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# BIOLOGICAL FUNCTIONS OF CARBOHYDRATES: GLUCOSE AND GLYCOGEN METABOLISM IN HUMAN PHYSIOLOGY

**A.Xolmatov**
Central Asian Medical University Clinical residents

**Abstract:** Carbohydrates are among the most important biomolecules in living organisms, serving as primary sources of energy, structural components, and regulators of numerous physiological processes. Glucose represents the central molecule of carbohydrate metabolism and functions as the principal energy substrate for most tissues, particularly the brain and erythrocytes. Glycogen serves as the major storage form of glucose in animals and plays a critical role in maintaining blood glucose homeostasis. The metabolism of glucose and glycogen involves a complex network of biochemical pathways regulated by hormonal, enzymatic, and genetic mechanisms. Disturbances in carbohydrate metabolism contribute to the pathogenesis of numerous diseases, including diabetes mellitus, glycogen storage diseases, obesity, metabolic syndrome, and cardiovascular disorders. This review summarizes the biological functions of carbohydrates, the molecular mechanisms underlying glucose and glycogen metabolism, regulatory pathways involved in carbohydrate homeostasis, and the clinical significance of metabolic disturbances. Recent advances in molecular biology and metabolic research have improved understanding of carbohydrate metabolism and opened new opportunities for diagnosis and treatment of metabolic diseases.

**Keywords:** carbohydrates, glucose metabolism, glycogen metabolism, glycolysis, glycogenesis, glycogenolysis, gluconeogenesis, metabolic regulation.

## Introduction

Carbohydrates constitute one of the three major classes of macronutrients essential for life. They are synthesized primarily through photosynthesis and represent the most abundant organic compounds in nature. In humans, carbohydrates account for a significant proportion of daily energy intake and serve as critical substrates for cellular metabolism.[1,2,3,4,5,6]

The importance of carbohydrates extends beyond energy production. They participate in cell signaling, molecular recognition, immune responses, and structural organization of tissues. Among all carbohydrates, glucose occupies a central position in metabolism because it serves as the primary fuel for numerous organs and tissues.[7,8,9,10]

The regulation of glucose concentration in blood is vital for maintaining physiological homeostasis. Excess glucose is stored in the form of glycogen, while insufficient glucose availability stimulates glycogen breakdown and alternative metabolic pathways. Understanding the mechanisms governing glucose and glycogen metabolism is therefore essential for understanding both normal physiology and disease development.[11,12,13,14]

**Classification and Biological Functions of Carbohydrates**

Carbohydrates are classified according to their chemical structure and complexity.

**Monosaccharides**

These are the simplest carbohydrate units.

Examples include:

- Glucose
- Fructose
- Galactose

**Disaccharides**

Disaccharides consist of two monosaccharide molecules.

Examples include:

- Sucrose
- Lactose
- Maltose

**Polysaccharides**

Polysaccharides are complex carbohydrates composed of multiple monosaccharide units.

Examples include:

- Glycogen
- Starch
- Cellulose

**Biological Functions of Carbohydrates**

Carbohydrates perform multiple physiological functions.

**Energy Function**

The most important role of carbohydrates is energy production.

Oxidation of one gram of carbohydrate produces approximately 4 kilocalories of energy.[15,16,17,18,19]

Glucose serves as the principal energy substrate for:

- Brain tissue
- Erythrocytes
- Skeletal muscle
- Cardiac muscle
- Renal medulla

Under normal physiological conditions, glucose accounts for a substantial portion of cellular ATP production.

**Storage Function**

Excess glucose is stored as glycogen.

Major glycogen reserves are located in:

- Liver
- Skeletal muscle

This storage mechanism ensures a continuous energy supply during fasting and physical activity.

**Structural Function**

Carbohydrates are important structural components of cells and tissues.

Examples include:

- Glycoproteins
- Glycolipids
- Proteoglycans
- Extracellular matrix components

These molecules contribute to membrane stability and cell communication.

**Protective Function**

Mucopolysaccharides and glycoproteins protect epithelial surfaces from mechanical and chemical injury.

Protective carbohydrate-containing structures are found in:

- Gastrointestinal tract
- Respiratory system
- Urogenital tract

**Cell Recognition and Signaling**

Cell-surface carbohydrates participate in:

- Immune recognition
- Cell adhesion
- Signal transduction
- Blood group antigen determination

These functions are essential for normal physiological communication between cells.[20,21,22,23,24]

**Glucose Metabolism**

Glucose metabolism encompasses multiple interconnected biochemical pathways.

The major pathways include:

1. Glycolysis
2. Glycogenesis
3. Glycogenolysis
4. Gluconeogenesis
5. Pentose phosphate pathway

Together these pathways maintain energy balance and metabolic homeostasis.

**Glycolysis**

Glycolysis is the metabolic pathway through which glucose is converted into pyruvate.

The overall reaction is:

Glucose → Pyruvate + ATP + NADH

Glycolysis occurs in the cytoplasm of all cells and does not require oxygen.

Major functions include:

- ATP production
- Generation of metabolic intermediates
- Maintenance of erythrocyte energy metabolism

Key regulatory enzymes include:

- Hexokinase
- Phosphofructokinase-1
- Pyruvate kinase

The pathway is tightly regulated according to cellular energy requirements.

**Aerobic Oxidation of Glucose**

Under aerobic conditions, pyruvate enters mitochondria and is converted into acetyl-CoA.

Acetyl-CoA enters the citric acid cycle, resulting in:

- Carbon dioxide production
- Electron transport chain activation
- Large-scale ATP synthesis

Complete oxidation of one glucose molecule generates approximately 30–32 ATP molecules.[25,26,27,28]

This process represents the most efficient mechanism of cellular energy production.

**Pentose Phosphate Pathway**

The pentose phosphate pathway serves several essential functions.

It generates:

- NADPH
- Ribose-5-phosphate

NADPH is required for:

- Fatty acid synthesis
- Cholesterol synthesis
- Antioxidant defense

Ribose-5-phosphate is necessary for nucleotide synthesis.

The pathway is especially important in erythrocytes, liver, and adipose tissue.

**Glycogen Metabolism**

Glycogen is the principal storage polysaccharide in animals.

Its highly branched structure enables rapid synthesis and degradation.

Approximately:

- 100–120 g glycogen is stored in the liver
- 300–500 g glycogen is stored in skeletal muscles

These reserves provide a readily available source of glucose during increased metabolic demand.[29,30,31,32]

**Glycogenesis**

Glycogenesis refers to glycogen synthesis.

The process occurs primarily after meals when glucose availability is abundant.

Major steps include:

1. Glucose phosphorylation
2. Formation of glucose-1-phosphate
3. Synthesis of UDP-glucose
4. Glycogen chain elongation

The key enzyme is:

**Glycogen Synthase**

Insulin stimulates glycogenesis by activating glycogen synthase and promoting glucose uptake into tissues.[33,34]

**Glycogenolysis**

Glycogenolysis is the breakdown of glycogen into glucose-containing products.

This pathway becomes active during:

- Fasting
- Exercise
- Stress
- Hypoglycemia

The key enzyme is:

**Glycogen Phosphorylase**

In the liver, glycogenolysis contributes directly to blood glucose maintenance.

In skeletal muscle, glycogen breakdown primarily supports local energy production.

**Hormonal Regulation of Glucose and Glycogen Metabolism**

Carbohydrate metabolism is controlled by several hormones.

**Insulin**

Insulin promotes:

- Glucose uptake
- Glycogenesis
- Glycolysis
- Lipogenesis

It lowers blood glucose concentration.

**Glucagon**

Glucagon stimulates:

- Glycogenolysis
- Gluconeogenesis

It increases blood glucose levels during fasting.

**Epinephrine**

Epinephrine activates glycogen breakdown during stress and physical activity.

**Cortisol**

Cortisol enhances gluconeogenesis and supports adaptation to prolonged stress.

The coordinated actions of these hormones maintain glucose homeostasis.

**Gluconeogenesis**

Gluconeogenesis is the synthesis of glucose from non-carbohydrate precursors.

Major substrates include:

- Lactate
- Glycerol
- Amino acids

The process occurs mainly in:

- Liver

- Kidney cortex

Gluconeogenesis is essential during prolonged fasting and starvation.

**Disorders of Glucose and Glycogen Metabolism**

Abnormal carbohydrate metabolism contributes to numerous diseases.

**Diabetes Mellitus**

Characterized by:

- Hyperglycemia
- Insulin deficiency or resistance
- Altered glucose utilization

Long-term complications affect:

- Blood vessels
- Kidneys
- Eyes
- Nervous system

**Glycogen Storage Diseases**

These inherited disorders result from deficiencies of enzymes involved in glycogen metabolism.

Examples include:

- Von Gierke disease
- Pompe disease
- Cori disease
- McArdle disease

Clinical manifestations vary depending on the affected enzyme.

**Hypoglycemia**

Low blood glucose levels may result from:

- Excess insulin
- Liver disease
- Endocrine disorders
- Glycogen storage diseases

Severe hypoglycemia can impair brain function and become life-threatening.

**Recent Advances in Carbohydrate Metabolism Research**

Recent scientific developments have improved understanding of metabolic regulation.

Important advances include:

- Continuous glucose monitoring systems
- Metabolomics technologies
- Gene therapy approaches
- Precision medicine strategies
- Artificial intelligence-assisted metabolic analysis

These innovations are transforming the diagnosis and treatment of metabolic diseases.[35,36]

**Conclusion**

Carbohydrates perform diverse biological functions that extend beyond energy production. Glucose serves as the central metabolic fuel, while glycogen provides an efficient storage mechanism that maintains energy homeostasis during periods of fluctuating nutrient availability. The pathways of glycolysis, glycogenesis, glycogenolysis, gluconeogenesis, and the pentose phosphate pathway are intricately regulated by enzymes and hormones to ensure stable blood glucose concentrations. Disturbances in these processes contribute to the development of major metabolic disorders, including diabetes mellitus and glycogen storage diseases. Continued research into carbohydrate metabolism is essential for improving prevention, diagnosis, and treatment of metabolic diseases in modern medicine.

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