Carbohydrate Catabolism

By

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Most microorganisms oxidize carbohydrates as their primary source of cellular energy. **Carbohydrate catabolism,** the breakdown of carbohydrate molecules to produce energy, is therefore of great importance in cell metabolism. Glucose is the most common carbohydrate energy source used by cells. Microorganisms can also catabolize various lipids and proteins for energy production

To produce energy from glucose, microorganisms use two general processes: *cellular respiration* and *fermentation*. Both cellular respiration and fermentation usually start with the same first step, glycolysis, but follow different subsequent pathways

Glycolysis

Glycolysis, the oxidation of glucose to pyruvic acid, is usually the first stage in carbohydrate catabolism. Most microorganisms use this pathway; in fact, it occurs in most living cells.

Glycolysis is also called the *Embden-Meyerhof pathway or ED P* . The word *glycolysis* means splitting of sugar, and this is exactly what happens. The enzymes of glycolysis catalyze the splitting of glucose, a six-carbon sugar, into two three-carbon sugars. These sugars are then oxidized, releasing energy, and their atoms are rearranged to form two molecules of pyruvic acid.

During glycolysis

NAD+ is reduced to NADH,

and there is a net production of two ATP molecules by substrate-level phosphorylation.

Glycolysis does not require oxygen; it can occur whether oxygen is present or not.

This pathway is a series of ten chemical reactions, each catalyzed by a different enzyme.

To summarize the process, glycolysis consists of two basic stages, a preparatory stage and an energy-conserving stage:

1. First, in the preparatory stage

two molecules of ATP are used as a six-carbon glucose molecule is phosphorylated, restructured, and split into two three-carbon compounds: **glyceraldehyde 3-phosphate (GP)** and dihydroxyacetone phosphate 1(DHAP). DHAP is readily converted to GP. (The reverse reaction may also occur.) The conversion of DHAP into GP means that from this point on in glycolysis, two molecules of GP are fed into the remaining chemical reactions.

2. In the energy-conserving ,

the two three carbon molecules are oxidized in several steps to two molecules of pyruvic acid. In these reactions, two molecules of NAD+ are reduced to NADH, and four molecules of ATP are formed by substrate-level phosphorylation.

Because two molecules of ATP were needed to get glycolysis started and four molecules of ATP are generated by the process, *there is a net gain of two molecules of ATP for each molecule of glucose that is oxidized.*

Stapes of glycolysis

1-Glucose enters the cell and is phosphorylated. A molecule of ATP is invested. The product is glucose 6 phosphate.

2-Glucose 6-phosphate is rearranged to form fructose 6-phosphate.

3- Another ATP is used to produce fructose 1,6-diphosphate, still a six-carbon compound. (Note the total investment of two ATP molecules up to this point.)

4-An enzyme cleaves (splits) the sugar into two three-carbon molecules: dihydroxyacetone phosphate (DHAP) and glyceraldehyde 3-phosphate (GP).

5- DHAP is readily converted to GP (the reverse action may also occur).

6- The next enzyme converts each GP to another three-carbon compound, 1,3-diphosphoglyceric acid. Because each DHAP molecule can be converted to GP and each GP to 1,3-diphosphoglyceric acid, the result is two molecules of 1,3-diphosphoglyceric acid for each initial molecule of glucose. GP is oxidized by the transfer of two hydrogen atoms to NAD+ to form NADH. The enzyme couples this reaction with the creation of a high-energy bond between the sugar and a P . The three-carbon sugar now has two P groups.

7-The high-energy is moved to ADP, forming ATP, the first ATP production of glycolysis. (Since the sugar splitting in step 4, all products are doubled. Therefore, this step actually repays the earlier investment of two ATP molecules.)

8- An enzyme relocates the remaining of 3-phosphoglyceric acid to form phosphoglyceric acid in preparation for the next step.

9-By the loss of a water molecule, phosphoglyceric acid is converted to phosphoenolpyruvic acid (PEP). In the process, the phosphate bond is upgraded to a high-energy bond.

10 - This high-energy is transferred from PEP to ADP, forming ATP. For each initial glucose molecule, the result of this step is two molecules of ATP and two molecules of a three-carbon compound called pyruvic acid.

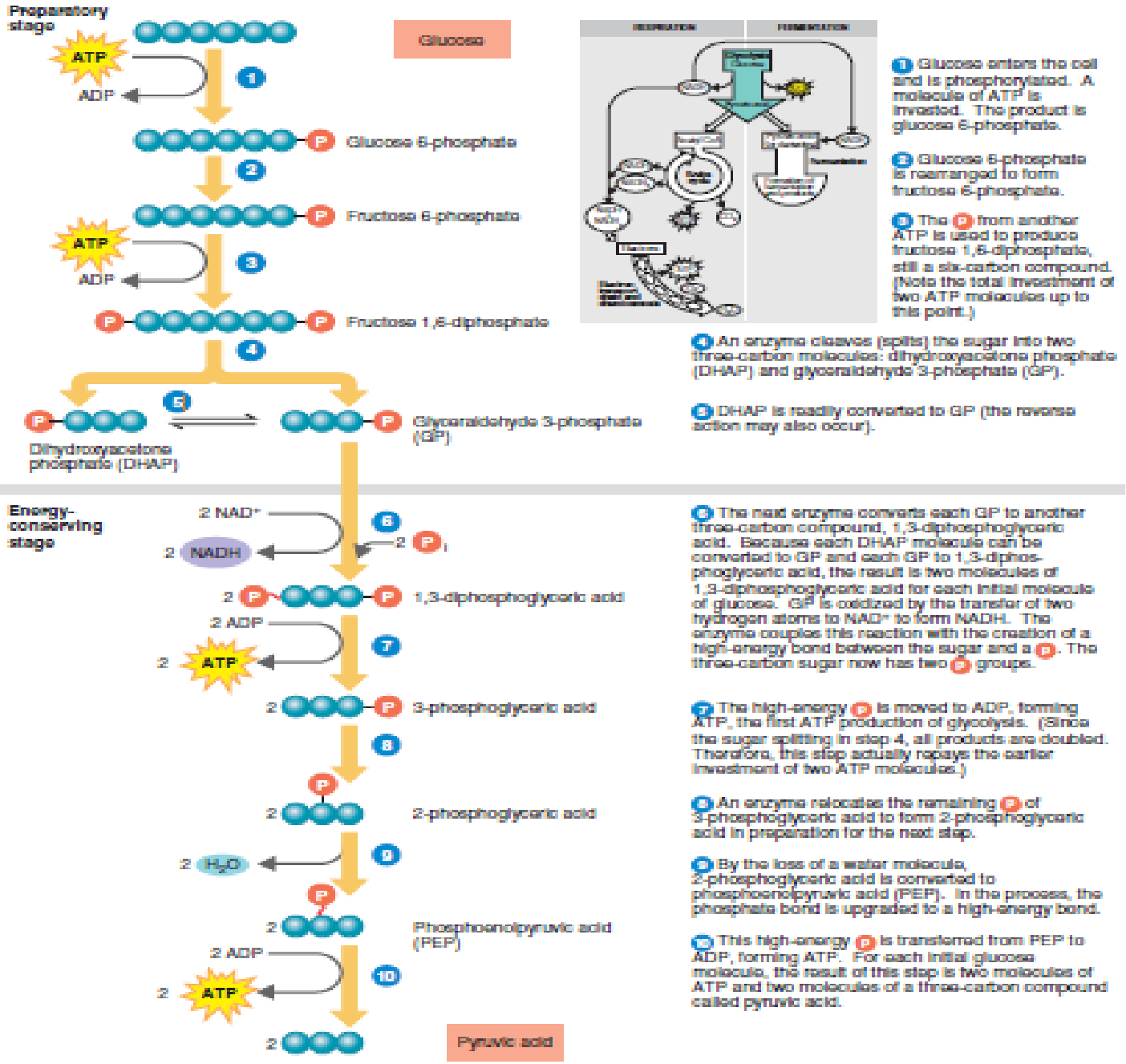

Figure 5.12 An outline of the reactions of glycolysis (Embden-Meyerhof pathway). The inset indicates the relationship of glycolysis

Alternatives to Glycolysis

Many bacteria have another pathway in addition to glycolysis for the oxidation of glucose. The most common alternative is the pentose phosphate pathway; another alternative is the Entner- Doudoroff pathway.

The Pentose Phosphate Pathway

The **pentose phosphate pathway** (or *hexose monophosphate shunt*) operates simultaneously with glycolysis and provides a means for the breakdown of five-carbon sugars (pentoses) as well as glucose.

.A key feature of this pathway is that it produces important intermediate pentoses used in the synthesis of

(1) nucleic acids,

(2) glucose from carbon dioxide in photosynthesis

(3) certain amino acids.

The pathway is an important producer of the reduced coenzyme NADPH from NADP+. The pentose phosphate pathway yields a net gain of only one molecule of ATP for each molecule of glucose oxidized. Bacteria that use the pentose phosphate pathway include *Bacillus subtilis*, *E. coli, Leuconostoc mesenteroides*

The Entner-Doudoroff Pathway

From each molecule of glucose, the **Entner-Doudoroff pathway** produces two molecules of NADPH and one molecule of ATP for use in cellular biosynthetic reactions. Bacteria that have the enzymes for the Entner-Doudoroff pathway can metabolize glucose without either glycolysis or the pentose phosphate pathway.

The Entner-Doudoroff pathway is found in some gram-negative bacteria, including *Rhizobium, Pseudomonas* ,and *Agrobacterium* ,it is generally not found among gram-positive bacteria. Tests for the ability to oxidize glucose by this pathway are sometimes used to identify *Pseudomonas* in the clinical laboratory.

The Tricarboxylic Acid Cycle

Although some energy is obtained from the breakdown of glucose to pyruvate by the pathways previously described, much more is released when pyruvate is degraded aerobically to CO2 in stage three of catabolism. The multi enzyme system called the **pyruvate dehydrogenase complex** first oxidizes pyruvate to form CO2 and **acetyl coenzyme A (acetyl-CoA),** an energy-rich molecule composed of coenzyme A and acetic acid joined by a high energy thiol ester bond .

Acetyl-CoA arises from the catabolism of many carbohydrates, lipids, and amino acids .It can be further degraded in the **tricarboxylic acid cycle**.

The substrate for the **tricarboxylic acid (TCA) cycle**, **citric acid cycle,** or **Krebs cycle** is acetyl-CoA .

In the first reaction acetyl-CoA is condensed with a four carbon intermediate, oxaloacetate, to form citrate and to begin the six-carbon stage.

Citrate is rearranged to give isocitrate, a more readily oxidized secondary alcohol.

Isocitrate is subsequently oxidized and decarboxylated twice to yield -ketoglutarate, then succinyl-CoA.

At this point two NADHs are formed and two carbons are lost from the cycle as CO2

Because two carbons were added as acetyl-CoA at the start, balance is maintained and no net carbon is lost.

The cycle now enters the four-carbon stage during which two oxidation steps yield one FADH2 and one NADH per acetyl-CoA. In addition, GTP (a high-energy molecule equivalent to ATP) is produced from succinyl-CoA by substrate-level phosphorylation. Eventually oxaloacetate is reformed and ready to join with another acetyl-CoA.

Inspection shows that the TCA cycle generates two CO2s, three NADHs, one FADH2, and one GTP for each acetyl- CoA molecule oxidized

Another way to think of the TCA cycle is in terms of its function as a pathway that oxidizes acetyl-CoA to CO_2.

- From this perspective, the first step is the attachment of an acetyl group to the acetyl carrier, oxaloacetate, to form citrate.
- The second stage begins with citrate and ends in the formation of succinyl-CoA. Here, the acetyl carrier portion of citrate loses two carbons when it is oxidized to give two CO_2s.
- The third and last stage converts succinyl-CoA back to oxaloacetate, the acetyl carrier, so that it can pick up another acetyl group.

TCA cycle enzymes are widely distributed among microorganisms. The complete cycle appears to be functional in many aerobic bacteria, free-living protozoa, and most algae and fungi. This is not surprising because the cycle is such an important source of energy.

However, the facultative anaerobe *E. coli* does not use the full TCA cycle under anaerobic conditions or when the glucose concentration is high but does at other times. Even those microorganisms that lack the complete TCA cycle usually have most of the cycle enzymes, because one of TCA cycle's major functions is to provide carbon skeletons for use in biosynthesis

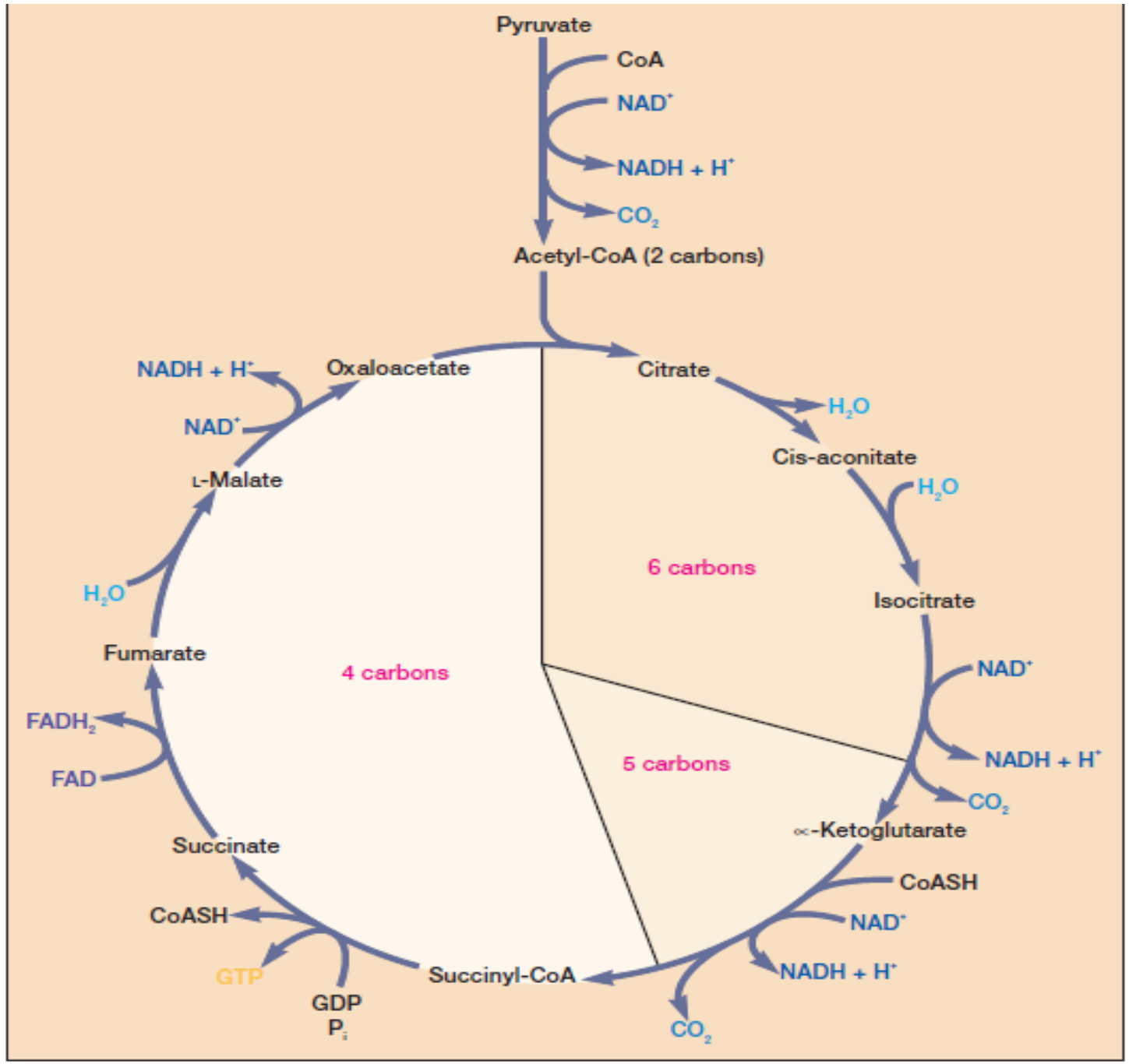

Figure 9.12 The Tricarboxylic Acid Cycle. The cycle may be divided into three stages based on the size of its intermediates. The three stages are separated from one another by two decarboxylation reactions (reactions in which carboxyl groups are lost as CO_2). The pyruvate dehydrogenase complex forms acetyl-CoA through pyruvate oxidation.