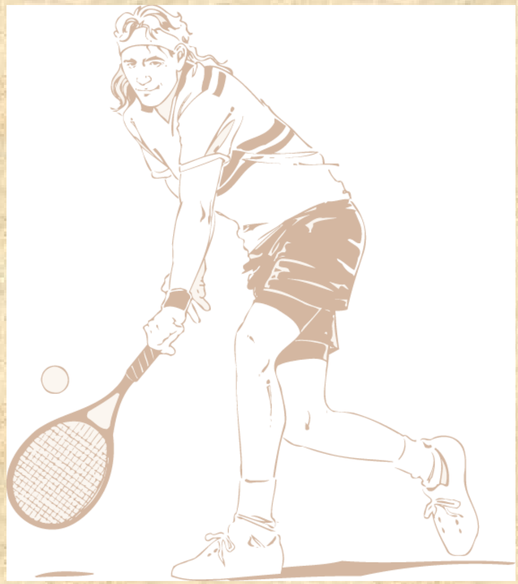

1 ATP-PCr System
Storage: about 25 µmol/g of muscle
CrP
ADP
creatin-kinase
Cr
ATP
Very short, demanding performance
2 Anaerobic Glycolysis
glykogen
Storage: about 100 µmol/g of muscle
Blood glucose
Liver
Glucose-6-P
1 ATP
1 ATP
Anaerobic
Net yield:
2 mol ATP/mol glucose
(3 mol ATP/mol Glucose-6-P)
Longer, still demanding performance
4 ATP
lactic acid accumulation
reduction of pH
2 pyruvic acid ⇌ 2 pyruvate + 2H+
2 lactic acid ⇌ 2 H+ + 2 lactate -
Degradation in liver & heart
3 Oxidative System
2 acetyl-CoA
6 O2
Total net yield:
36 mol ATP/mol glucose
Aerobic
H2O
6 CO2
Krebs cycle
Electron transport chain
34 ATP
Endurance performance

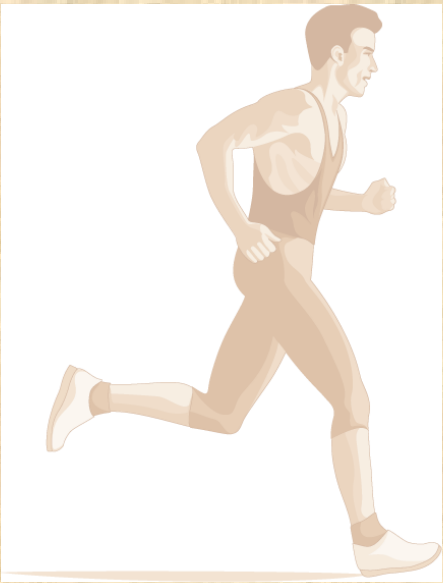
Did You Know…?

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.



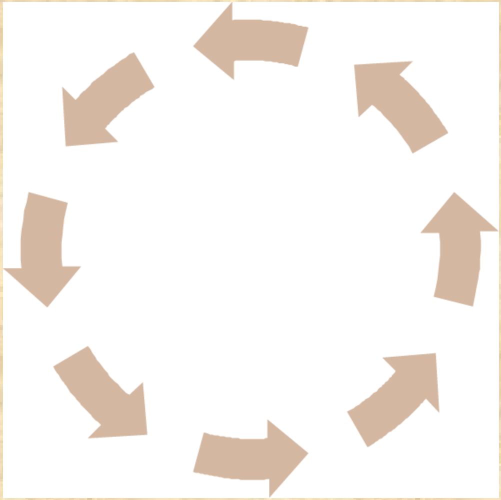
3) Oxidative System

- 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

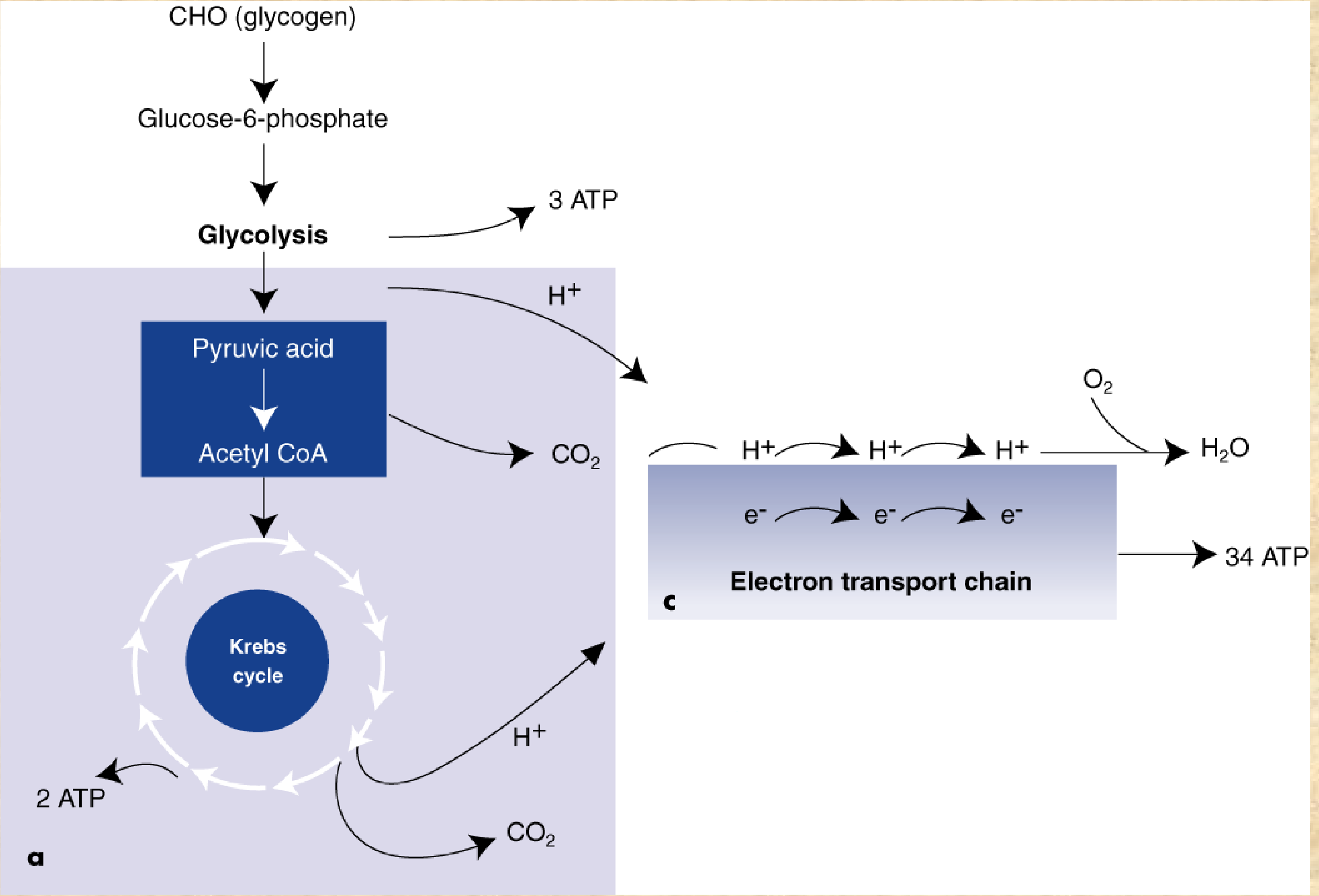
1. Aerobic glycolysis—cytoplasm
2. Krebs cycle—mitochondria
3. Electron transport chain—mitochondria



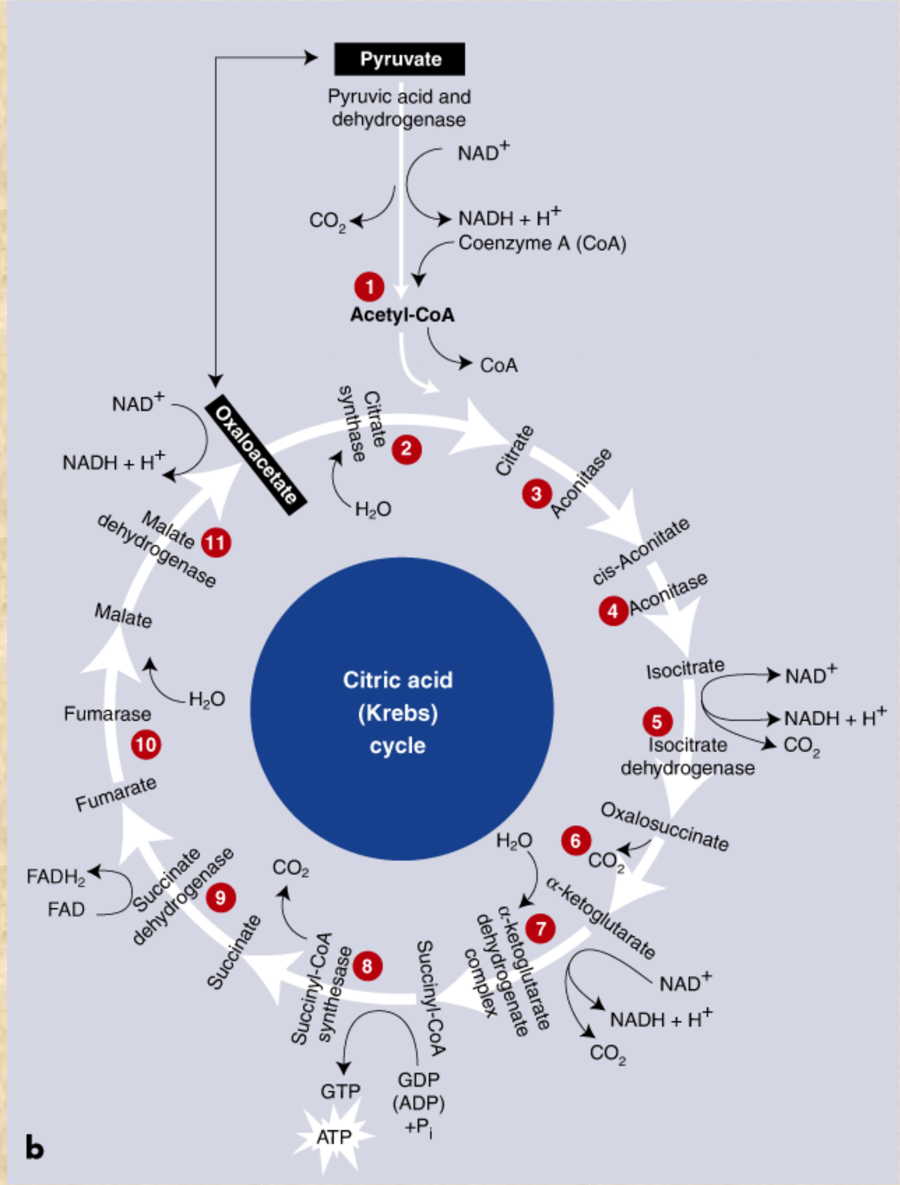
Oxidation of Carbohydrate

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.

AEROBIC GLYCOLYSIS AND THE ELECTRON TRANSPORT CHAIN



KREBS CYCLE

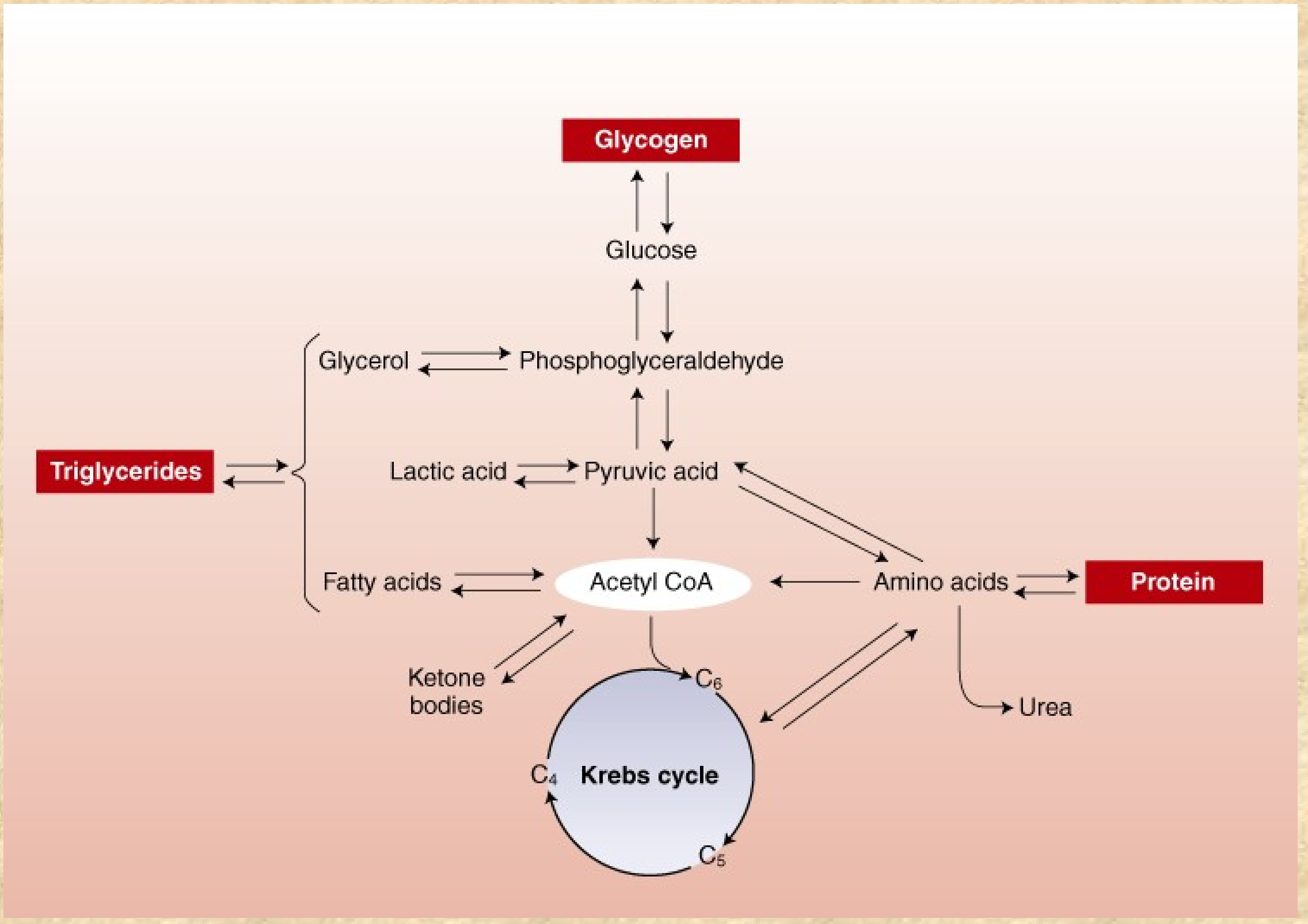


Pyruvate
Pyruvic acid and dehydrogenase
NAD+
NADH + H+
CO2
Coenzyme A (CoA)
1
Acetyl-CoA
CoA
Citrate synthase
2
H2O
Citrate
3
Aconitase
cis-Aconitate
4
Aconitase
Isocitrate
NAD+
NADH + H+
CO2
5
Isocitrate dehydrogenase
Oxalosuccinate
6
CO2
H2O
α-ketoglutarate
7
α-ketoglutarate dehydrogenate complex
NAD+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

Oxidation of Fat

- Lipolysis—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.

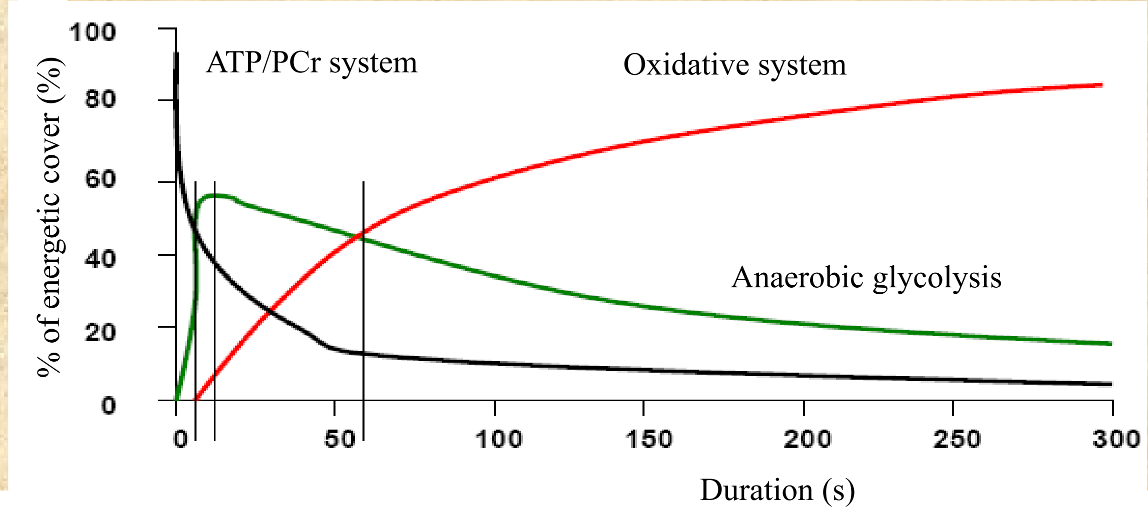
Metabolism of Fat and Protein

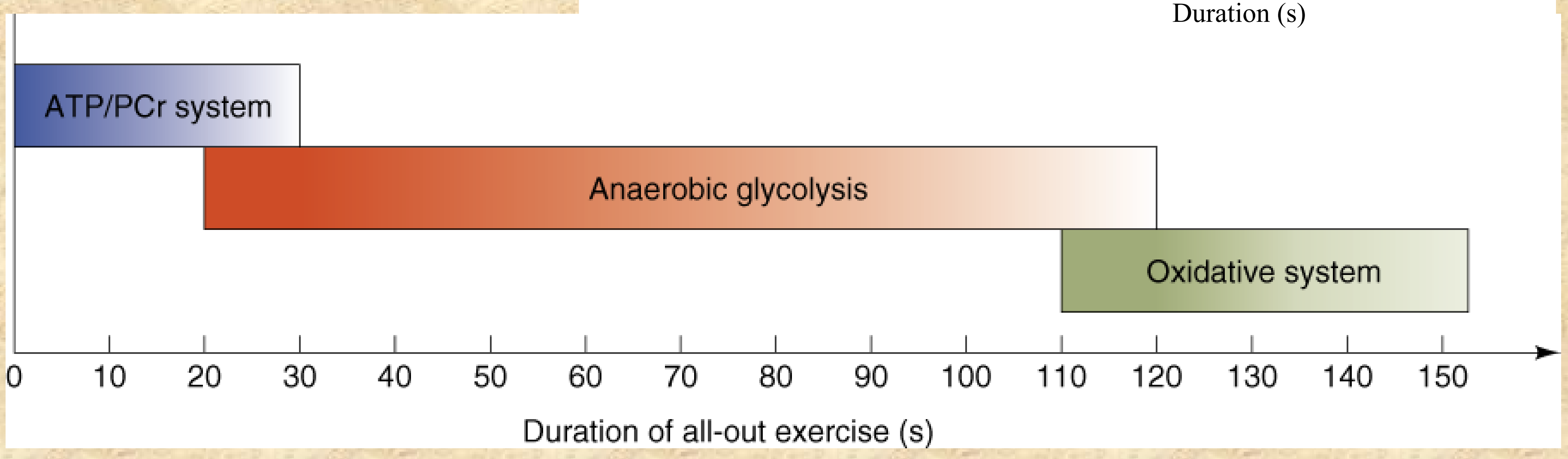


Protein Metabolism

- 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?

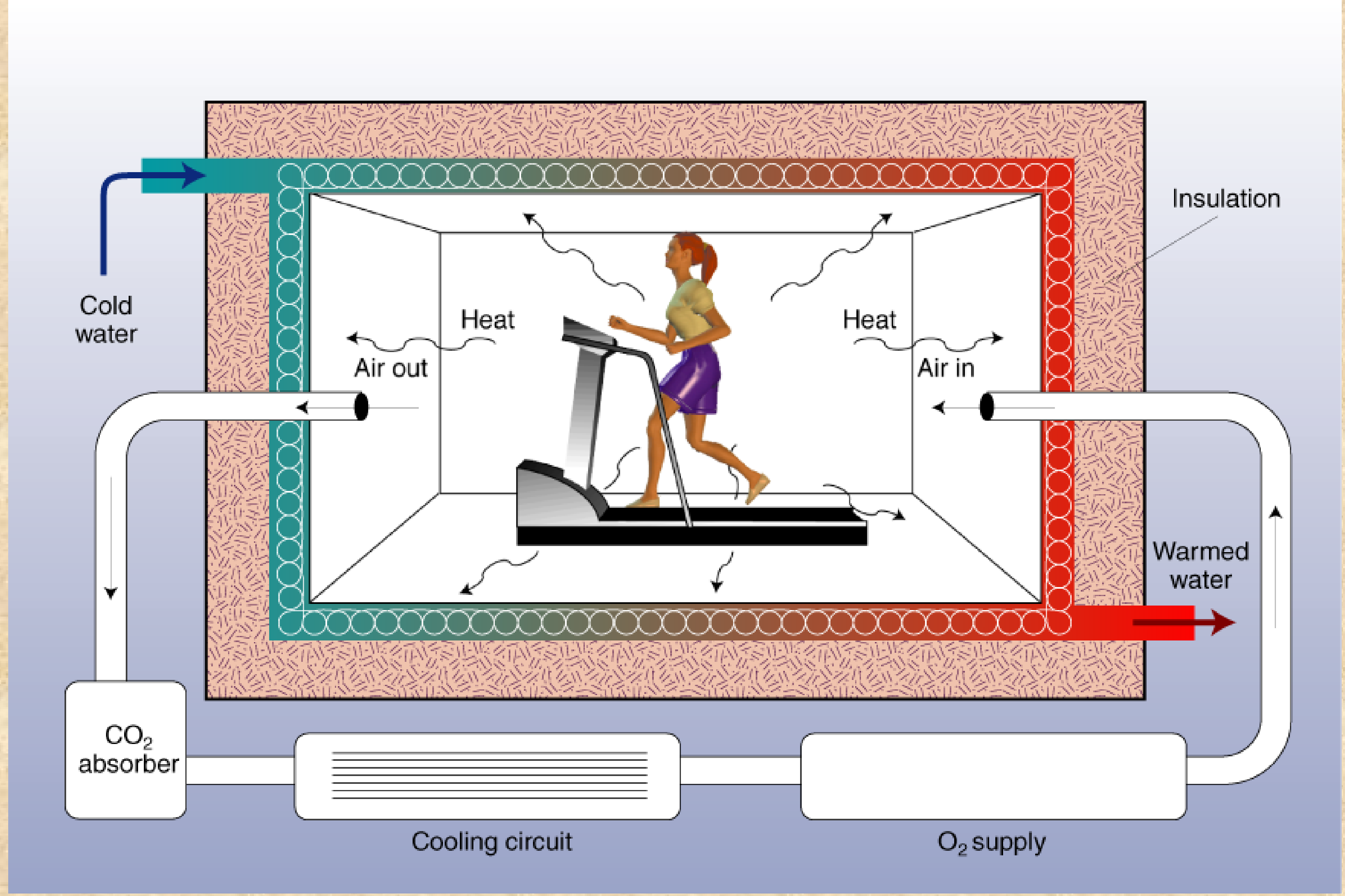
- Oxidative enzyme activity within the muscle
- Fiber-type composition and number of mitochondria
- Endurance training
- Oxygen availability and uptake in the lungs

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 $\dot{V}O_2$.

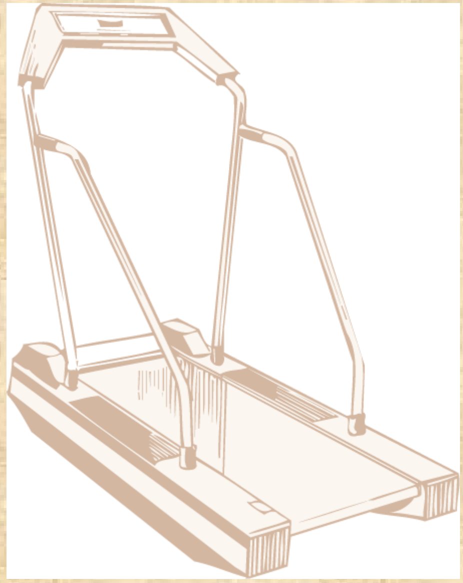
CALORIMETRIC CHAMBER



MEASURING RESPIRATORY GAS EXCHANGE

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 carbohydrates and 0.70 indicating fat (higher need for O_2).

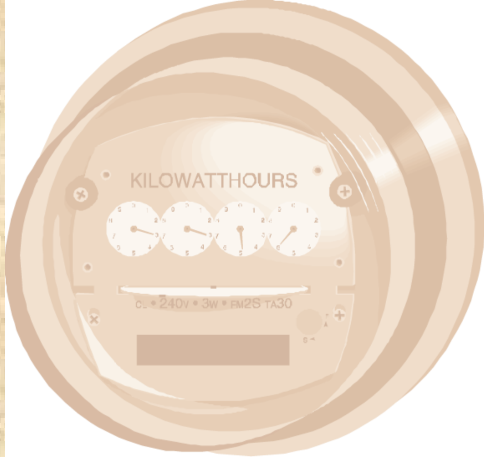


Caloric Equivalence of the RER (VCO_2/VO_2) and % kcal From Carbohydrates and Fats

	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

Metabolic Rate

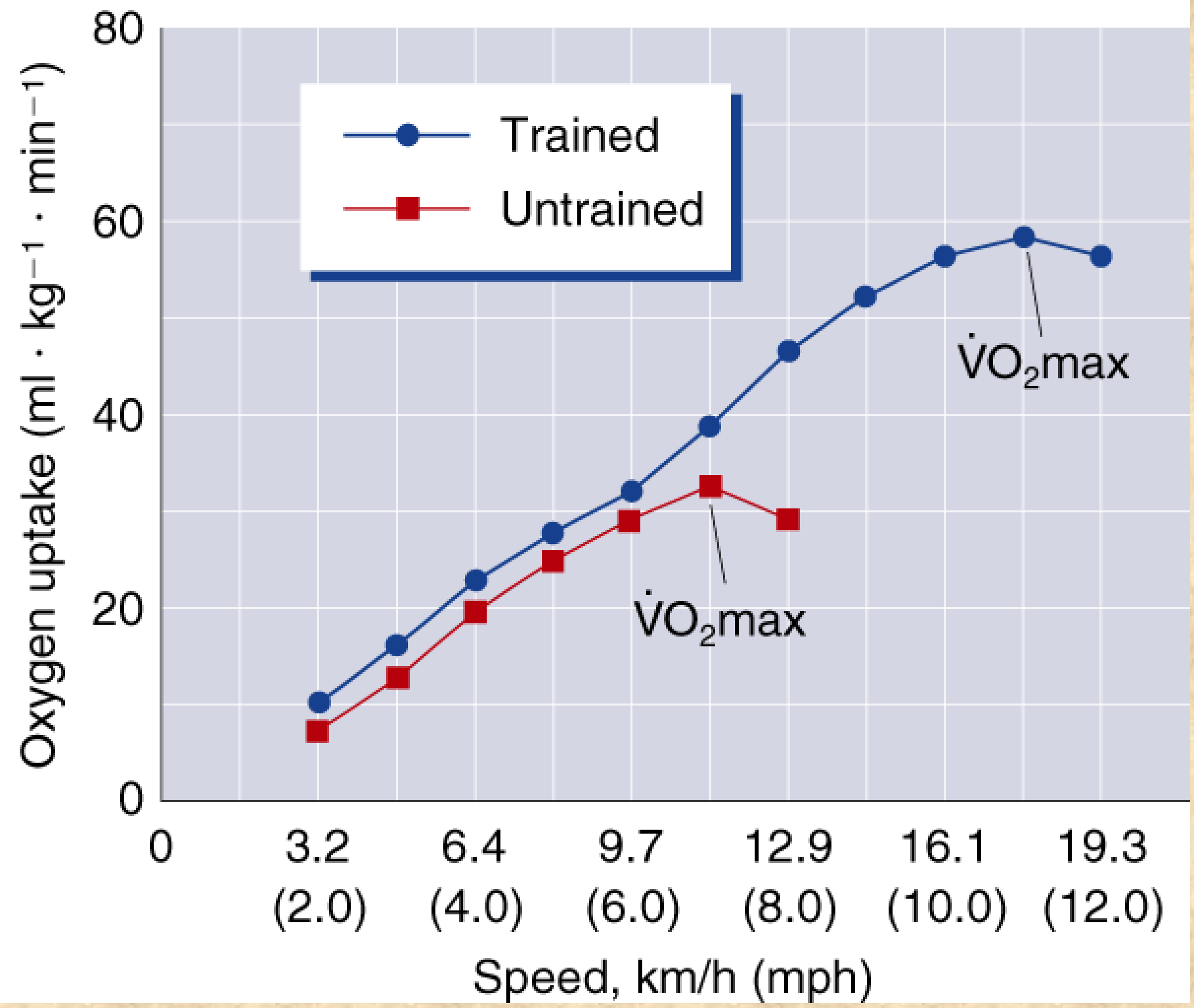
- Rate at which the body expends energy at rest and during exercise
- Measured as whole-body oxygen consumption and its caloric equivalent
- Basal or resting metabolic rate (BMR) is the minimum energy required for essential physiological function (varies between 1,200 and 2,400 kcal/24 hr)
- The minimum energy required for normal daily activity is about 1,800 to 3,000 kcal/24 hr
- 1 kcal = 4.2 kJ



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 in ml of O_2 consumed per body weight per min ($ml \cdot kg^{-1} \cdot min^{-1}$).

EXERCISE INTENSITY AND OXYGEN UPTAKE

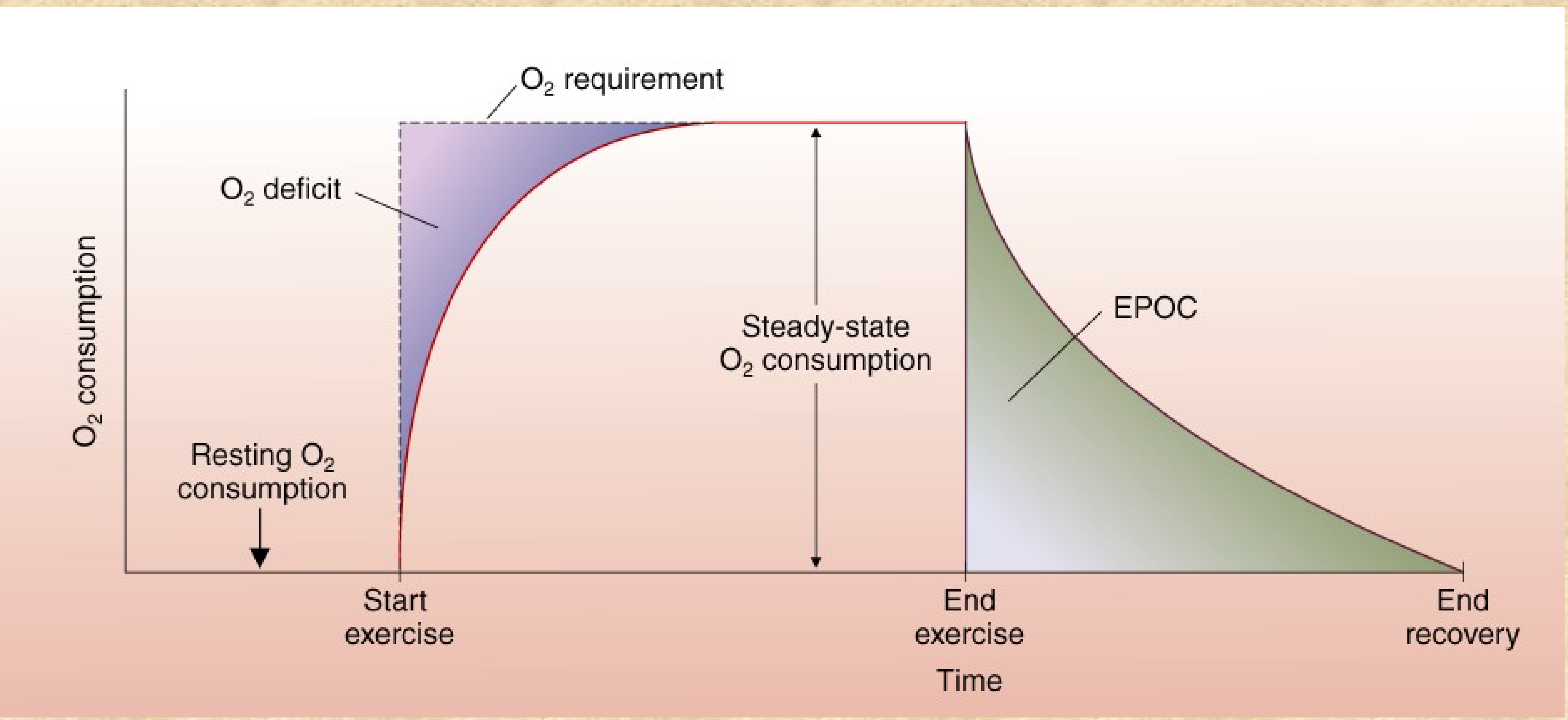


Estimating Anaerobic Effort

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 **spiroergometry**, or the **Wingate anaerobic test** which also show good promise for estimating the metabolic potential of anaerobic capacity

OXYGEN DEFICIT AND EPOC



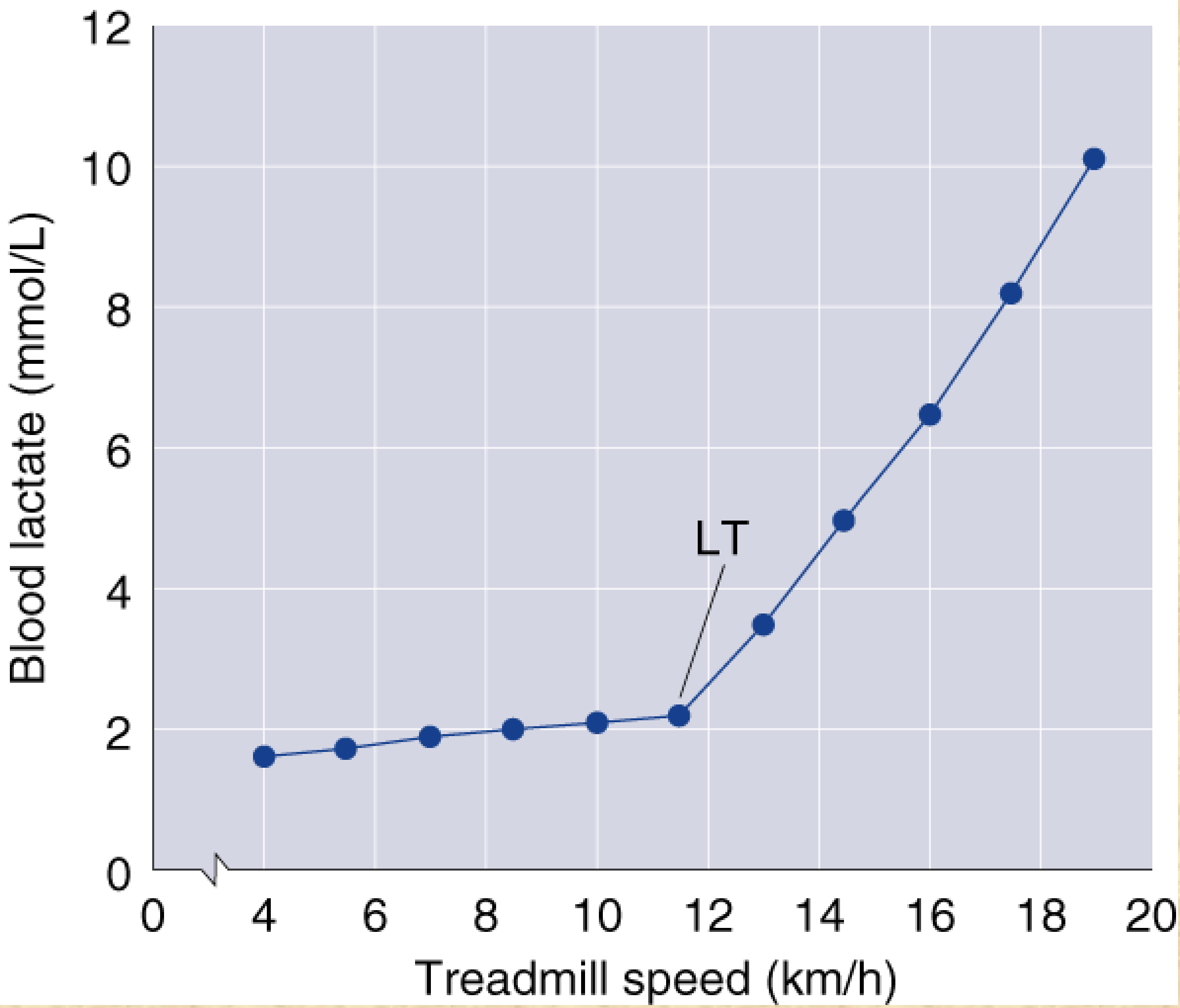
Factors Responsible for EPOC

- Rebuilding depleted ATP supplies
- Balancing pH dropped 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

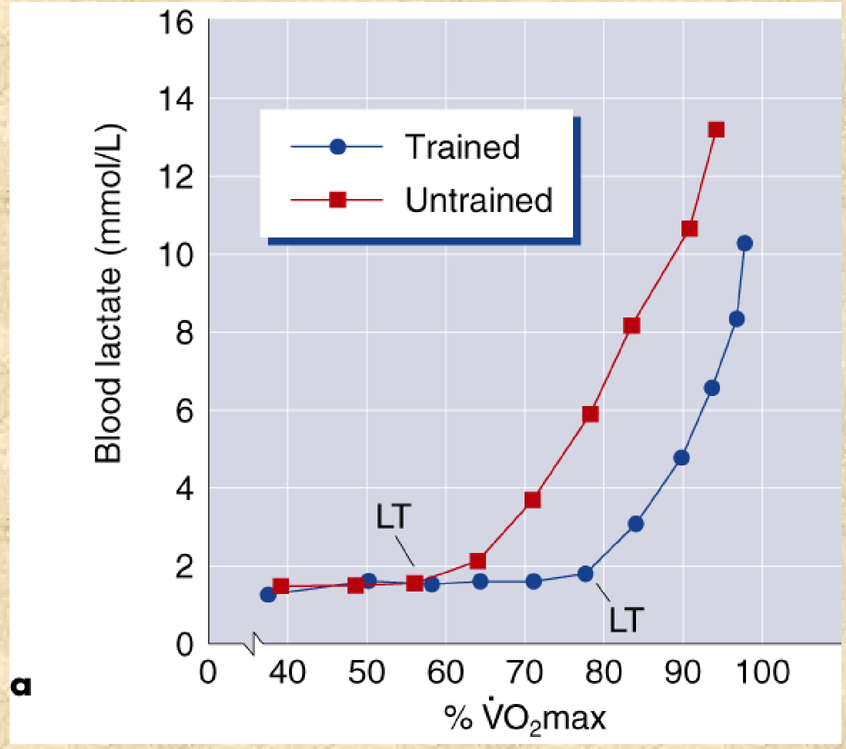
Lactate Threshold

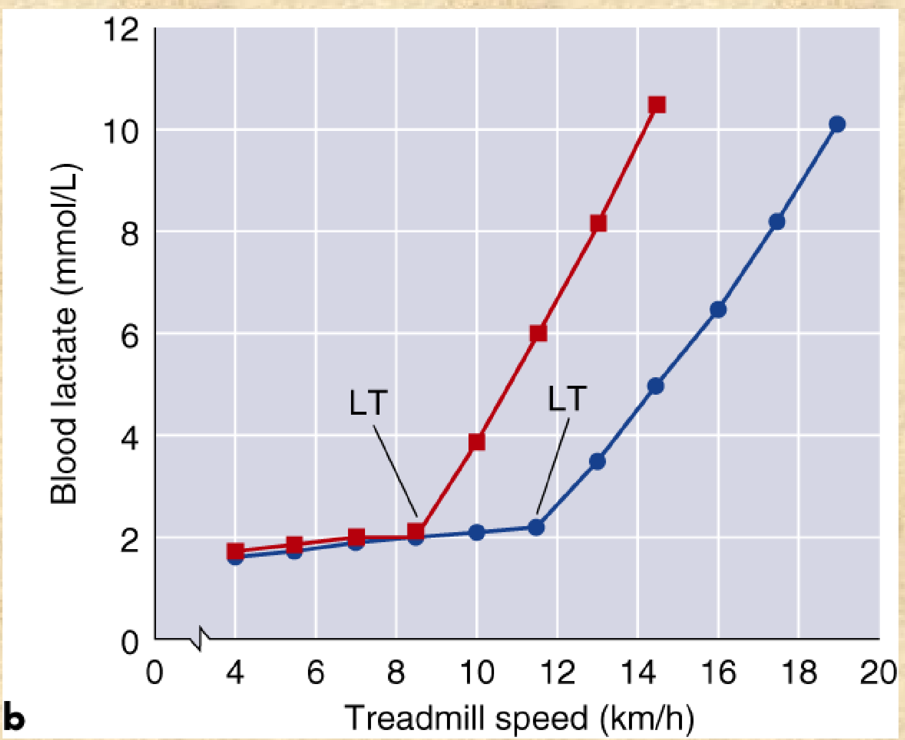
- The point at which blood lactate begins to accumulate above resting levels during exercise of increasing intensity, where lactate production exceeds lactate clearance (by oxidation)
- Sudden increase in blood lactate with increasing effort can be the result of an increase in the production of lactate 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



CHANGES IN LACTATE THRESHOLD WITH TRAINING





Did You Know…?

Lactate threshold (LT), when expressed as a percentage of $\dot{V}O_2max$, 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 $\dot{V}O_2max$, elite athletes may not reach LT until around 70% or 80% $\dot{V}O_2max$.

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

Fatigue and Its Causes

- Phosphocreatine (PCr) depletion
- Glycogen depletion (especially in activities lasting longer than 30 minutes)
- Accumulation of phosphate (especially in events shorter than 30 minutes), and H^+ increased acidity
- Neuromuscular fatigue (Na^+ and K^+ imbalance)

Aerobic vs Anaerobic Training

Aerobic (endurance) training leads to

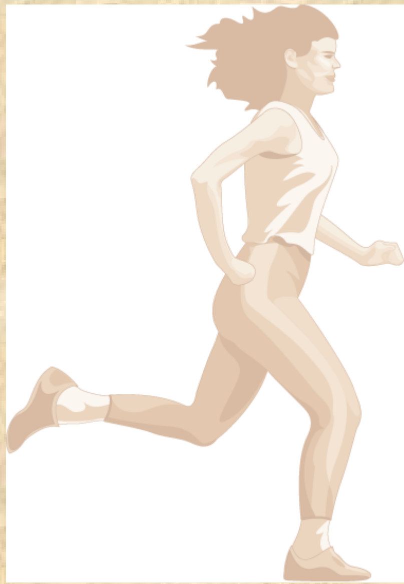
- Improved blood flow, and
- Increased capacity of muscle fibers to generate ATP.

Anaerobic training leads to

- Increased muscular strength, and
- Increased tolerance for acid-base imbalances during highly intense effort.

Adaptations to Aerobic Training

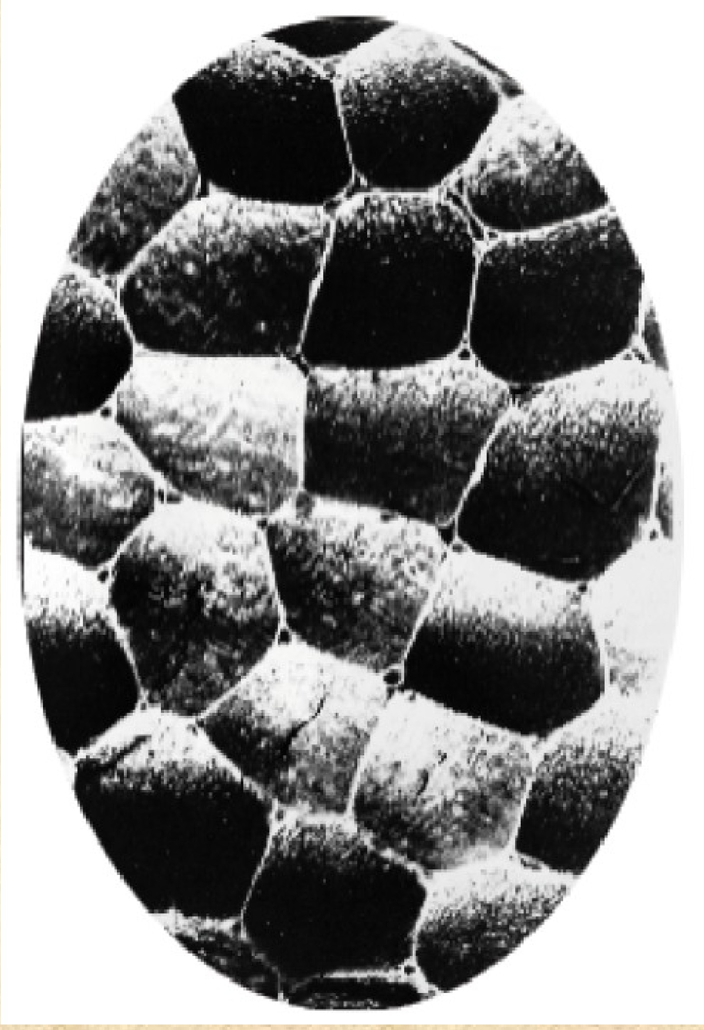
- Improved submaximal aerobic endurance and $\dot{V}O_2max$
- Muscular changes in fiber size, blood and oxygen supply, and efficiency of functioning
- Improved efficiency of energy production
- <u>The magnitude of these changes depend on genetic factors</u>



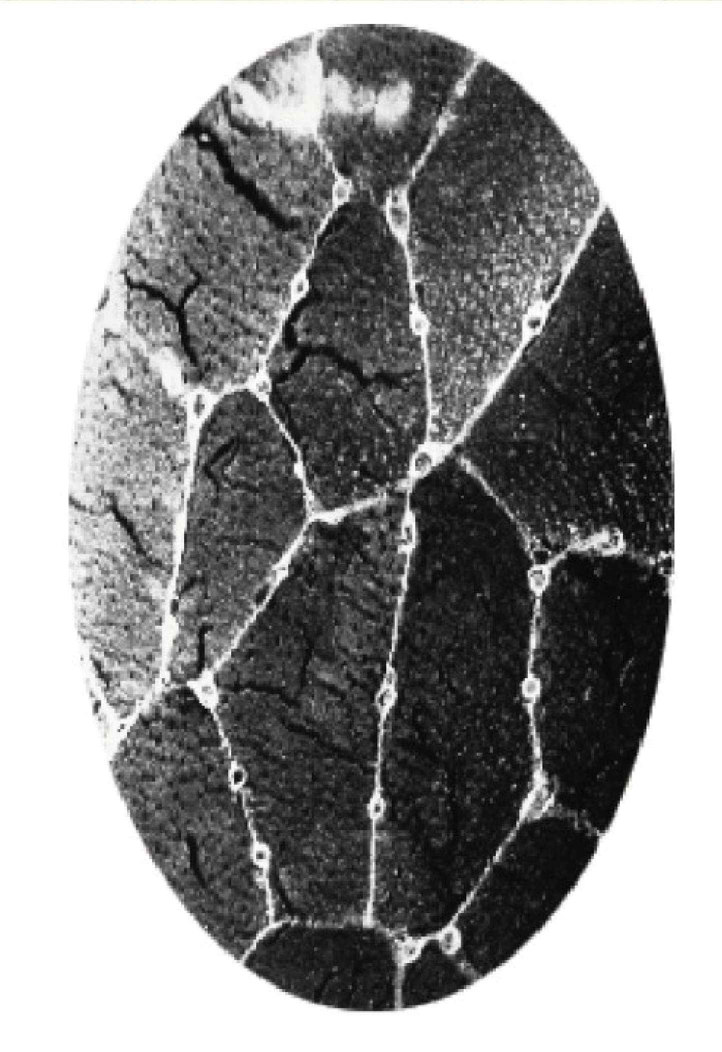
Muscular Adaptations

- Increased cross-sectional area of ST fibers
- Small transition of FT_b to FT_a fibers, but there can also be a small transition of FT to ST fibers
- Increased number of capillaries supplying the muscles which likely is an important factor that allows increase in $\dot{V}O_2max$
- Increased myoglobin content of muscle by 75% to 80% (allowing muscle to store more oxygen)
- Increased number, size, and oxidative enzyme activity of mitochondria

Capillarization in muscles



Untrained



Trained

Adaptations to Anaerobic Training

- Increased muscular strength
- Slightly increased ATP-PCr and glycoytic enzymes; changes in muscle enzyme activity depend on type of training.
- Improved mechanical efficiency
- Increased muscle oxidative capacity (for sprints longer than 30 s)

Did You Know…?

Performance improvements after anaerobic training (short, high-intensity training) appear to be related more to muscular strength gains than improvements in the anaerobic yield of ATP through the ATP-PCr and glycolytic systems.