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THE ROLE OF TRACE ELEMENTS IN THE HUMAN BODY: PHYSIOLOGICAL SIGNIFICANCE AND CONSEQUENCES OF IMBALANCE

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Abstract:
Trace elements play a critical role in maintaining homeostasis, despite their low content in the human body. This article examines the main biological functions of essential trace elements (iron, zinc, iodine, selenium, and copper), their mechanisms of action, and the consequences of their metabolic disorders.

Introduction

Trace elements are chemical elements present in the human body in extremely small amounts (less than 0.001% of body weight) but are absolutely necessary for normal vital activity. Unlike macroelements, they are not sources of energy; however, they act as crucial catalysts and regulators of biochemical processes.

The relevance of this study is driven by the global increase in diet-related diseases. According to the World Health Organization (WHO), "hidden hunger" (a deficiency of vitamins and trace elements) affects more than 2 billion people worldwide. A deficiency or excess of these nutrients leads to severe metabolic shifts, decreased immunity, and the development of chronic pathologies.

The aim of the study is to systematize current scientific data on the biological role of key essential trace elements in the human body and to analyze the consequences of their imbalance.

The human body is a complex, self-regulating biochemical system, the functioning of which is impossible without the participation of minerals. Macro- and trace elements are part of all tissues and biological fluids, providing the structural organization of cells, the activity of enzyme systems, and the stability of the internal environment. Even though minerals have no energy value, their deficiency or excess leads to pronounced metabolic disorders and the development of chronic diseases.

In the context of a modern lifestyle characterized by changes in dietary patterns, the issue of optimal mineral intake has become highly relevant. Of particular interest is the study of plant-based foods as a natural source of macro- and trace elements in an organically bound and easily digestible form. In this regard, investigating the biological role of minerals and the pathways of

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their rational intake into the body is an urgent task for modern nutritionology and preventive medicine.

Materials and Methods

To achieve this goal, a systematic review of current scientific literature was conducted.

- **Data Sources:** Searches were conducted using PubMed, Scopus, and Web of Science databases.
- **Selection Criteria:** The analysis included peer-reviewed original studies, meta-analyses, and reviews from the last 15 years focusing on human trace element metabolism.
- **Search Keywords:** "trace elements", "micronutrient deficiency", "zinc immunity", "iron metabolism", "selenium antioxidant".
- **Analysis Procedure:** Data on the biochemical functions of five main essential trace elements (Fe, Zn, I, Se, Cu), their role in enzymatic reactions, and the clinical picture of their deficiency/excess were extracted from the identified sources.

Results

The analysis of literature data establishes that the biological role of trace elements is not isolated but rather operates as a complex, integrated system for regulating metabolic processes. The results confirm that even minimal changes in the trace element composition of the diet affect the activity of enzyme complexes, hormonal regulation, and cellular metabolism.

It has been established that trace elements such as iron, zinc, copper, and manganese form functional clusters that ensure the coordinated operation of enzyme systems involved in energy, protein, and carbohydrate metabolism. Thus, iron deficiency leads not only to impaired hematopoiesis but also to decreased activity in the mitochondrial respiratory chain, which is expressed in reduced ATP (adenosine triphosphate) production and decreased tissue respiration. These data align with the understanding of the key role of iron-containing proteins in cellular bioenergetics.

Analysis of the role of zinc showed that its participation in the regulation of gene expression and protein synthesis makes this trace element critically important for regeneration processes and the immune response. The results indicate that a decrease in zinc status is accompanied by the suppression of antioxidant defense enzyme activity and the weakening of the body's barrier functions. This confirms the concept of zinc as a universal metabolic regulator.

Of particular interest are the data regarding selenium. It has been established that adequate selenium intake contributes to the stabilization of membrane structures and the inhibition of lipid peroxidation processes. In conjunction with vitamin E, selenium forms an effective antioxidant system that prevents the accumulation of free radicals and damage to cellular components. These results allow us to consider selenium as one of the key factors in the prevention of degenerative and oncological processes.

The results of analyzing the role of iodine confirm its decisive significance in regulating basal metabolism. Inadequate iodine intake leads to decreased synthesis of thyroid hormones, which affects energy metabolism, thermoregulation, and the functional state of the nervous system. Under conditions of chronic iodine deficiency, a decrease in the body's adaptive capabilities is observed, which has important clinical and preventive significance.

Discussion of the obtained data shows that the bioavailability of trace elements is a critical factor in their physiological effectiveness. Elements obtained from plant foods are included in organic complexes, which ensures their more complete absorption and participation in metabolic processes compared to inorganic salts. This confirms the priority role of plant-based products in establishing an adequate trace element status.

Thus, the results and their discussion indicate that trace elements act not only as structural components of biological molecules but also as fine-tuners of metabolic integration. Systemic trace element deficiency should be considered a pathogenetic basis for the development of diet-related and metabolic disorders, and rational nutrition as an effective tool for their prevention.

Classification and General Characteristics of Minerals

Mineral elements are divided into macro- and trace elements depending on their content in the body. Macroelements (calcium, phosphorus, potassium, sodium, magnesium, chlorine) are required in relatively large quantities and primarily perform structural and regulatory functions. Trace elements (iron, iodine, zinc, copper, manganese, cobalt, selenium, etc.) are needed in minimal doses but play a key role in enzymatic and hormonal processes.

Physiological Role of the Main Macroelements

Calcium and phosphorus form bone tissue, participate in blood coagulation processes, and neuromuscular transmission. Magnesium activates energy metabolism enzymes and normalizes the activity of the cardiovascular system. Potassium and sodium provide water-salt balance, osmotic pressure, and the conduction of nerve impulses, while chlorine participates in the formation of hydrochloric acid in gastric juice.

Biological Significance of Trace Elements

Trace elements represent a group of chemical elements present in the human body in trace amounts, yet their physiological and biochemical significance is disproportionately higher than their quantitative content. They are structural and functional components of enzyme systems, hormones, vitamins, and organometallic complexes, ensuring the precise regulation of metabolic processes at the molecular and cellular levels.

One of the key functions of trace elements is their participation in the catalytic activity of enzymes. More than 200 human enzyme systems function exclusively in the presence of metal ions such as iron, zinc, copper, manganese, and molybdenum. These elements act as cofactors, stabilizing the active centers of enzymes and enabling redox, hydrolytic, and synthetic reactions. A disturbance in trace element status leads to decreased enzyme activity and the disorganization of metabolic pathways.

Iron occupies a special place among trace elements due to its participation in tissue respiration and hematopoiesis. It is a component of hemoglobin, myoglobin, and cytochromes of the mitochondrial respiratory chain, ensuring oxygen transport and energy synthesis in the form of adenosine triphosphate. Iron deficiency is accompanied by the development of hypochromic anemia, decreased physical and mental performance, and weakened immune defense.

Zinc is a universal metabolic regulator found in more than 300 enzymes and transcription factors. It participates in the synthesis of nucleic acids, proteins, and insulin; regulates the processes of cell division, differentiation, and tissue repair. The key role of zinc in shaping the immune response and the body's antioxidant defense has been proven.

Copper is functionally closely related to iron and participates in hematopoiesis, tissue respiration, and connective tissue synthesis. It is a part of oxidases and superoxide dismutase, protecting cells from free radical damage. Copper deficiency can lead to anemic states, impaired bone mineralization, and reduced vascular elasticity.

Manganese is necessary for the functioning of enzymes in carbohydrate, lipid, and protein metabolism. It participates in the synthesis of glycosaminoglycans that make up cartilage tissue, as well as in the regulation of antioxidant processes. Its deficiency is associated with impaired growth, reproductive function, and osteogenesis.

Iodine is an essential trace element for endocrine regulation since it is a component of the thyroid hormones thyroxine and triiodothyronine. These hormones control basal metabolic rate, thermoregulation, and the growth and development of the nervous system. Chronic iodine deficiency leads to endemic goiter, delayed physical and intellectual development, and decreased adaptive capabilities of the body.

Selenium is considered one of the key antioxidant trace elements. It is a component of selenoproteins, including glutathione peroxidase, which protects cell membranes from lipid peroxidation. Selenium is involved in the regulation of the immune response, thyroid hormone metabolism, and possesses significant anticarcinogenic potential.

Cobalt is necessary for the synthesis of vitamin B12, which is involved in hematopoiesis and the functioning of the nervous system. Molybdenum and chromium ensure the normal course of redox reactions and the regulation of carbohydrate metabolism, including tissue sensitivity to insulin. Fluorine plays an important role in the mineralization of bone and dental tissue, increasing enamel resistance to demineralization.

Thus, trace elements are essential regulators of biochemical, hormonal, and cellular processes. Their optimal intake through food, predominantly of plant origin, ensures the stability of metabolic reactions, the body's adaptive capabilities, and the prevention of diet-related diseases. Disruption of trace element balance should be considered one of the key risk factors for developing chronic pathologies.

Plant-Based Foods as a Source of Minerals

Mineral elements supplied by plant foods are highly bioavailable because they are incorporated into organic complexes—vitamins, phytohormones, enzymes, and amino acids. This ensures their effective absorption and utilization in metabolic processes. Regular consumption of fruits, vegetables, grains, and legumes helps maintain an optimal mineral balance and reduces the risk of chronic diseases.

An analysis of the literature has allowed us to highlight the specific physiological functions of key trace elements, which are presented in the table and described below.

Trace Element	**Main Localization**	**Key Biological Functions**
Iron (Fe)	Erythrocytes, liver, spleen	Oxygen transport (hemoglobin), cellular respiration (cytochromes), DNA synthesis.
Zinc (Zn)	Muscles, bones, skin, prostate	Cofactor for over 300 enzymes, regulation of gene expression, immune response, wound healing.
Iodine (I)	Thyroid gland	Synthesis of thyroid hormones (thyroxine, triiodothyronine), regulation of basal metabolism and thermogenesis.
Selenium (Se)	Liver, kidneys, heart	Antioxidant defense (part of glutathione peroxidase), thyroid hormone metabolism.
Copper (Cu)	Liver, brain, kidneys	Iron absorption and transport, collagen and elastin synthesis, myelin formation in nerve fibers.

Iron and Oxygen Exchange

Iron is the central component of the heme group. Results indicate that about 70% of iron in the body is bound to hemoglobin and myoglobin, facilitating tissue gas exchange. Additionally, iron-sulfur proteins are critically important for electron transport in the mitochondrial respiratory chain.

Zinc as a Universal Regulator

It has been established that zinc is necessary for the structural stabilization of proteins (forming "zinc fingers"), making it indispensable in DNA transcription. It also modulates the activity of T-lymphocytes and macrophages.

Antioxidant Complex (Selenium and Copper)

Selenoproteins neutralize free radicals, protecting cell membranes from lipid peroxidation. Copper, in turn, is a component of superoxide dismutase (SOD)—a first-line enzyme in antioxidant defense.

Discussion

The obtained results emphasize that trace elements do not act in isolation; their metabolism represents a complex network with a narrow therapeutic window.

The Problem of Deficiency:

Iron deficiency remains the most common nutritional problem worldwide, leading to iron-deficiency anemia, which is accompanied by chronic tissue hypoxia, cognitive decline, and reduced physical endurance. Iodine deficiency during fetal development and early childhood leads to irreversible CNS damage (cretinism). Zinc deficiency is associated with stunted growth in children and increased susceptibility to infectious diseases.

The Problem of Excess and Toxicity:

Unlike water-soluble vitamins, trace elements can accumulate in tissues, causing intoxication. For example, excessive copper intake leads to liver and nervous system damage (which is genetically manifested in Wilson-Konovalov disease). Iron overload triggers free radical reactions (Fenton reaction), damaging DNA and cellular structures.

Competitive Interactions:

Particular attention should be paid to the antagonism of trace elements during their absorption in the gastrointestinal tract. High doses of zinc (often taken as supplements) induce the synthesis of the protein metallothionein in enterocytes, which firmly binds copper and prevents its absorption into the blood. This highlights the danger of uncontrolled intake of single-trace-element supplements.

Conclusions

Trace elements form the foundation of the biochemical balance in the human body. Their role is not limited to supporting basal metabolism; they are critically important for antioxidant defense, the immune response, and genetic expression. A balanced diet remains the optimal way to maintain trace element homeostasis. Pharmacological correction (the use of supplements) should be carried out exclusively based on a laboratory-confirmed deficiency and taking into account the complex synergistic and antagonistic interactions between elements.

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