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Cellular Respiration

Bio 103 Lecture

Dr. Largen

2 Topics

- ✓Introduction to cellular respiration
- ✓Basic mechanisms of energy release and storage
- ✓Stages of cellular respiration and fermentation
- ✓Interconnections between molecular breakdown and synthesis

3 Introduction to Cellular Respiration -
Energy flow and chemical recycling in ecosystems

- ✓Photosynthesis
  - carried out in chloroplasts
    -
  - uses
    - light energy from sun
    - raw materials - carbon dioxide, water
  - produces
    - organic molecules
    - waste product - oxygen
    - required for cellular respiration

4 Introduction to Cellular Respiration -
Energy flow and chemical recycling in ecosystems

- ✓Cellular respiration
  - carried out in mitochondria
  - uses
    - organic molecules
    - oxygen
    - produced by photosynthesis
  - produces
    - energy
      - converted to ATP
    - waste (or by products)
      - carbon dioxide, water, heat energy

5 Figure 9.1 Energy flow and chemical recycling in ecosystems (Campbell & Reece)

6 Introduction to Cellular Respiration -
Principles of energy harvest

- ✓cellular respiration & fermentation are catabolic, energy-yielding pathways
- ✓cells recycle the ATP they use for work
- ✓redox reactions release energy when electrons move closer to electronegative atoms
- ✓electrons “fall” from organic molecules to oxygen during cellular respiration
- ✓“fall” of electrons during respiration is stepwise, via NAD^+ and an electron transport chain

7 Introduction to Cellular Respiration -
Breathing supplies oxygen to our cells and removes carbon dioxide

✓ Respiration
- often used as synonym for breathing
- refers to exchange of gases
  - organism
    - obtains O_2
    - releases CO_2

✓ **Cellular respiration**
- aerobic harvesting of energy from food molecules by cells

8 Introduction to Cellular Respiration -
Breathing supplies oxygen to our cells and removes carbon dioxide

✓ Breathing and cellular respiration are related
- organism
  - distributes O_2 to its cells
    - mitochondria use O_2 in cellular respiration
      - »
      - »

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10 Introduction to Cellular Respiration
Cellular respiration banks energy in ATP molecules

✓ Harvesting energy from food molecules
- fundamental function of cellular respiration
- glucose used as representative food molecule
  - cells use many organic molecules in cellular respiration

✓ summary equation for cellular respiration
- $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{ATPs}$
- bond energy from reactants is shifted to and stored in chemical bonds of ATP

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12 Introduction to Cellular Respiration -
Cellular respiration banks energy in ATP molecules

✓ Efficiency of cellular respiration
- glucose contains lot of chemical energy
  - each ATP molecule made by cellular respiration
    - contains only ~1% of amount of chemical energy present in one glucose molecule
- cellular respiration not able to harvest all energy of glucose in usable form
  - typical cell banks about 40% of glucose's energy in ATP molecules
    - most of other 60% is converted to heat

13 Introduction to Cellular Respiration -
Cellular respiration banks energy in ATP molecules

✓ Efficiency of cellular respiration
- comparison
  - glucose burned in a lab converts 100% of its energy to heat and light

- glucose “burned” in cell converts about 40% its energy into stored energy in ATP molecules
-

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15 Introduction to Cellular Respiration - Cellular respiration banks energy in ATP molecules

✓Cellular respiration
- more efficient than any other process a cell can perform without oxygen
- yeast cell in anaerobic environment harvests ~ 2% of energy in glucose

16 Basic Mechanisms of Energy Release & Storage - Cells tap energy from electrons

✓Underlying mechanisms of energy release and harvest in cell
- energy available to cell is contained in specific arrangement of electrons in chemical bonds (glucose)
- cellular respiration dismantles glucose in a series of steps
  - taps energy carried by electrons
    - rearranged when old bonds break and new bonds form

17 Basic Mechanisms of Energy Release & Storage - Cells tap energy from electrons

✓cellular respiration
- shuttles electrons through series of energy releasing reactions
- at each step, electrons
  - start out in molecule where they have more energy
  - end up in molecule where they have less energy
  - thus, energy is released in small amounts
    - cell stores some of that energy in ATP

✓cells transfer energy from glucose to ATP by coupling exergonic & endergonic reactions

18 Basic Mechanisms of Energy Release & Storage - Cells tap energy from electrons

✓cellular respiration shuttles electrons
- movement of hydrogen atoms can illustrate electron transfers
  - glucose
    - loses hydrogen atoms
      - » converted to carbon dioxide
  - oxygen
    - gains hydrogen atoms
      - » converted to water
    - serves as ultimate electron acceptor in cellular respiration

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20 Mechanisms of Energy Release & Storage- Carriers shuttle electrons in redox reactions

✓**oxidation-reduction reactions (redox)**
- movement of electrons from one molecule to another
- **oxidation**

- loss of electrons from one substance
  - molecule is **oxidized**
- **reduction**
  - addition of electrons to another substance
    - molecule is **reduced**
- always go together because
  - electron transfer requires both donor & acceptor

21 Mechanisms of Energy Release & Storage
Carriers shuttle electrons in redox reactions

✓ **oxidation-reduction reactions (redox)**
- glucose gives up energy as it is oxidized
  - **enzymes** remove electrons from(oxidize) glucose and transfer them to (reduce) a **coenzyme**
- electrons are moved about by moving hydrogen atoms (along with their electrons)

22 Mechanisms of Energy Release & Storage -
Carriers shuttle electrons in redox reactions

✓ **enzymes** remove electrons from(oxidize) glucose and transfer them to (reduce) a **coenzyme**
- two key players are
  - enzyme **dehydrogenase**
  - coenzyme **NAD^+**

23 Mechanisms of Energy Release & Storage-
Carriers shuttle electrons in redox reactions

✓ enzyme **dehydrogenase** & coenzyme **NAD^+**
- oxidize a molecule by removing two H atoms
  - **NAD^+** becomes reduced
    - accepting 2 electrons & 1 proton from the 2H
      - » becomes **NADH** (other H proton goes into solution in cell)
    - electrons added to NAD^+ to make NADH carry energy the cell has harvested

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25 Figure 9.4 NAD^+ as an electron shuttle Campbell & Reece)

26 Mechanisms of Energy Release & Storage-
Redox reactions release energy when electrons “fall” from H carrier to O

✓ Glucose is an “electron bank”
- rich source of electrons for energy-yielding redox reactions

✓ NAD^+ and dehydrogenase
- work together to “withdraw” those electrons
- NADH that results conveys electrons to other molecules, called **electron carriers**
  - a series of electron carriers in the cell is called an **electron transport chain** (ETC)

27 Mechanisms of Energy Release & Storage-
Redox reactions release energy when electrons “fall” from H carrier to O

- ✓ NADH transfers electron to an electron carrier
  - – that reaction is a redox reaction
    - NADH is <u>oxidized</u> to NAD^+
      - – when it gives up the electron
    - electron carrier is <u>reduced</u>
      - – when it gains the electron
  - – this reaction starts an electron cascade
    - in which electrons “fall” down an energy “hill”
      - – consisting of a series of electron carriers

28 Mechanisms of Energy Release & Storage-
Redox reactions release energy when electrons “fall” from H carrier to O

- ✓ electron cascade
  - – each electron carrier is a different molecule
  - – electrons move “downhill”
    - each carrier molecule has greater affinity for electrons (more electronegative) than its uphill neighbor
  - – at each step, redox reactions release energy in small amounts
  - – last molecule at the bottom of the hill is O_2
    - with greatest electron affinity of all the carriers

29 Mechanisms of Energy Release & Storage-
Redox reactions release energy when electrons “fall” from H carrier to O

- ✓ **Electron transport chains (ETC)**
  - – series of electron carriers
  - – ordered groups of molecules
    - in eukaryotes
      - – embedded in membranes of cell’s mitochondria
    - in prokaryotes
      - – in cell’s plasma membrane
  - – as electrons pass along chain, they lose energy
    - which cell can use to make ATP

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31 Figure 9.5 An introduction to electron transport chains (Campbell & Reece)

32 Mechanisms of Energy Release & Storage-
Two mechanisms generate ATP

- ✓ Every cell relies on ATP for energy
- ✓ ATP generated by
  - – **phosphorylation**
    - adding a phosphate group to ADP
  - – two methods
    - **chemiosmotic (oxidative) phosphorylation**
    - **substrate level phosphoryaltion**

33 Mechanisms of Energy Release & Storage-
Two mechanisms generate ATP

- ✓ **chemiosmotic (oxidative) phosphorylation**

– makes ATP using potential energy in concentration gradients

•

– process incorporates plasma membrane, electron transport chain, enzymes, concentration gradient

34 Mechanisms of Energy Release & Storage-
Two mechanisms generate ATP

✓ **chemiosmotic (oxidative)** phosphorylation

– enzymes for process are are in mitochondria membrane

– energy released as electrons cascade down ETC

• enables proteins in membrane to **actively transport** H^+ ions to outside of membrane

– creating H^+ ion concentration gradient

– H^+ ions diffuse back across membrane

» fuel reaction of **ATP synthase** to generate ATP from ADP + phosphate

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36 Figure 9.14 ATP synthase, a molecular mill (Campb & Reece)

37 Mechanisms of Energy Release & Storage-
Two mechanisms generate ATP

✓ **Substrate-level phosphorylation**

– simpler than chemiosmotic (oxidative)

– does not involve a membrane

– enzyme transfers a phosphate group from an organic substrate molecule to ADP

•

– is possible because bond holding phosphate group in substrate is less stable than new bond in ATP

– **accounts for small percentage of ATP production**

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39 Figure 9.7 Substrate-level phosphorylation (Campbell & Reece)

40 Stages of Cellular Respiration & Fermentation
-Overview: Respiration occurs in 3 stages

✓ Cellular respiration

– a continuous process

• can be divided into three main stages

– 1st & 2nd stages are exergonic

» **glycolysis**

» **Krebs cycle**

– 3rd stage is endergonic

» **electron transport chain & chemiosmosis**

41 Stages of Cellular Respiration & Fermentation-
Overview: Respiration occurs in 3 stages

✓ **Glycolysis**

– first stage of cellular respiration
– occurs outside mitochondria in <u>cytoplasm</u>
– begins breakdown of glucose molecule
  • by breaking it into 2 molecules of **pyruvic acid**
– contributes electrons to 3rd stage
– produces 2 molecules of ATP
  • by substrate-level phosphorylation

42 Figure 9.6 An overview of cellular respiration (Layer 3) (Campbell & Reece)

43 Stages of Cellular Respiration & Fermentation-
Overview: Respiration occurs in 3 stages

✓**Krebs cycle**
– 2nd stage
– takes place in mitochondria
– completes breakdown of glucose
  • by decomposing a derivative of pyruvic acid to carbon dioxide
– contributes electrons to 3rd stage
– produces 2 molecules of ATP
  • by substrate-level phosphorylation
– produces other energy-rich molecules

44 Figure 9.6 An overview of cellular respiration (Layer 3) (Campbell & Reece)

45 Stages of Cellular Respiration & Fermentation-
Overview: Respiration occurs in 3 stages

✓**Electron transport chain**
– 3rd stage
– takes place in mitochondria
– chain uses downhill flow of electrons from electron carriers to oxygen
  • uses that energy to pump hydron ions across membrane
    – which provides energy for ATP synthase to make ATP by chemiosmosis

46 Figure 9.6 An overview of cellular respiration (Layer 3) (Campbell & Reece)

47 Stages of Cellular Respiration & Fermentation-
Glycolysis harvests chemical energy

✓**Glycolysis**
– means “splitting of sugar”
– universal energy-harvesting process of life
  • occurs in <u>all</u> cells
  • because of its universality, is thought to be an ancient metabolic system
– starts with glucose
– ends with pyruvic acid
– produces 2 ATP and 2 NADH

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49 Figure 9.8 The energy input and output of glycolysis (Campbell & Rece)

50 Stages of Cellular Respiration & Fermentation - Glycolysis harvests chemical energy

✓**Glycolysis**
- from glucose to pyruvic acid
  - requires 9 chemical steps
    - a number of organic compounds called **intermediates** are formed
    - enzymes catalyze
      - » rearrangement of chemical bonds
    - carbon skeleton of glucose is broken in half

51 Stages of Cellular Respiration & Fermentation- Glycolysis harvests chemical energy

✓**Glycolysis**
- 9 chemical steps can be broken into 2 phases
  - **preparatory phase**
  - **energy payoff phase**

52 Stages of Cellular Respiration & Fermentation- Glycolysis harvests chemical energy

✓**Glycolysis**
- 9 chemical steps can be broken into 2 phases
  - **preparatory phase**
    - 4 steps (1-4)
      - » consumes energy
      - » requires 2ATP to split glucose molecule

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54 Stages of Cellular Respiration & Fermentation- Glycolysis harvests chemical energy

✓**Glycolysis**
- 9 chemical steps can be broken into 2 phases
  - **energy payoff phase**
    - 5 steps (5-9)
      - » all reactions occur in duplicate because glucose was split in preparatory phase
      - » generates 2NADH and 4ATP
- net gain of ATP from glycolysis is 2 ATP
  - (4ATP generated - 2ATP required in preparatory phase = 2ATP)

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56 Stages of Cellular Respiration & Fermentation- Pyruvic acid is chemically groomed for Krebs cycle

✓Pyruvic acid that forms at end of glycolysis
- diffuses from cytoplasm into mitochondria

- where Krebs cycle occurs
- pyruvic acid doesn't enter Krebs cycle
  - first undergoes major chemical grooming
    - converted to **acetyl coenzyme A (acetyl CoA)**
      - » using energy from NADH
    - acetyl coA is high-energy fuel molecule for Krebs cycle

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58 Figure 9.10 Conversion of pyruvate to acetyl CoA, the junction between glycolysis and the Krebs cycle (Campbell & Reece)

59 Stages of Cellular Respiration & Fermentation-
Krebs cycle completes oxidation of organic fuel

✓ Krebs cycle
- only the 2-carbon acetyl part of acetyl CoA enters the Krebs cycle
  - CoA helps acetyl fragment enter cycle
    - CoA then splits off, is recycled
- ends with oxaloacetic acid
- occurs in mitochondria
- pays big energy dividends for cell
- produces per cycle 2CO_2, 3NADH, 1$FADH_2$, and 1ATP (double that per glucose)

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61 Stages of Cellular Respiration & Fermentation-
Krebs cycle completes oxidation of organic fuel

✓ Krebs cycle
- from acetyl CoA to oxaloacetic acid
- two "turns" of Krebs cycle occur for each original molecule of glucose
  -
- requires 5 chemical steps
    - a number of organic compounds called **intermediates** are formed
    - original carbons are completely oxidized to CO_2

62 Stages of Cellular Respiration & Fermentation-
Krebs cycle completes oxidation of organic fuel

✓ Krebs cycle
- Step 1
  - acetyl CoA "stokes furnace"
- Steps 2 & 3
  - NADH, ATP and CO_2 are generated during redox reactions
- Steps 4 & 5
  - redox reactions generate $FADH_2$ and NADH

63 Stages of Cellular Respiration & Fermentation-
Krebs cycle completes oxidation of organic fuel

✓ Krebs cycle
- Step 1
  - acetyl CoA "stokes furnace"
    - CoA is stripped away from acetyl CoA
      - » CoA is recycled

– remaining 2-carbon acetyl fragment is combined with oxaloacetic acid to produce citric acid
  » Krebs cycle is sometimes called citric acid cycle for this reason

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65 Figure 9.12 A summary of the Krebs cycle (Campbell & Reece)

66 Stages of Cellular Respiration & Fermentation-
Chemiosmosis powers most ATP production

✓Electron transport chain
- final stage of cellular respiration
- results in synthesis of ATP by chemiosmosis
- occurs in inner membrane of mitochondria
  - extra folds (cristae) provide enlarged surface area for many copies of ETC and ATP synthase
- most carrier molecules reside in three protein complexes that span membrane and two mobile carriers

67 Stages of Cellular Respiration & Fermentation-
Chemiosmosis powers most ATP production

✓Electron transport chain
- an electron enters first protein complex of ETC
  - when a molecule of NADH (made in Krebs cycle) shuttles it there
- electrons are shuttled down ETC through series of protein complexes
  - protein complexes use energy derived from electrons to actively transport H^+ ions across membrane into inner membrane space
    - creating H^+ ion concentration gradient

68 Stages of Cellular Respiration & Fermentation-
Chemiosmosis powers most ATP production

✓Electron transport chain (con't)
- oxygen accepts electrons at end of ETC
  - then joins with H^+ ions to form water
    - a final products of cellular respiration
- H^+ ions from inner membrane space diffuse down their concentration gradient
  - through ATP synthase
    - which uses potential energy stored in H^+ ion conc. gradient to produce ATP
- by means of chemiosmosis, cell couples exergonic reactions of electron transport to endergonic synthesis of ATP

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70 Figure 9.15 Chemiosmosis couples the electron transport chain to ATP synthesis (Campbell & Reece)

71 Stages of Cellular Respiration & Fermentation-
Certain poisons interrupt critical events in cellular respiration

✓Certain poisons produce their effects by interfering with critical events in cellular respiration

✓three categories
- electron transport chain blockers
- ATP synthase inhibitors
- uncouplers

72 Stages of Cellular Respiration & Fermentation-
Certain poisons interrupt critical events in cellular respiration

✓ three categories
  – electron transport chain blockers
    • prevents ATP synthesis & starves cells of energy
    • examples are rotenone, cyanide, carbon monoxide

73 Stages of Cellular Respiration & Fermentation-
Certain poisons interrupt critical events in cellular respiration

✓ three categories
  – ATP synthase inhibitors
    • blocks passage of H^+ ions through channel in ATP synthase
    • prevents cell from using potential energy of conc. Gradiernt to make ATP
    • example is oligomycin

74 Stages of Cellular Respiration & Fermentation-
Certain poisons interrupt critical events in cellular respiration

✓ three categories
  – uncouplers
    • makes membrane of mitochondria “leaky” to H^+ ions
    • electron transport proceeds but no H^+ ions conc gradient develops o no ATP can be made
    • example is dinitrophenol (DNP)

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76 Stages of Cellular Respiration & Fermentation-
Review: Each molecule of glucose yields many ATP molecules

✓ What does the cell accomplish in aerobic cellular respiration by oxidizing a molecule of glucose?
  – three stages of cellular respiration
  – where each stage occurs
  – starting material for each stage
  – net yield for each stage in energy rich molecules

77 Stages of Cellular Respiration & Fermentation-

Review: Each molecule of glucose yields many ATP molecules

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79 Figure 9.16 Review: how each molecule of glucose yields many ATP molecules during cellular respiration (Campbell & Reece)

80 Stages of Cellular Respiration & Fermentation-
Fermentation is an anaerobic alternative to aerobic respiration

- ✓ Under anaerobic conditions (oxygen-lacking)
  - many organisms can use glycolysis alone to produce small amounts of ATP
  - to do this, cell must have a way to replenish its supply of NAD^+
    - can be done by converting the pyruvic acid produced by glycolysis to another molecule
      - alcoholic fermentation
        - » pyruvic acid is converted to CO_2 and ethanol
      - lactic acid fermentation
        - » pyruvic acid is converted to lactic acid only

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82 Figure 9.17a Fermentation (Campbell & Reece)

83

84 Figure 9.17b Fermentation (Campbell & Reece)

85 Figure 9.18 Pyruvate as a key juncture in catabolism (Campbell & Reece)

86 **The End**