Chapter 5

Fundamentals of Human Energy Transfer

Slide Show developed by:
Richard C. Krejci, Ph.D.
Professor of Public Health
Columbia College  6.18.11
Objectives

1. Describe the first law of thermodynamics related to energy balance and biologic work.

2. Define the terms potential energy and kinetic energy, and give examples of each.

3. Give examples of exergonic and endergonic chemical processes within the body, and indicate their importance.

4. State the second law of thermodynamics, and give a practical application.

5. Identify and give examples of three forms of biologic work.

6. Discuss the role of enzymes and coenzymes in bioenergetics.

7. Identify the high-energy phosphates and discuss their contributions in powering biologic work.
8. Outline the process of electron transport-oxidative phosphorylation.

9. Explain oxygen’s role in energy metabolism.

10. Describe how anaerobic energy release occurs in cells.

11. Describe lactate formation during progressively increasing exercise intensity.

12. Outline the general pathways of the citric cycle during macronutrient catabolism.

13. Contrast ATP yield from carbohydrate, fat, and protein catabolism.

14. Explain the statement, “fats burn in a carbohydrate flame.”
Energy: The Capacity for Work

- The body’s capacity to extract energy from food nutrients and transfer it to the contractile elements in skeletal muscle determines our capacity to move.

- Energy transfer occurs through thousands of complex chemical reactions that require the proper mixture of macro- and micronutrients continually fueled by oxygen.

- The term energy suggests a dynamic state related to change; thus, the presence of energy emerges only when change occurs.
The First Law of Thermodynamics

- Energy cannot be created nor destroyed, but transformed from one form to another without being depleted.

- Conservation of energy:
  - In the body, chemical energy stored within the bonds of macronutrients does not immediately dissipate as heat during energy metabolism.
  - A large portion remains as chemical energy, which the musculoskeletal system then changes into mechanical energy.

---

FIGURE 1-2
Conservation of energy principle for the human body.
Potential and Kinetic Energies

- Constitute the total energy of a system
- Releasing potential energy transforms the basic ingredient into kinetic energy of motion.
- In some cases, bound energy in one substance directly transfers to other substances to increase their potential energy.
  - The transfer provides the required energy for the body’s chemical work known as biosynthesis
Examples of Potential and Kinetic Energies

- Potential energy:
  - Potential energy dissipates to kinetic energy as the water flows down the hill.
  - Work results from harnessing potential energy.
  - Lower potential energy.

- Kinetic energy:

- Heat energy:
Exergonic and Endergonic Reactions

• **Exergonic:** Any physical or chemical process that releases energy to its surroundings.
  
  ▪ Represent “downhill” processes; they produce a decline in free energy.

• **Endergonic:** Chemical processes store or absorb energy.
  
  ▪ Represent “uphill” processes, and proceed with an increase in free energy for biologic work.
Second Law of Thermodynamics

- Tendency of potential energy to convert to kinetic energy of motion with a lower capacity for work (entropy)
- Ultimately, all of the potential energy in a system degrades to the unusable form of kinetic or heat energy (degradation)
Six Forms of Energy

1. Chemical
2. Mechanical
3. Heat
4. Light
5. Electric
6. Nuclear
Interconversions of Six Forms of Energy

Forms of Energy
- Chemical
- Mechanical
- Heat
- Light
- Electric
- Nuclear

- Chemical energy (fossil fuel, oil burner)
- Heat energy (solar panels)
- Mechanical energy (hydroelectric generating plant)
- Nuclear energy (reactor)
- Light energy (Sun)
- Electric energy
Three Forms of Biologic Work

1. **Mechanical Work:** Muscle contraction
2. **Chemical Work:** Synthesis cellular molecules
3. **Transport Work:** Concentration of various substances in the intracellular and extracellular fluids
Exergonic Process of Cellular Respiration

Cellular respiration (reverse of photosynthesis)

Glucose + 6 $O_2$ $\rightarrow$ 6 $CO_2$ + 6 $H_2O$ + ATP
Four Factors Affecting Bioenergetics

1. **Enzymes:** A highly specific and large protein catalyst that accelerates the forward and reverse rates of chemical reactions within the body without being consumed or changed in the reaction.

2. **Reaction Rates:** Operation rate of enzymes

3. **Mode of Action:** How an enzyme interacts with its specific substrate

4. **Coenzymes:** Complex non-protein that facilitate enzyme action by binding the substrate with its specific enzyme
Adenosine Triphosphate (ATP)

- An enzyme found in skeletal muscle that provides the required energy for movement.
- Cell’s “energy currency”
- Cells’ two major energy-transforming activities:
  1. Form and conserve ATP from food’s potential energy
  2. Use energy extracted from ATP to power all forms of biologic work
ATP - The Energy Currency of Cell

TRIPHOSPHATE

High-energy bonds

ADENOSINE
Energy Currency Powering Biologic Work

- Digestion
- Muscle contraction
- Nerve transmission
- Glandular secretion
- Hypothalamus
- Circulation
- Tissue synthesis
- Amino acids → Protein

ADENOSINE

Copyright © 2011 Wolters Kluwer Health | Lippincott Williams & Wilkins
Limited Quantity of ATP

- The body stores only 80 to 100 g of ATP.
  - Provides enough intramuscular stored energy for several seconds of explosive, all-out exercise
- Represents an additional advantage due to its molecule’s heaviness
- Because cells store only a small quantity of ATP, it must be re-synthesized continually at its rate of use.
Phosphocreatine (PCr)

- Provides some energy for ATP re-synthesis.
- PCr releases a large amount of energy when the bond splits between the creatine and phosphate molecules.
- The hydrolysis of PCr begins at the onset of intense exercise, does not require oxygen, and reaches a maximum in about 8 to 12 seconds.
- Cells store PCr in considerably larger quantities than ATP.
ATP & PCr - Anaerobic Sources of Phosphate-Bond Energy

ATP → PCr

ATPase

Creatine kinase

Biologic work

ATP → ADP + P_i

PCR + ADP → Cr + ATP

Energy
Application of the ATP-PCr System
Phosphorylation

- The energy transfer through the phosphate bonds of ATP to other compounds to raise them to a higher activation level
Oxidation

- Biologic burning of macronutrients in the body for the energy needed for **phosphorylation**
  - Occurs on inner lining of mitochondrial membranes
  - Involves transferring electrons from NADH and FADH$_2$ to molecular oxygen, which release and transfer chemical energy to combine ATP from ADP plus a phosphate ion.
  - During aerobic ATP re-synthesis, oxygen combines with hydrogen to form water.
  - More than 90% of ATP synthesis takes place in the respiratory chain by oxidative reactions coupled with phosphorylation.
Examples of Harnessing Potential Energy

The electron transport chain removes electrons from molecules of hydrogen and ultimately delivers them to oxygen (oxidation-reduction process).

Captured energy from mechanical work.
"OIL RIG"

- To remember that oxidation involves the loss of electrons and reduction involves the gain of electrons
  - **OIL**: Oxidation Involves Loss
  - **RIG**: Reduction Involves Gain
Energy Summary

• Energy release in the human body occurs slowly and in small amounts.
• ~40% of potential energy in food nutrients transfers to the high energy compound ATP.
• Splitting of ATP’s terminal phosphate bond liberates free energy to power muscular work.
• Although in limited quantities, ATP represents the cell’s overall energy currency.
• PCr interacts with ADP to form ATP, this non-aerobic high-energy reservoir replenishes ATP rapidly (high energy phosphates).
• Phosphorylation represents energy transfer as energy-rich phosphate bonds. In this process, ADP and Cr continually recycle into ATP and PCr.
• Cellular oxidation occurs on the inner lining of the mitochondrial membranes and involves the transfer of electrons form NADH and FADH$_2$ to molecular oxygen for re-synthesizing ATP.
• During aerobic re-synthesis, oxygen (the final electron acceptor in the respiratory chair) combines with hydrogen to form water (an aerobic end product),
Macronutrient Fuel Sources for Oxidation

1. Tri-acylglycerol and glycogen molecules are stored within muscle cells
2. Stored glycogen (liver and skeletal muscle)
3. Free fatty acids (adipose tissue and diet)
4. Intramuscular- and liver-derived carbon skeletons of amino acids
5. Anaerobic reactions in the cytosol in the initial phase of glucose or glycogen breakdown
6. Phosphorylation of ADP by PCr under enzymatic control by creatine kinase and adenylate kinase
Macronutrient Fuel Sources for Oxidation
Carbohydrate Energy Release

- Carbohydrates’ primary function supplies energy for cellular work.

- Represents the only macronutrient whose potential energy generates ATP aerobically.

- The complete breakdown of one mole of glucose to carbon dioxide and water yields a maximum of 686 kCal of chemical free energy available for work.

- Oxidation of one glucose molecule in skeletal muscle yields a total of 32 ATP molecules.
Anaerobic vs. Aerobic Energy

- **Glycolysis:** Carbohydrate breakdown

  1. **Aerobic:** Relatively slow process resulting in substantial ATP formation
     - The second stage of carbohydrate breakdown converts pyruvate to acetyl-CoA, which then progresses through the citric acid cycle.

  2. **Anaerobic:** Rapid but limited ATP production that produces lactate as the end product
Glycolysis
Lactate Formation

1. \( \text{NADH}_2 + \text{Pyruvate} \rightarrow \text{Lactate} \)

2. \( \text{LDH} \)

Pyruvate: \( \text{C}_3\text{H}_4\text{O}_3 \)

Lactate: \( \text{C}_3\text{H}_6\text{O}_3 \)

2 hydrogen atoms
A Net Yield of 32 ATPs
Fat Energy Release

- Stored fat is the most plentiful source of potential energy.
- Three specific energy sources for fat catabolism:
  1. **Triacylglycerols stored directly** within the muscle fiber in close proximity to the mitochondria.
  2. **Circulating triacylglycerols in lipoprotein complexes** that become hydrolyzed on the surface of a tissue’s capillary endothelium.
  3. **Adipose tissue that provides circulating free fatty acids** mobilized from triacylglycerols in adipose tissue.
- The breakdown of a triacylglycerol molecule yields about 460 molecules of ATP.
Breakdown of Glycerol and Fatty Acid Fragments

1 molecule glycerol
Glycolysis + Citric acid cycle
19

3 molecules of 18-carbon fatty acid
Beta oxidation + Citric acid cycle
441
TOTAL: 460 ATP
“Fats Burn in a Carbohydrate Flame”

• Depleting carbohydrate decreases pyruvate production during glycolysis, which further reduces citric acid cycle intermediates, slowing citric acid cycle activity.

• Fatty acid degradation in the citric acid cycle depends on sufficient oxaloacetate availability to combine with the acetyl-CoA formed during β-oxidation.

• When carbohydrate level decreases, the oxaloacetate level may become inadequate, reducing fat catabolism.
Protein Energy Release

• Protein can serve as an energy substrate.

• When deamination removes nitrogen from an amino acid molecule, the remaining carbon skeleton can enter metabolic pathways to produce ATP aerobically.

• Protein can act as an energy substrate during very long duration, endurance-type activities.
Protein-To-Energy Pathways

Amino Acids

Glucogenic amino acids synthesize glucose or become catabolized

Ketogenic amino acids convert to acetyl-CoA for triacylglycerol formation or become catabolized

Some amino acids directly enter the citric acid cycle for catabolism

Glucose

Pyruvate

Acetyl-CoA

CoA

CO₂

NH₂

CITRIC ACID CYCLE

CO₂

Energy

Electron Transport

Energy

Energy

Energy
The “Metabolic Mill”

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Can Form Glucose?</th>
<th>Can Form Amino Acids?</th>
<th>Can Form Fat?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbohydrates</td>
<td>Yes</td>
<td>Yes; addition of nitrogen yields non-essential amino acids</td>
<td>Yes</td>
</tr>
<tr>
<td>Fats</td>
<td>Fatty acids no; only glycerol portion</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Proteins</td>
<td>Yes; glucogenic amino acids</td>
<td>Yes</td>
<td>Yes; ketogenic amino acids</td>
</tr>
</tbody>
</table>
The End