NASM CHAPTER 4
EXERCISE METABOLISM
AND
BIOENERGETICS
Objectives

After this presentation, the participant will be able to:

- Describe the body’s primary energy production for exercise.
- Differentiate between aerobic and anaerobic metabolism.
- Distinguish which energy pathways predominate for various intensities and durations of exercise.
- Understand the interaction of carbohydrate, fat, and protein as fuels for exercise.
- State the differences in energy use during steady state and exhaustive exercise.
- Discriminate between the energy requirements of steady state versus intermittent exercise.
- Describe basic training-induced adaptations in energy production.
Bioenergetics is the study of how energy is transformed through various biochemical reactions:

• **Metabolism** refers to all the chemical reactions that occur in the body to maintain itself.

• **Exercise metabolism** refers to the examination of bioenergetics as it relates to the unique physiologic changes and demands placed on the body during exercise.
**Energy and Work**

- **Adenosine triphosphate (ATP)**
  - Primary sources of immediate energy for cellular metabolism stored in chemical bonds
  - Energy source used to drive muscle contraction
  - When the chemical bonds that hold ATP together are broken, energy is released for cellular work leaving behind another molecule called *adenosine diphosphate* (ADP).
Overview of Energy Metabolism

Chemical energy
- Carbohydrates
- Fats
- Others

Chemical waste
- Carbon dioxide
- Water

ATP
body's energy currency

Metabolism

Heat
Energy Transformations

ATP

ADP

+ P_i

ENERGY FROM FOOD

Supplier
- Creatine Phosphate
- Carbohydrates
- Fats
- Proteins

Intermediary
Biological
Universal Currency
ATP

ENERGY FOR WORK

Consumer
- Muscle Movement
- Synthesis
- Nerve Transmission
- Etc.
Nutrient Substrates

- **Carbohydrates (4 kcal/gm)**
  - Building Block: Glucose
    - Stored as glycogen in muscle & liver

- **Fats (9 kcal/gm)**
  - Building Block: fatty acids (& glycerol)
    - Stored as triglycerides in adipose tissue & active cells.

- **Proteins (4 kcal/gm)**
  - Building Block: amino acids
  - Not a primary energy source during exercise
    - *Branched chain amino acids* are used for fuel when glycogen stores are depleted
Supplying the Body With Energy

Food consumption

- Digestion
- Absorption into blood transported to active cells (site of energy production)
- Immediate usage or storage

Fat
- Fatty acids
  - Metabolic pathways yielding ATP
  - Storage as adipose tissue
  - ATP

Carbohydrate
- Glucose
  - Metabolic pathways yielding ATP
  - Storage as glycogen
  - ATP

Protein
- Amino acids
  - Growth and repair of tissue
  - Lean body mass
  - Excretion of excess
  - Metabolic pathways yielding ATP
  - ATP

Note: ATP = Adenosine triphosphate
Energy and Work-Overview

• **ATP-PC system:** Provides energy for short-duration, high-intensity work, by replenishing ATP rapidly (6–10 seconds).

• **Glycolysis:** Provides energy through the breakdown of glucose to create ATP for moderate-intensity, moderate-duration work (30–50 seconds).

• **Oxidative system:** The most complex of the three energy systems is the process that uses substrates with the aid of oxygen to generate ATP.
Energy Systems for Exercise

- **Immediate energy systems (ATP-PC)**: Active for short periods, up to 10 seconds.
- **Short-term energy systems (glycolysis)**: Active for moderate periods, up to 2 minutes.
- **Long-term energy systems (aerobic)**: Active for extended periods, beyond 2 minutes.

**Exercise duration**
- 10 sec
- 30 sec
- 2 min
- 5 min

**Percent capacity of energy systems**
- 100%
ATP-PC System

- **Immediate Energy System (ATP-PC)**
  - Anaerobic system involving the breakdown of creatine phosphate (CP) and stored ATP to resynthesize ATP for immediate use.
  - Only lasts about 6-10 seconds.
Glycolysis: Aerobic vs Anaerobic
Oxidative Systems

- **Aerobic systems: aerobic glycolysis & beta-oxidation of fats**
  - When sufficient oxygen is available, more ATP can be produced via the breakdown of carbohydrates and fat.
  - The aerobic metabolism of fat yields larger amounts of ATP compared to glucose (fat = 9 kcal/gram; carbohydrate = 4 kcal/gram).
  - Because carbohydrate metabolism requires less oxygen than fat metabolism, the body will use more glucose and less fat for energy as exercise intensity increases.
The Oxidative System

The three processes involved in the oxidative or aerobic systems include:

1. Aerobic glycolysis
2. The Krebs cycle
3. The electron transport chain (ETC)

- Fat can also be metabolized aerobically; the first step in the oxidation of fat is a process referred to as \( \beta \)-oxidation.

- Produces lots of ATP, but very slowly.
OVERVIEW OF AEROBIC METABOLISM

- Carbohydrates: Glucose
- Triglycerides: Fatty acids
- Proteins: Amino acids

Glycolysis: Glucose → Pyruvic acid
Krebs cycle
Electron transport chain and oxidative phosphorylation

ATP production

Cytosol
## Energy System Contributions During Exercise

### The Three Energy Systems and Their Contributions to Total Energy Needs

<table>
<thead>
<tr>
<th>System</th>
<th>Rate of ATP Production</th>
<th>Substrate</th>
<th>System Capacity</th>
<th>Utilization</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphagen</td>
<td>Very rapid</td>
<td>Creatine phosphate, ATP</td>
<td>Very Limited</td>
<td>High-intensity, very short-duration activities</td>
<td>Limited energy supply</td>
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<tr>
<td>Anaerobic Glycolysis</td>
<td>Rapid</td>
<td>Blood/muscle glucose, glycogen</td>
<td>Limited</td>
<td>High-intensity, short-duration activities</td>
<td>Lactic acid production</td>
</tr>
<tr>
<td>Aerobic</td>
<td>Slow</td>
<td>Blood glucose, glycogen, fatty acids, proteins</td>
<td>Unlimited</td>
<td>Lower-intensity, longer-duration activities</td>
<td>Slow rate of oxygen production</td>
</tr>
</tbody>
</table>

*Note: ATP = Adenosine triphosphate*
Energy During Exercise

Intensity and duration of exercise are inversely related:

- The amount of energy available from stored ATP and phosphocreatine is small, whereas the amount of energy from stored carbohydrate has a greater capacity, but is still limited.

- The amount of available fuel for exercise from fats is essentially unlimited.

- The bioenergetics of exercise can be indirectly measured in a laboratory using various modes of exercise.
Contribution of Anaerobic/Aerobic

<table>
<thead>
<tr>
<th>% Aerobic</th>
<th>% Anaerobic</th>
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<tr>
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Activities and their contribution to aerobic or anaerobic energy systems:

- **Weight lifting**
- **Diving**
- **Gymnastics**
- **Wrestling**
- **Ice hockey**
- **Fencing**
- **100-meter swim**
- **Tennis**
- **Field hockey**
- **Soccer**
- **200-meter swim**
- **Skating (1500 meters)**
- **1500-meter run**
- **800-meter swim**
- **Cross-country running**
- **Cross-country skiing**
- **Jogging**

- **100-meter dash**
- **Football**
- **Basketball**
- **Baseball**
- **Volleyball**
- **400-meter dash**
- **Rowing** (2000 meters)
- **1-mile run**
- **400-meter swim**
- **2-mile run**
- **3-mile run**
- **Skating**
- **10,000 meters**
- **10,000-meter run**
- **Marathon**
All chemical reactions in the body are designed to create the common high-energy compound called ATP.

ATP is used to create movement, synthesize chemicals, and other energy consuming tasks.

Synthesizing ATP requires energy.

Food (substrates) provide the energy needed to synthesize or “recycle” ATP from ADP + P_i.

Carbohydrates are the primary fuel used by the body during most exercise.
For simplicity, the systems are described as occurring separately, but they actually come into play as more of an overlapping continuum.

Generally, anaerobic systems are used when working intensely.

Generally, aerobic systems are used when working for longer durations (over 3 minutes).

Generally fat begins to contribute fuel after 20 minutes of exercise.

Generally, protein becomes an important fuel source when glycogen stores are depleted (usually after about 2 hours of exercise).
The body uses several systems to create ATP.

- **ATP-CP** (a.k.a. phosphagen or immediate)
- **Anaerobic glycolysis** (a.k.a. non-oxidative or fast glycolysis)
- **Oxidative System** (a.k.a. *aerobic glycolysis* and *beta oxidation*)
Fuel Selection
During Exercise
Exercise and Fuel Selection

- How is fuel selection measured?
- What role do the following factors play in fuel selection?
  - Intensity
  - Duration
  - Recovery
How is fuel selection measured?

The respiratory quotient (RQ), a.k.a. respiratory exchange ration (RER) is the amount of carbon dioxide (CO$_2$) expired divided by the amount of oxygen (O$_2$) consumed, measured during rest or at steady state of exercise using a metabolic analyzer:

<table>
<thead>
<tr>
<th>RQ</th>
<th>Calories Derived from Carbohydrates (%)</th>
<th>Calories Derived from Fats (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.70</td>
<td>0.0</td>
<td>100.0</td>
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<tr>
<td>0.75</td>
<td>15.6</td>
<td>84.4</td>
</tr>
<tr>
<td>0.80</td>
<td>33.4</td>
<td>66.6</td>
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<tr>
<td>0.85</td>
<td>50.7</td>
<td>49.3</td>
</tr>
<tr>
<td>0.90</td>
<td>67.5</td>
<td>32.5</td>
</tr>
<tr>
<td>0.95</td>
<td>84.0</td>
<td>16.0</td>
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<tr>
<td>1.00</td>
<td>100.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Fuel Selection

- At rest, the average RER is 0.75, meaning that the body is burning approximately 85% fat and 15% carbohydrate.

- As intensity increases, so does RER, meaning a larger percentage of carbohydrate is being burned and a lesser percentage of fat.

- The use of RER has been linked to a common misconception that low-intensity exercise is the best way to lose more weight because it burns more fat.
Energy During Exercise

Costs of exercise vary depending on conditions:

- Lying supine burns fewer calories than standing exercise.
- The body prefers oxidative metabolism.
- **Excess postexercise oxygen consumption:** Elevated oxygen consumption after strenuous exercise.
- During intermittent work glycolysis provides energy for work, oxidative provides recovery.
Fuel Use During Exercise: Carbohydrates

- Carbohydrates are the major macronutrient for the metabolic production of adenosine triphosphate (ATP).
  - Stored as glycogen in the muscle and liver
  - Glycogenolysis is the primary regulator of blood glucose.

- Carbohydrates used during exercise come from both glycogen stores in muscle tissue and blood glucose.
  - The relative contribution of muscle glycogen and blood glucose used during exercise is determined by intensity and duration.
  - After the first hour of submaximal exercise, carbohydrate metabolism shifts from muscle glycogen to *glycogenolysis* in the liver.
  - *Gluconeogenesis* also contributes to blood glucose. It is the formation of glucose from non-glucose sources (e.g. lactate, amino acids, glycerol)
Muscle Glycogen Storage

- Approximately 300–400 grams of glycogen is stored in skeletal muscles and approximately 70 to 100 grams is stored in the liver.
  - Muscle glycogen can only be used by the muscle it is stored in.
  - Liver glycogen is predominantly used to regular blood glucose, but can also contribute to fuel for the muscles in some instances.
    - Glucose is the exclusive source of fuel for the brain and nervous system, thus making blood glucose levels a priority.
  - At intensities >60% VO$_2$max, muscle glycogen is the predominant fuel source. Liver glycogen is more important during low-intensity activity.
Fats are mainly stored as triglycerides in adipocytes, which must be broken down into FFAs (free fatty acids) and glycerol.

- During low-intensity exercise, circulating FFAs from adipocytes are the primary energy source from fat, but during higher intensities, muscle triglyceride metabolism increases.

- As duration increases, the role of plasma FFAs as a fuel source increases.
Protein plays a small role in the fueling of exercise.
- It must be broken down into amino acids, which can be supplied to the muscle tissue from the blood and from the muscle fiber itself.

Skeletal muscle can directly metabolize certain amino acids to produce ATP.

During exercise, glucose stored in a non-exercising muscle can be delivered indirectly to the exercising muscle via the glucose-alanine pathway.

The glucose-alanine cycle

Lactate as Fuel

- Lactate is generally thought of as a waste product of glycolysis.
- Plays a role in glucose production in the liver (gluconeogenesis)
  - During exercise, some of the lactic acid produced by skeletal muscle is transported to the liver via the blood and converted back to glucose.
  - It is released into the bloodstream, and travels back to the skeletal muscles to be used as an energy source.
  - The cycle of lactate to glucose between the muscle and the liver is called the Cori cycle.
  - Serves as a direct fuel source for skeletal muscle and the heart
During prolonged exercise, there is a shift from carbohydrate metabolism toward fat metabolism.
- High-intensity exercise (>70% VO$_{2\text{max}}$)
  - Higher energy requirements per minute.
  - CHO are primary fuel

- Low-intensity exercise (<30% VO$_{2\text{max}}$)
  - Lower energy requirements per minute.
  - Fats are primary fuel
Exercise Intensity and Fuel Selection
Rate of carbohydrate metabolism

- Glycogen depletion is greatest at about 75% $VO_{2\text{max}}$.
- At intensities of less than 60% and greater than 90% $VO_{2\text{max}}$, glycogen stores are not significantly depleted.
The highest rate of lipolysis is about 60-65% of VO$_2$max (upper end of moderate or lower end of vigorous intensities).
Fuel selection during exercise

- **Aerobic training** increases caloric expenditure during the activity and uses predominately carbohydrates and some fat for fuel if *moderately intense and lasting longer than 20 minutes.*

- **Strength training** may increase lean mass and cause an *increase in caloric requirement by 7–10 calories per day for each additional pound of lean mass gained.*

- **Vigorous workouts** burn carbohydrates almost exclusively, but recent research indicates that the body *burns more fat during the recovery (EPOC)* therefore making it a viable weight management tool as well.

- Therefore, a combination of moderate and vigorous aerobic exercise, as well as strength training, are recommended for burning fat and managing weight.
Summary of Fuel Selection

- Respiratory Exchange Ratio (RER), a.k.a Respiratory Quotient (RQ) is used to measure fuel selection.

- Carbohydrates and Fats are primary fuel sources.

- Protein is a secondary source of fuel, but is normally used by the body as a building block.

- Lactate, a metabolic by-product of anaerobic glycolysis, can be recycled by the liver to create glucose via a process called *gluconeogenesis*.
Summary of Fuel Selection

- Carbohydrates are the main source of fuel for intense exercise and early on during exercise.
  - Glycogen depletion is greatest at about 75% of VO₂max

- Fats are primary source of fuel for low intensity exercise and longer duration due to increased oxygen demands to burn.
  - The rate of fat metabolism is greatest at about 60-65% of VO₂max
UNDERSTANDING TERMS RELATED TO METABOLIC RATE
Metabolic rate

- Two terms are commonly used when describing metabolic rate:
  - *basal metabolic rate* (BMR)
  - resting metabolic rate (*RMR*).

- **BMR** is the body’s minimum daily energy requirement for normal function.
  - Typically, BMR is assessed after an overnight stay in a lab where the subject has been fasting for 12 hours and sleeping for 8 hours at a constant room temperature.
  - BMR includes the energy used for ventilation, blood circulation, and temperature regulation.
  - BMR is expressed in terms of daily energy requirements, or daily caloric requirements.
Metabolic equivalent (MET)

- A MET is the ratio of a person's working metabolic rate relative to his or her resting metabolic rate.
- METs can be used to classify physical activities based on their intensities (that is, based on their requirement for oxygen consumption).
- A workout of 2 to 4 METs (such as bowling) is considered light, while intensive running (8 minutes per mile) or martial arts can yield 12 or more METs.
- Aerobic exercise machines can display METs.
  - The numbers displayed are estimates, since the rate at which calories are burned while at rest varies from person to person.

1 MET = 3.5 mL/kg/min
MET calculation

- To determine the VO$_2$ equivalent of any MET value, simply multiply the MET value by 3.5.
  - For example, a typical step aerobics class is about 7 METs, i.e. requires 7 times more energy than rest.
  - Therefore, the oxygen consumption for a typical step aerobics class is:
    - 3.5 mL/kg/min x 7 METs = 24.5 mL/kg/min
RMR is a more common measurement than BMR.

- RMR can be measured with equipment that analyzes breathing gases, or it can be estimated with a mathematical equation.
- BMR is usually 10% lower than RMR and represents a controlled, clinically measured value.
  - Therefore, RMR is the preferred value for field measurements such as those that are conducted in the fitness setting.
- RMR is also expressed in terms of daily caloric requirements.
  - RMR typically ranges from 1,200 cal/day for women to 1,500 cal/day for men.
Metabolism and aging

- RMR decreases with advancing age.
  - For each decade after age 25, 3–5% of muscle mass is lost, which negatively impacts metabolic rate.
  - Some decline still occurs in individuals who exercise regularly.

- However, exercise training may slow the age-related declines in lean mass.
Metabolism Summary

- Basal Metabolic Rate (BMR) is a clinical measurement of minimum metabolic requirements of the body.
- Resting Metabolic Rate (RMR) is a more common measurement used to determine non-activity caloric expenditure.
- Typical RMR’s: ♀1200kcal/d  ♂1500kcal/d
- A Metabolic Equivalent (MET) is used to determine the relative amount of energy expenditure compared to rest.
- RMR decreases with advancing age, but exercise can decrease the rate of decline.