CHEMICAL CHANGES DURING MUSCULAR CONTRACTION

LIBERATION OF ENERGY

Energy necessary for muscular contraction is liberated during the processes of breakdown and resynthesis of ATP.

Breakdown of ATP

During muscular contraction, the supply of energy is from the breakdown of ATP. This is broken into ADP and inorganic phosphate (Pi) and energy is liberated.

$$\text{ATP} \rightarrow \text{ADP} + \text{Pi}$$
$$\downarrow$$
$$\text{Energy}$$

Energy liberated by breakdown of ATP is responsible for the following activities during muscular contraction:

1. Spread of action potential into the muscle
2. Liberation of calcium ions from cisternae of 'L' tubules into the sarcoplasm
3. Movements of myosin head
4. Sliding mechanism.

Energy liberated during ATP breakdown is sufficient for maintaining full contraction of the muscle for a short duration of less than one second.

Resynthesis of ATP

Adenosine diphosphate, which is formed during ATP breakdown, is immediately utilized for the resynthesis of ATP. But, for the resynthesis of ATP, the ADP cannot combine with Pi. It should combine with a high-energy phosphate radical. There are two sources from which the high-energy phosphate is obtained namely, creatine phosphate and carbohydrate metabolism.

Resynthesis of ATP from creatine phosphate

Immediate supply of high-energy phosphate radical is from the creatine phosphate (CP). Plenty of CP is available in resting muscle. In the presence of the enzyme creatine phosphotransferase, high-energy phosphate is released from creatine phosphate. The reaction is called Lohmann's reaction.

$$\text{ADP} + \text{CP} \rightarrow \text{ATP} + \text{Creatine}$$

Energy produced in this reaction is sufficient to maintain muscular contraction only for few seconds. Creatine should be resynthesized into creatine phosphate and this requires the presence of high-energy phosphate. So, the required amount of high-energy phosphate radicals is provided by the carbohydrate metabolism in the muscle.

Resynthesis of ATP by carbohydrate metabolism

Carbohydrate metabolism starts with catabolic reactions of glycogen in the muscle. In resting muscle, an adequate amount of glycogen is stored in sarcoplasm.

Each molecule of glycogen undergoes catabolism, to produce ATP. The energy liberated during the catabolism of glycogen can cause muscular contraction for a longer period. The first stage of catabolism of glycogen is via glycolysis. It is called glycolytic pathway or Embden-Meyerhof pathway (Fig. 31.10).

Glycolysis

Each glycogen molecule is converted into 2 pyruvic acid molecules. Only small amount of ATP (2 molecules) is synthesized in this pathway.

This pathway has 10 steps. Each step is catalyzed by one or two enzymes as shown in Figure 31.10.

During glycolysis, 4 hydrogen atoms are released which are also utilized for formation of additional molecules of ATP. Formation of ATP by the utilization of hydrogen is explained later.

Further changes in pyruvic acid depend upon the availability of oxygen. In the absence of oxygen, the pyruvic acid is converted into lactic acid that enters the Cori cycle. It is known as anerobic glycolysis. If oxygen is available, the pyruvic acid enters into Krebs cycle. It is known as aerobic glycolysis.

Cori cycle

Lactic acid is transported to liver where it is converted into glycogen and stored there. If necessary, glycogen breaks into glucose, which is carried by blood to muscle. Here, the glucose is converted into glycogen, which enters the Embden-Meyerhof pathway (Figs 31.11 and 31.12).

Krebs cycle

Krebs cycle is otherwise known as **tricarboxylic acid cycle (TCA cycle) or citric acid cycle**. A greater amount of energy is liberated through this cycle. The pyruvic acid derived from glycolysis is taken into mitochondria where it is converted into acetyl coenzyme A with release of 4 hydrogen atoms. The acetyl coenzyme A enters the Krebs cycle.

Krebs cycle is a series of reactions by which acetyl coenzyme A is degraded in various steps to form carbon dioxide and hydrogen atoms. All these reactions occur in the matrix of mitochondrion. During Krebs cycle, 2 molecules of ATP and 16 atoms of hydrogen are released. Hydrogen atoms are also utilized for the formation of ATP (see below).

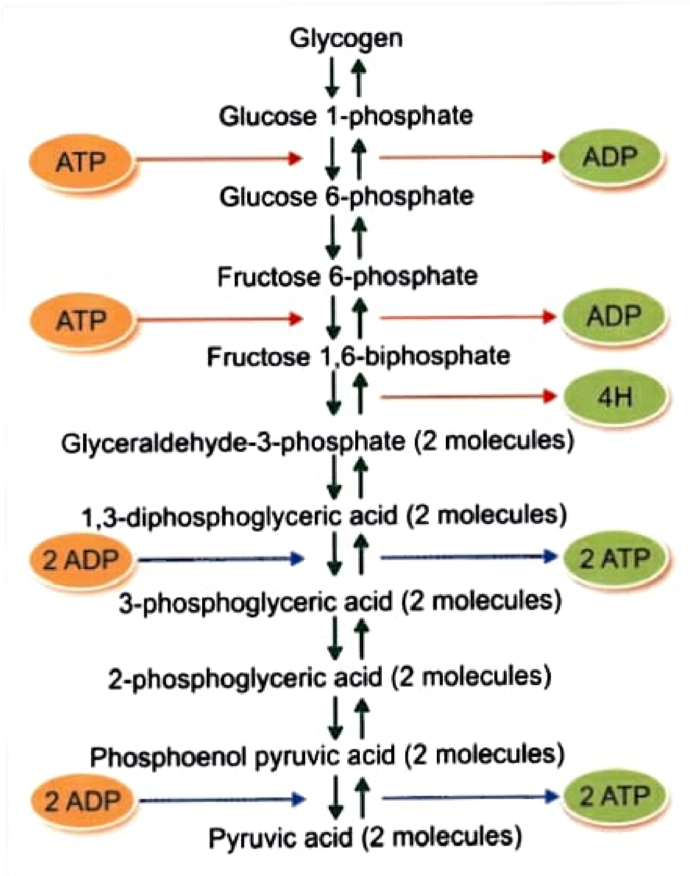

FIGURE 31.10: Glycolysis/Embden-Meyerhof pathway
Number of ATP molecules formed in this pathway:

Total ATP formed	=	4 molecules
Loss of ATP during phosphorylation	=	2 molecules
Net ATP formed during glycolysis	=	2 molecules

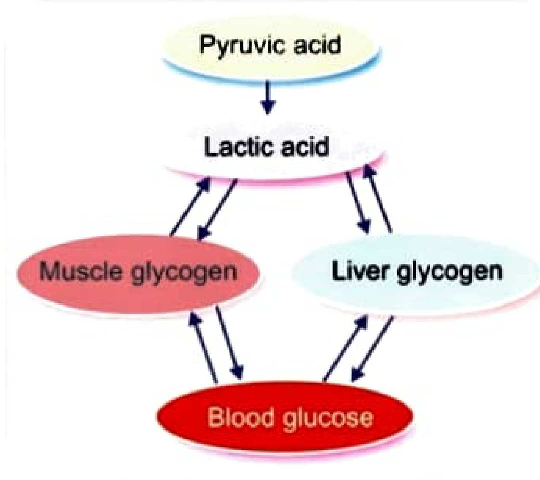

FIGURE 31.11: Cori cycle

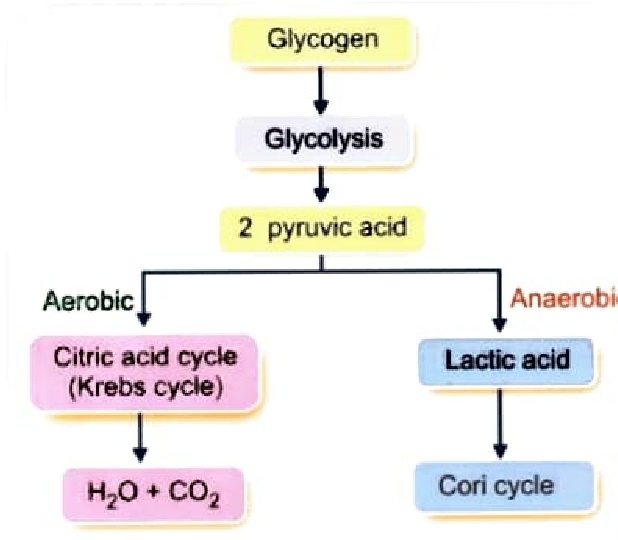

FIGURE 31.12: Schematic diagram showing carbohydrate metabolism in muscle

Significance of Hydrogen Atoms Released during Carbohydrate Metabolism

Altogether 24 hydrogen atoms are released during glycolysis and Krebs cycle:

4H : During breakdown of glycogen into pyruvic acid

4H : During formation of acetyl coenzyme A from pyruvic acid

16H : During degradation of acetyl coenzyme A in Krebs cycle.

Hydrogen atoms are released in the form of two pockets into intracellular fluid and it is catalyzed by the enzyme dehydrogenase. Once released, 20 hydrogen atoms combine with nicotinamide adenine dinucleotide (NAD), which acts as hydrogen carrier. NAD transfers the hydrogen atoms to the cytochrome system where oxidative phosphorylation takes place. Oxidative phosphorylation is the process during which the ATP molecules are formed by utilizing hydrogen atoms.

For every 2 hydrogen atoms 3 molecules of ATP are formed. So, from 20 hydrogen atoms 30 molecules of ATP are formed. Remaining 4 hydrogen atoms enter the oxidative phosphorylation processes directly without combining with NAD. Only 2 ATP molecules are formed for every 2 hydrogen atoms. So, 4 hydrogen atoms give rise to 4 ATP molecules. Thus, 34 ATP molecules are formed from the hydrogen atoms released during glycolysis and Krebs cycle.

Summary of Resynthesis of ATP during Carbohydrate Metabolism

A total of 38 ATP molecules are formed during breakdown of each glycogen molecule in the muscle as summarized below:

During glycolysis	:	2 molecules of ATP
During Krebs cycle	:	2 molecules of ATP
By utilization of hydrogen	:	34 molecules of ATP
Total	:	38 molecules of ATP

CHANGES IN pH DURING MUSCULAR CONTRACTION

Reaction and the pH of muscle are altered in different stages of muscular contraction.

In Resting Condition

During resting condition, the reaction of muscle is alkaline with a pH of 7.3.

During Onset of Contraction

At the beginning of the muscular contraction, the reaction becomes acidic. The acidity is due to dephosphorylation of ATP into ADP and Pi.

During Later Part of Contraction

During the later part of contraction, the muscle becomes alkaline. It is due to the resynthesis of ATP from CP.

At the End of Contraction

At the end of contraction, the muscle becomes once again acidic. This acidity is due to the formation of pyruvic acid and/or lactic acid.

THERMAL CHANGES DURING MUSCULAR CONTRACTION

During muscular contraction, heat is produced. Not all the heat is liberated at a time. It is released in different stages:

1. Resting heat
2. Initial heat
3. Recovery heat.

RESTING HEAT

Heat produced in the muscle at rest is called the resting heat. It is due to the basal metabolic process in the muscle.

INITIAL HEAT

During muscular activity, heat production occurs in three stages:

i. Heat of activation
ii. Heat of shortening
iii. Heat of relaxation.

i. *Heat of Activation*

Heat of activation is the heat produced before the actual shortening of the muscle fibers. Most of this heat is produced during the release of calcium ions from 'L' tubules. It is also called maintenance heat.

ii. *Heat of Shortening*

Heat of shortening is the heat produced during contraction of muscle. The heat is produced due to various structural changes in the muscle fiber like movements of cross bridges and myosin heads and breakdown of glycogen.

iii. *Heat of Relaxation*

Heat released during relaxation of the muscle is known as the heat of relaxation. In fact, it is the heat produced during the contraction of muscle due to breakdown of ATP molecule. It is released when the muscle lengthens during relaxation.

RECOVERY HEAT

Recovery heat is the heat produced in the muscle after the end of activities. After the end of muscular activities, some amount of heat is produced due to the chemical processes involved in resynthesis of chemical substances broken down during contraction.