Aerobic & Anaerobic Metabolism in Muscles

Musculoskeletal Block

1st year

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Objectives

Upon completion of this lecture, students should be able to:

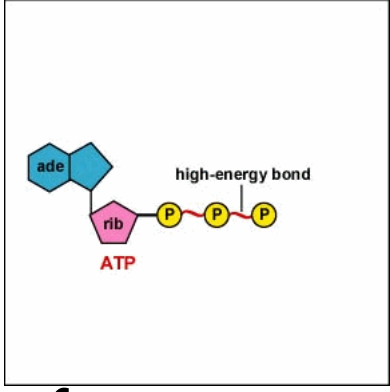
- Recognize the importance of ATP as energy source in skeletal muscle.
- Understand how skeletal muscle derive and utilize ATP for energy.
- Differentiate between energy metabolism in red and white muscle fibers.

Lecture contents:

- Energy requirements and source of energy for skeletal muscle.
- Types of skeletal muscle fibers
- Brief account on what is going on in resting muscle
- Brief account on what is going on in contracting muscle
- Brief account on the Cori's and glucose-alanine cycles

ENERGY REQUIREMENTS AND SOURCE OF ENERGY FOR SKELETAL MUSCLE

ATP as energy source



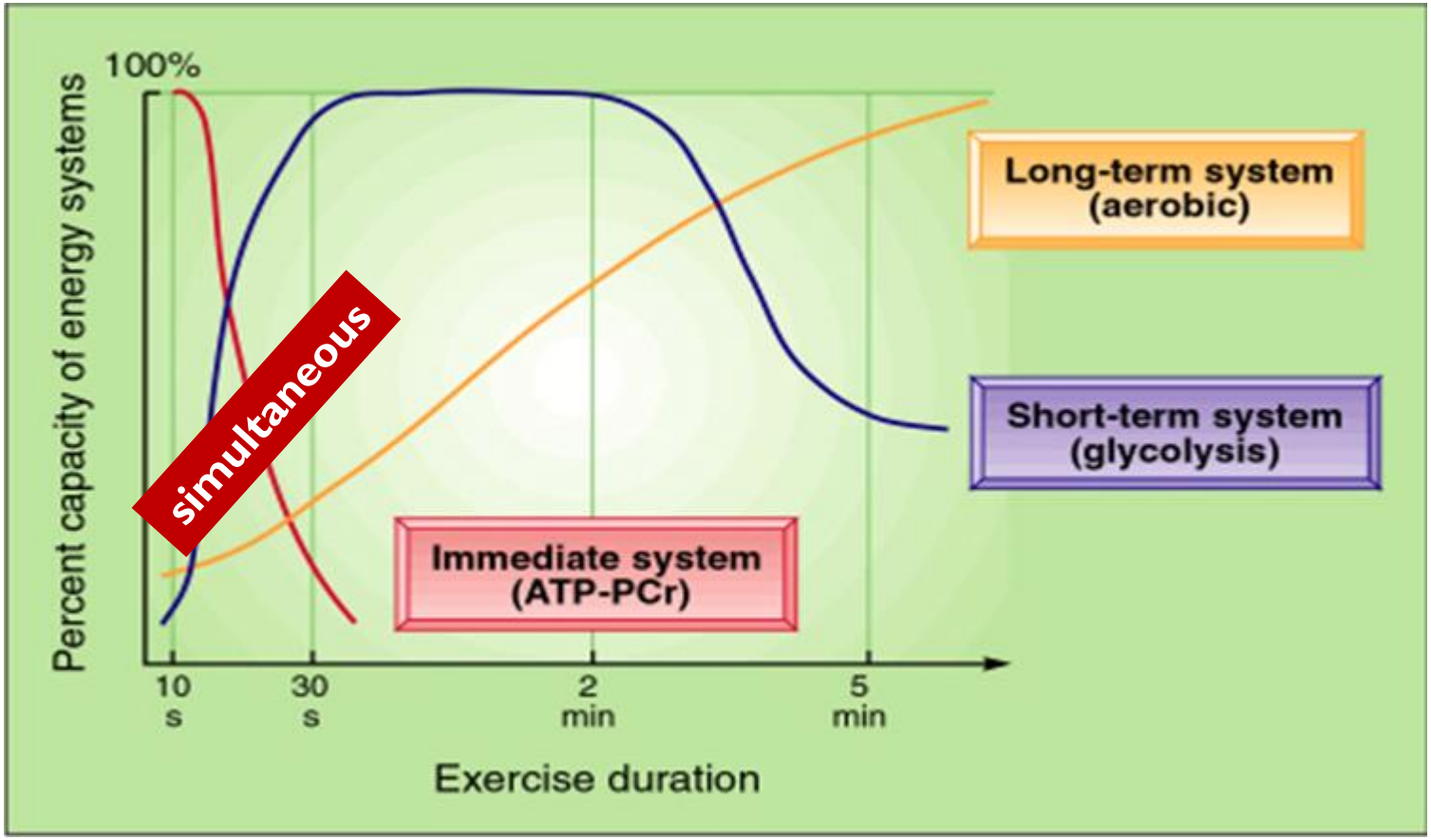
- The nucleotide coenzyme **adenosine triphosphate (ATP)** is the most important form of chemical energy stored in cells
- Breakdown of ATP into ADP+PO_4 releases energy
- This energy is used for all body functions (biosynthesis, membrane transport, muscle contraction, etc.)
- Muscles typically store limited amounts of ATP – enough to power 4-6s of activity
- So resting muscles must have energy stored in other ways.

Production of ATP:

- Contraction requires huge amounts of ATP
- Muscle fibers produce ATP three ways:

1. Creatine phosphate
2. Aerobic metabolism
3. Anaerobic metabolism

Three Systems of Energy



Energy Requirements

- The three energy systems often operate simultaneously during physical activity.
- Relative contribution of each system to total energy requirement differs markedly depending on exercise intensity & duration.
- Magnitude of energy from anaerobic sources depends on person's capacity and tolerance for lactic acid accumulation *(Athletes are trained so that they will have better tolerance for lactic acid)* .
- As exercise intensity diminishes and duration extends beyond 4 minutes, energy becomes more dependent on aerobic metabolism.

Energy Metabolism

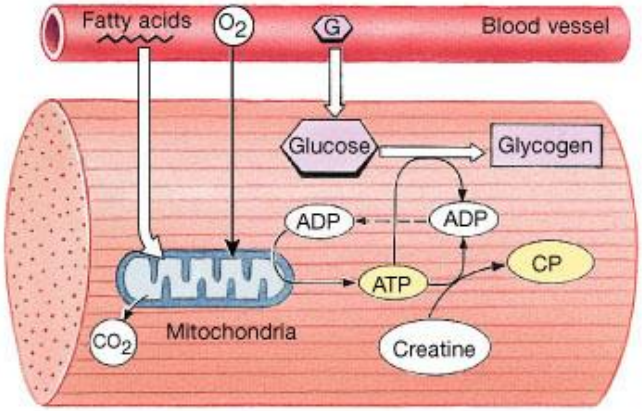
Aerobic

- With oxygen
- Source of energy: mainly **fatty acids**, then carbohydrate
- End products: CO_2, H_2O & ATP

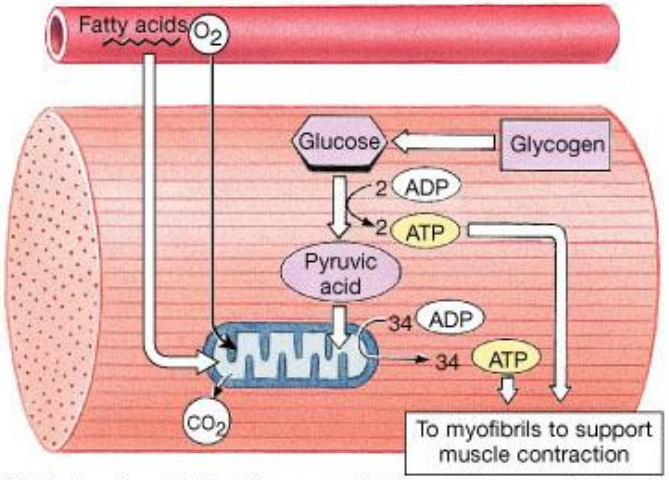
Anaerobic

- Without oxygen
- Source of energy: Carbohydrate (glycolysis)
- End products: Lactate & ATP

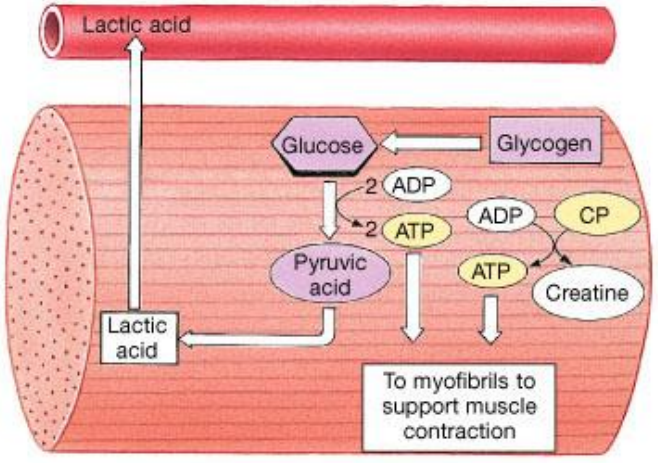
Muscle Metabolism



(a) Resting muscle: Fatty acids are catabolized; the ATP produced is used to build energy reserves of ATP, CP, and glycogen.



(b) Moderate activity: Glucose and fatty acids are catabolized; the ATP produced is used to power contraction.



(c) Peak activity: Most ATP is produced through glycolysis, with lactic acid as a by-product. Mitochondrial activity (not shown) now provides only about one-third of the ATP consumed.

Muscle Fatigue

- Fatigued muscle no longer contracts due to:
  - Build up of lactic acid (low pH of sarcoplasm)
  - Exhaustion of energy resources (↑ ADP & ↓ ATP)
  - Ionic imbalance

How would a fatigued muscle be able again to contract?

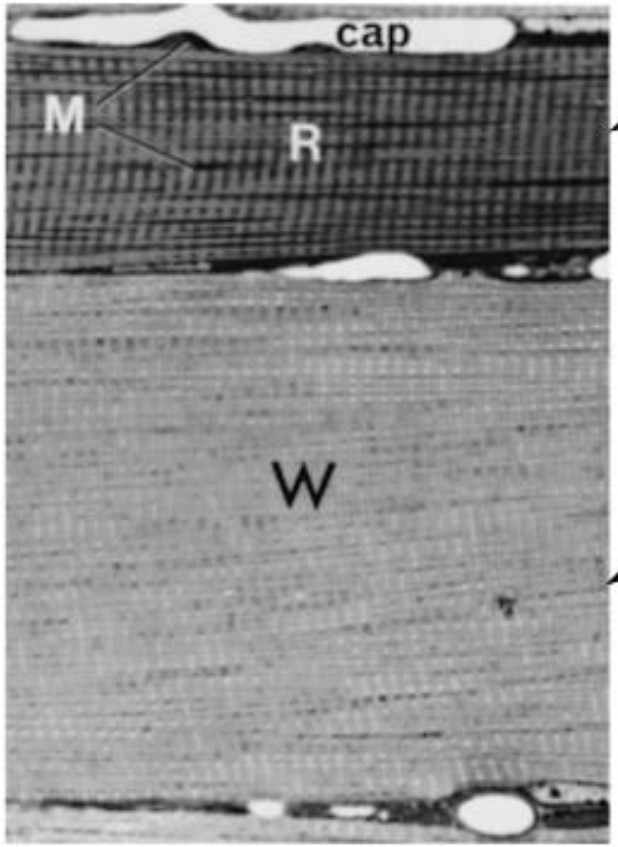
- Recovery period: Begins immediately after activity ends
- Oxygen debt (excess post-exercise oxygen consumption)
  - Amount of oxygen required during resting period to restore muscle to normal conditions

TYPES OF SKELETAL MUSCLE FIBERS

Types of skeletal muscle fibers

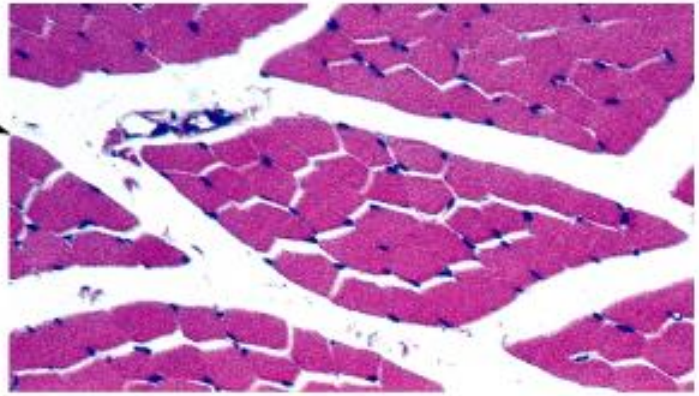
- Mainly:
  - **Fast fibers *(White, Glycolytic)***
  - **Slow fibers *(Red, Oxidative)***

Fast versus Slow Fibers



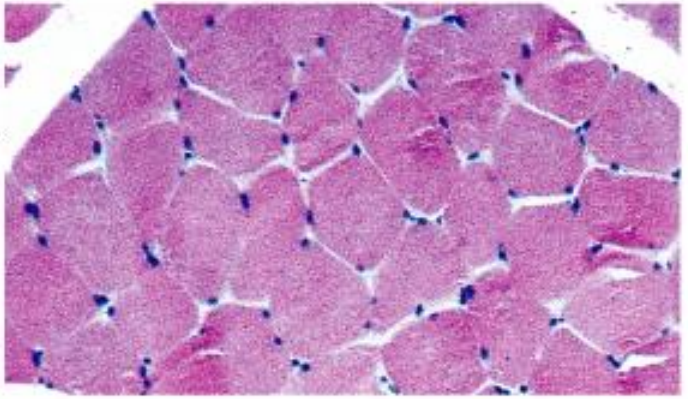
Type I

Slow-twitch oxidative muscle fibers
Note smaller diameter, darker color due to myoglobin. Fatigue-resistant.

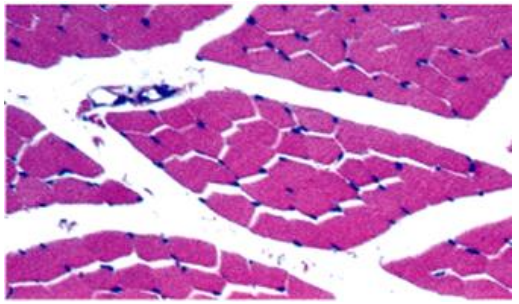


Type II

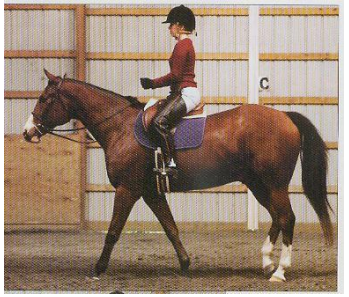
Fast-twitch glycolytic muscle fibers
Larger diameter, pale color. Easily fatigued.



Slow fibers

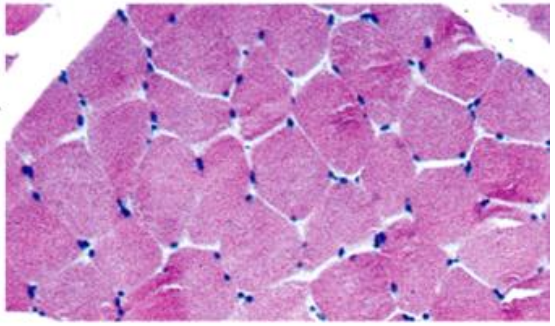


- Half the diameter of fast fibers
- Take three times as long to contract after stimulation

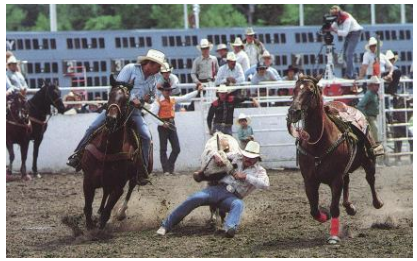


- Abundant mitochondria
- Extensive capillary supply
- High concentrations of myoglobin
- Can contract for long periods of time
- Fatigue resistant
- Obtain their ATP mainly from **FA β-oxidation,** TCA cycle, and the ETC

Fast fibers

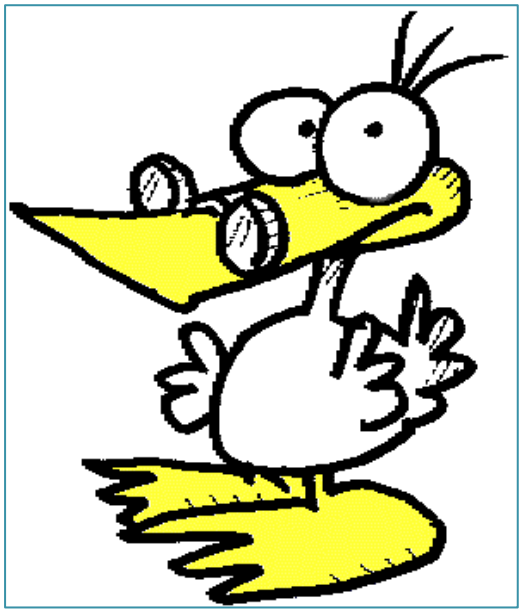


- Large in diameter
- Contain densely packed myofibrils
- Large glycogen reserves
- Relatively few mitochondria



- Produce rapid, powerful contractions of short duration
- Easily fatigued
- Obtain their ATP mainly from **Anaerobic glycolysis**

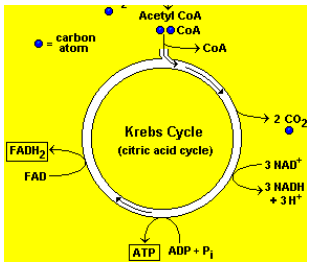
Why do chickens have white breast meat and dark leg meat? Why do migrating ducks have dark breast meat?

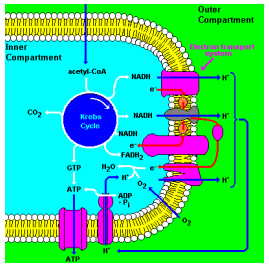


WHAT IS GOING ON IN RESTING MUSCLE?

Muscle at rest

Resting Muscle and the Krebs Cycle





- Resting muscle fibers typically takes up fatty acids from the blood stream.
- Inside the muscle fiber, the FA's are oxidized (in the **mitochondria**) to produce **Acetyl-CoA** & several molecules of NADH and FADH2
- Acetyl-CoA will then enter the **Krebs cycle** (in the **mitochondria**) →CO_2, **ATP,** NADH, FADH2, and oxaloacetate
- NADH and FADH2 will enter **the Electron Transport Chain.** (in the inner **mitochondrial** membrane)→ synthesis of **ATP**

ATP Use in the Resting Muscle Cell

- ATP is necessary for cellular housekeeping duties, e.g.:
  - ATP is used for glycogenesis (storage form of glucose)
  - ATP is used to create another energy storage compound called creatine phosphate

WHAT IS GOING ON IN CONTRACTING MUSCLE?

Working muscle

Working Muscle

- As we begin to exercise, we almost immediately use our stored ATP

- For the next 15 seconds or so, we turn to the creatine-phosphate.

This system dominates in events such as the 100m dash or lifting weights.

Working Muscle

- After the phosphagen system is depleted, the muscles must find another ATP source.
- *The process of anaerobic metabolism can maintain ATP supply for about 45-60s.
- Glycogen → Glucose → 2 pyruvic acid (2 ATP + 2 NADH)
- 2 Pyruvic acid → 2 lactic acid (2 NAD^+)
- Lactic acid diffuses out of muscles →blood → taken by the liver → Glucose (by gluconeogenesis) →blood → taken by the muscle again

* *It usually takes a little time for the respiratory and cardiovascular systems to catch up with the muscles and supply O_2 for aerobic metabolism.*

Anaerobic Metabolism, continued…

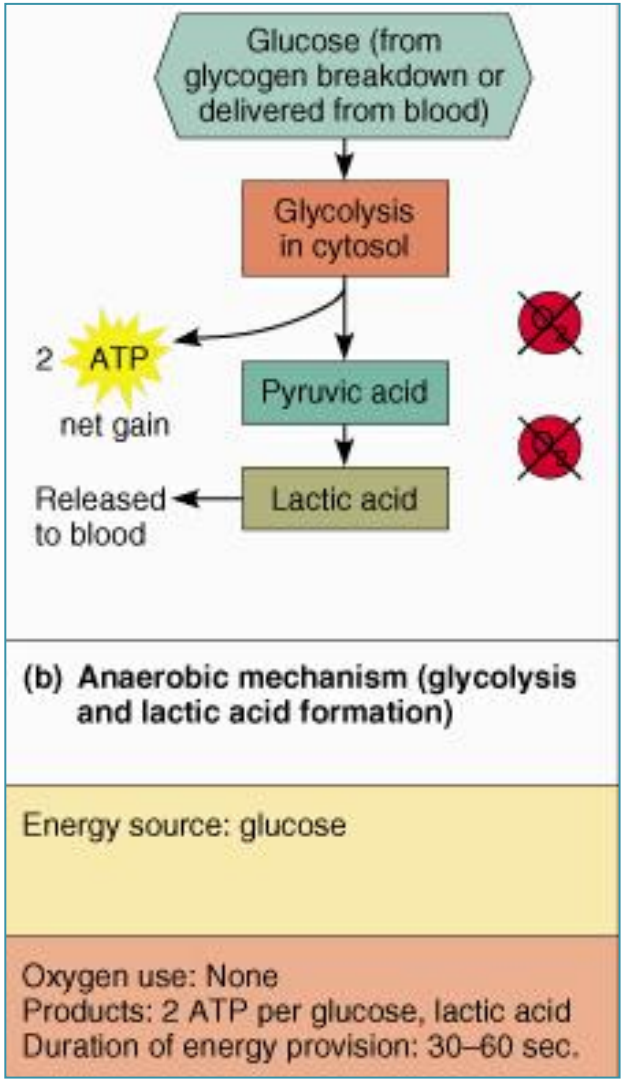
Anaerobic metabolism is inefficient… Why?

- Large amounts of glucose are used for very small ATP returns.
- Lactic acid is produced whose presence contributes to muscle fatigue

Which type of sports uses anaerobic metabolism?

- Sports that requires bursts of speed and activity, e.g., basketball.

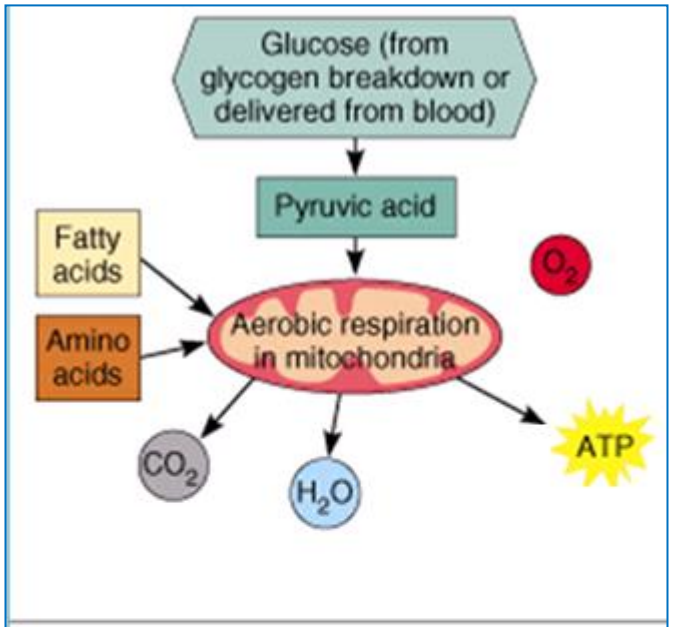
Anaerobic Metabolism in muscles, summary



Aerobic Metabolism

- Occurs when the respiratory and cardiovascular systems have "caught up with" the working muscles.
  - Prior to this, some aerobic respiration will occur thanks to the muscle protein, **myoglobin**, which binds and stores oxygen.
- During **rest** and **light to moderate** exercise, aerobic metabolism contributes 95% of the necessary ATP.
- Compounds which can be aerobically metabolized include:
  - **Fatty acids,** Pyruvic acid (made via glycolysis), and amino acids.

Aerobic Metabolism, summary



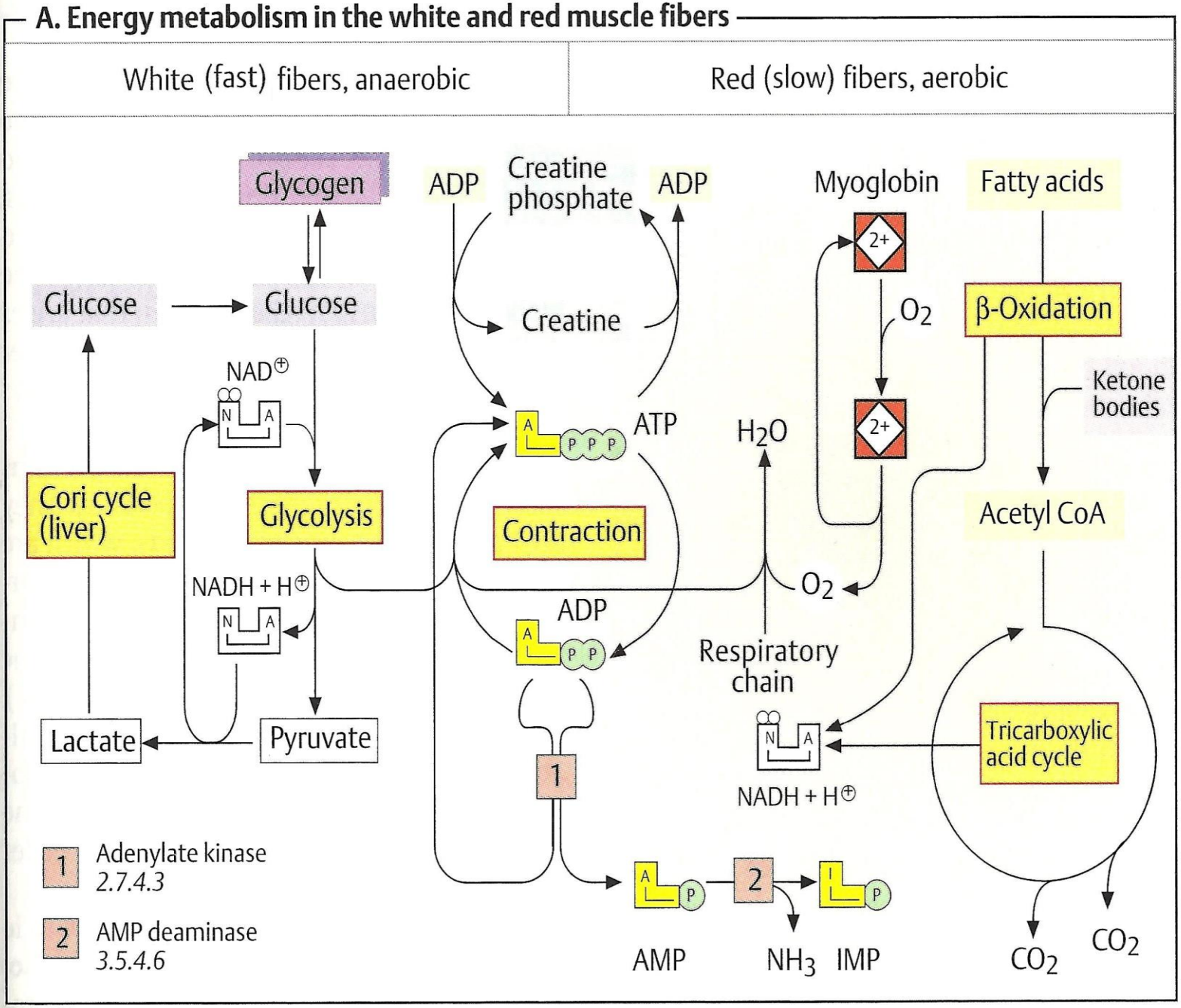
(c) **Aerobic mechanism (oxidative phosphorylation)**

Energy source: glucose; pyruvic acid; free fatty acids from adipose tissue; amino acids from protein catabolism

Oxygen use: Required
Products: 38 ATP per glucose, CO_2, H_2O
Duration of energy provision: Hours

THE CORI CYCLE & THE ALANINE CYCLE

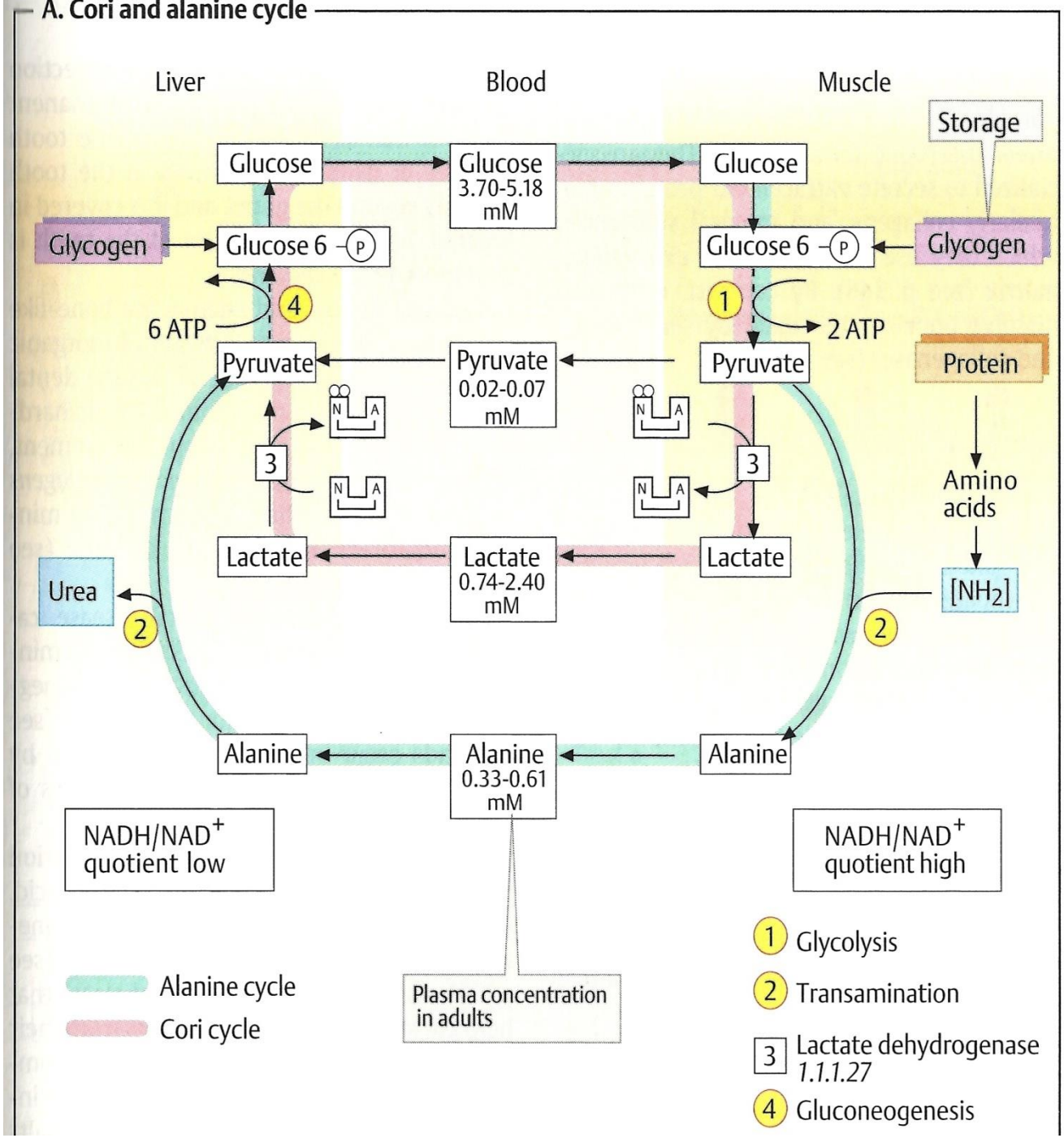
A. Energy metabolism in the white and red muscle fibers



The Cori cycle

- Liver converts lactate into glucose via gluconeogenesis

- The newly formed glucose is transported to muscle to be used for energy again


A. Cori and alanine cycle
Liver
Blood
Muscle
Storage
Glucose
Glucose
3.70-5.18 mM
Glucose
Glycogen
Glucose 6 P
Glucose 6 P
Glycogen
4
6 ATP
1
2 ATP
Pyruvate
Pyruvate
0.02-0.07 mM
Pyruvate
Protein
N A
3
N A
3
Amino acids
Lactate
Lactate
0.74-2.40 mM
Lactate
Urea
2
[NH2]
2
Alanine
Alanine
0.33-0.61 mM
Alanine
NADH/NAD+ quotient low
NADH/NAD+ quotient high
Alanine cycle
Cori cycle
Plasma concentration in adults
1 Glycolysis
2 Transamination
3 Lactate dehydrogenase 1.1.1.27
4 Gluconeogenesis

The glucose-alanine cycle

- Muscles produce:
  - Pyruvate from glycolysis during exercise and NH2 produced from normal protein degradation produce Alanine

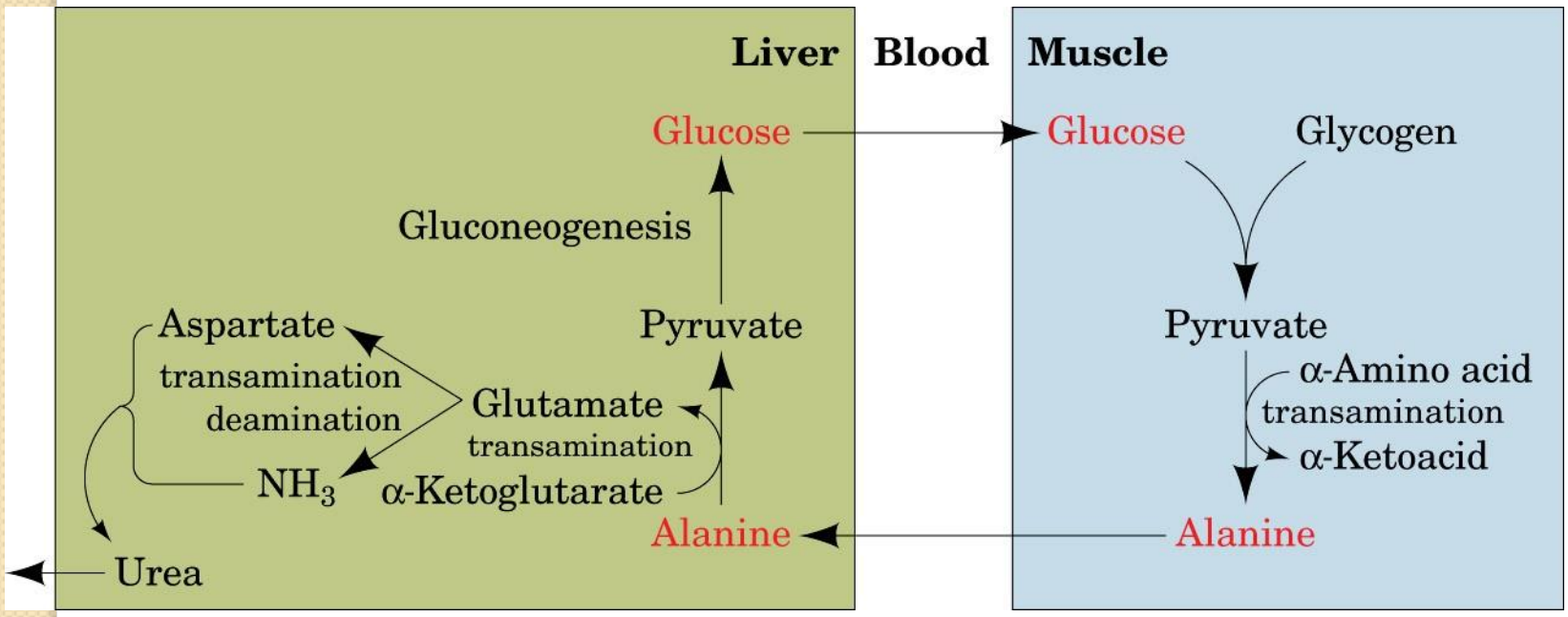
Pyruvate + NH_2 → Alanine

- This alanine is transported through the blood to liver
- Liver converts alanine back to pyruvate

Alanine – NH_2 = Pyruvate

- Pyruvate is used in gluconeogenesis
- The newly formed glucose is transported to muscle to be used for energy again

The glucose–alanine cycle



The glucose-alanine cycle

- What happened to NH_2?
  - **Liver converts it to urea for excretion (urea cycle)**

Take home message

- There are mainly 2 types of muscle fibers:
  - Type I (slow, aerobic, red, rich in mitochondria and myoglobin, mainly generate ATP from fatty acid oxidation, fatigue resistant, involved in endurance activity), &
  - Type II (fast, glyocolytic, white, mainly generate ATP from anaerobic glycolysis, easily fatigued, used for sports required burst of activity)

Take home message..continued

- Muscle metabolism can obtain its energy through:
  - ATP Stores and CP
  - Anaerobic metabolism (relatively inefficient, large amounts of glucose are used for very small ATP returns, lactic acid is accumulated,)
  - Aerobic (relatively efficient, large amount of ATP produced per each glucose molecule used, requires the presence of O_2 & intact mitochondria)

Take home message..continued

- Muscle fatigue is the result of several factors, e.g.
  - Decrease in sarcoplasmic pH (due to ↑ lactic acid)
  - Exhaustion of energy sources (↑ ADP & ↓ ATP)
  - Ionic imbalance
- The glycogen stores in the muscles are rapidly mobilized for ATP production in muscle

Take home message..continued

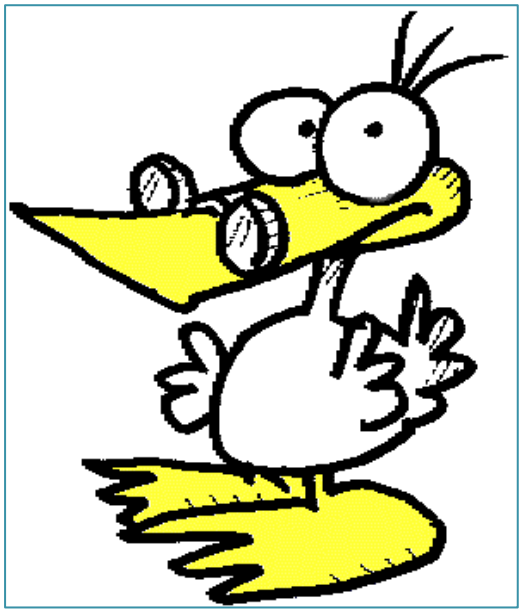
- Glucose-alanine cycle:
  - In the muscles, Pyruvate is converted to Alanine by transamination→ Ala is transported through blood to liver→liver converts Ala back to Pyruvate → Pyruvate is converted to glucose (gluconeogenesis) → glucose is transported to muscle to be used for energy again

Take home message..continued

- Cori's cycle:
  - Lactate produced in exercising muscle is transported to liver→ liver converts lactate back to glucose (gluconeogenesis) → glucose is transported to muscle to be used for energy again

And now, again …

Why do chickens have white breast meat and dark leg meat? Why do migrating ducks have dark breast meat?



THANK YOU ☺