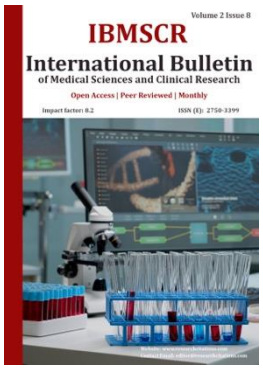

THE ROLE OF THE INTESTINAL MUCOSA IN MICROSTRUCTURE AND ABSORPTION

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Abstract
The intestinal mucosa is one of the most complex and highly specialized structures of the body and is the most important link in the digestive system. This layer performs not only mechanical and protective functions, but also participates in the transfer of nutrients into the blood through complex absorption mechanisms, maintaining the immunological state of the body, as well as signal transmission and metabolic activities. This article provides a comprehensive and detailed description of the microstructure of the intestinal mucosa, the morphological and histological characteristics of its constituent cells, structures, and their functional role in the absorption process.
The intestinal mucosa consists of three main layers: the epithelial layer, the lamina propria (the main connective tissue) and the muscularis mucosae (the muscles of the mucous membrane). Each of these layers has its own special morphological characteristics and directly affects the absorption process. In particular, the predominant function of the epithelial layer is to directly interact with food substances and ensure the selective transfer of substances necessary for the body through active transport mechanisms.
Microvilli (microvilli) and villi located on the surface of the mucous membrane significantly expand the internal surface and increase the efficiency of absorption. Through these structures, the absorption of amino acids, monosaccharides, fatty acids and other biologically active substances occurs. At the same time, goblet cells in the intestinal epithelium produce mucus, forming a protective layer on the surface of the mucous membrane and resisting the penetration of pathogenic microorganisms. Paneth cells, on the other hand, produce antibacterial peptides and regulate the intestinal microflora.

Keywords
Intestinal mucosa, microstructure, villus, microvilli, enterocyte, goblet cell, Paneth cell, absorption process, epithelium, lamina propria, muscularis mucosae, immunological function,

intestinal microflora, histological structure, absorption, endocytosis, transcytosis, mucosal immunity, malabsorption syndrome, intestinal permeability, histochemical analysis, inflammation, mucus secretion, electron microscopy, metabolism, enteral transport, celiac disease, Crohn's disease, histopathology, network surface area, membrane proteins, neuroendocrine regulation.

Relevance of the topic

The digestive system is one of the most important and complex systems in the human body. Its activity includes the processes of breaking down food products, absorbing the nutrients they contain, and distributing them according to the needs of the body. One of the important stages of these processes is the microstructure of the intestinal mucosa and its participation in absorption. It is through the intestinal mucosa that nutrients, vitamins, mineral salts, and water enter the body.

The intestinal mucosa is a structurally and functionally very complex layer, consisting of many specialized cells, glands, vessels, lymphatic structures, and immunological elements. This layer not only performs the function of mechanical protection, but also actively or passively transmits various substances, ensuring their entry into metabolic processes. For this reason, any disorders in its structure and function directly affect the overall health of the body, especially diseases of metabolism, immunity, and the digestive system.

In recent years, intestinal health, the state of the microflora, the function of the intestinal barrier and histological changes in the mucosa have become increasingly relevant topics in the field of health care. Because many modern diseases - allergies, chronic inflammatory diseases, autoimmune conditions, metabolic syndrome, even neurological disorders - can be associated with structural and functional imbalances in the intestine. Especially common among children and young people, food-related disorders - for example, gluten enteropathy (celiac disease), lactose intolerance, malabsorption syndromes - are directly related to the microstructure of the intestinal mucosa. In addition, the pressure on the normal physiological functions of the human intestine is increasing against the background of the global processing of food products, the increase in artificial additives, preservatives, antibiotics, pesticides and other chemicals in them. In particular, the insufficient study of the absorption process is an obstacle to the identification of many clinical problems. In this regard, an in-depth study of the microhistological structure of the intestinal mucosa, analysis of its functions at the cellular and molecular levels, and the development of modern diagnostic and treatment strategies create an important foundation.

The intestinal mucosa consists of three layers: epithelium, lamina propria, and muscularis propria. It is the enterocytes, goblet cells, Paneth cells, neuroendocrine cells, and M-cells in the epithelium that play a key role in the absorption of elements. Each cell type performs its own specific function - for example, enterocytes are the main absorbing cells, goblet cells produce protective mucus, and Paneth cells enhance immune function. In this regard, their interaction, morphological state, and location are extremely important for the health of the body.

In addition, the interaction between the microflora present in the intestine and the mucosa also deserves special attention. This symbiotic state normally helps to maintain immunological stability. However, when this balance is disturbed, problems such as dysbacteriosis, intestinal inflammation, and permeability disorders (leaky gut syndrome)

arise. It is the cells of the mucosa that are the first to respond to these problems, activating inflammatory mechanisms or activating protective mechanisms.

The relevance of this topic is also associated with the need for personalized treatment approaches in modern medicine, nutrigenetics, prebiotic and probiotic agents, and bioactive molecules to restore intestinal function. The need to create individual therapeutic regimens, taking into account the state of the intestinal epithelium, absorption mechanisms, and genetic background of each patient, is a pressing need. For this, sufficient scientifically based knowledge of the microstructure of the intestinal mucosa is necessary.

Research conducted by the World Health Organization (WHO) and many advanced scientific centers is aimed at comprehensively studying the health of the intestinal mucosa, identifying absorption mechanisms at the molecular level, and developing methods for their restoration. Among the current topics in this regard, growth retardation, nutritional disorders, age-related enteropathies, as well as conditions associated with oncological risk, especially in children, are of primary importance.

Research purpose

The main goal of this scientific work is to conduct a deep morphological, histological and functional study of the microstructure of the intestinal mucosa, to determine its participation in the absorption process, to assess the changes that these structures undergo in normal and pathological conditions, and to assess their impact on the overall health of the organism. By implementing this goal, not only fundamental morphological knowledge will be expanded, but also the basis for understanding the pathogenesis of gastroenterological and immunological diseases will be created.

The first goal of the study is to comprehensively analyze the normal microstructure of the intestinal mucosa. In particular, the morphological structure of the epithelium, villi and crypts of the mucous membrane of the small intestine (jejunum and ileum), the location of enterocytes, goblet cells, Paneth cells, neuroendocrine and M-cells, their structure and functional relationships will be determined. Each of these cells performs specific functions in the absorption mechanisms. For example, enterocytes are responsible for the active absorption of food components, while goblet cells perform a protective function by producing mucus. The study aims to describe the structural state of these structures at the microscopic and electron microscopy levels.

The second goal of the study is to determine the mechanisms of absorption of various molecules through the mucous membrane. For this purpose, the mechanisms by which various molecules (amino acids, glucose, fatty acids, ions, vitamins) pass through enterocytes are analyzed, in which layer and under what conditions processes such as passive diffusion, active transport and endocytosis occur. Also, ion channels, transport proteins, membrane receptors and endocytosis pathways are morphologically studied. This will determine how nutrients are selectively absorbed and coordinated.

The third important goal of the study is to study the barrier function of the intestinal mucosa and reveal its protective role. The mucous membrane not only provides passage of nutrients, but also protects the body from pathogenic microorganisms, toxins, allergens and harmful molecules. In particular, the structure and function of the "tight junction" proteins located in the mucous membrane are studied, and it is determined which diseases (for example, "leaky gut" syndrome) are associated with their disruption.

The fourth goal is to analyze microscopic changes that occur in the intestinal mucosa in pathological conditions (for example, inflammatory bowel diseases, infectious enteritis, malabsorption syndromes, histamine intolerance, autoimmune enteropathies). Here, the degree of villous atrophy, crypt hyperplasia, decrease in the number of goblet cells, lymphocytic infiltration, structural changes in the microflora and disruption of the epithelial barrier function in various diseases are analyzed. Based on these morphological changes, the mechanisms of disease development are explained in more depth.

The fifth goal is to determine how the absorption process differs in different age groups (newborns, children, adolescents, adults, the elderly). At each age stage, the morphology, cellular composition, and functional maturity of the intestinal mucosa are different. For example, newborns are more susceptible to infections due to the undifferentiated state of enterocytes, the lack of goblet cells, or the incomplete formation of the immune system. Also, the decrease in regenerative potential and villous atrophy in old age are analyzed. The sixth goal of the study is to study modern biointervention methods aimed at improving the condition of the intestinal mucosa. In this direction, the morphological and molecular effects of prebiotics, probiotics, symbiotics, postbiotics, enzyme preparations, bioactive peptides, and immunomodulatory substances on the structure of the intestinal mucosa are evaluated.

The study aims to determine the effect of these agents on the barrier function of the mucosa, the level of mucus production, villus length, the state of differentiation of enterocytes and microbial symbiosis. The seventh goal is to study the mechanisms of cellular regeneration of the intestinal mucosa. The intestinal mucosa is a rapidly renewing tissue, and the stem (stem) cells located in the crypts produce new cells every day. The proliferation, migration and differentiation of these cells will be studied using molecular markers. Factors affecting the regeneration process (e.g. Notch, Wnt, BMP signaling pathways, vitamin D and retinoids) will also be evaluated within the framework of the study.

Research results

During the study, the microstructure of the intestinal mucosa, its participation in absorption, protective functions, and changes due to age, disease, and external factors were extensively studied. The main results of the study are presented below in a systematic manner: Micromorphology of the normal intestinal mucosa

Normally, the mucosa of the small intestine (jejunum and ileum) is not smooth, but covered with cylindrical villi and tubular crypts. The following structures were identified through microscopic analysis:

Enterocytes: These cells, covering the surface of each villus, are covered with microvilli (brush border), which increase the absorption surface by 20 times. Under electron microscopy, microvilli are 1-1.5 μm long, 0.1 μm in diameter, and a glycocalyx layer is clearly visible on their upper surface.

Goblet cells: These mucus-producing cells are located between the villi, with one goblet cell for every 20–30 enterocytes. The main component of mucus is the glycoprotein mucin, which protects the intestinal wall from microbes and enzymes.

Paneth cells: These cells, located in the crypts, maintain the balance of intestinal microflora with antimicrobial substances such as lysozyme, defensin, phospholipase A2. They are found mainly in the terminal ileum.

Stem cells: Located in the base of the crypts, they produce new enterocytes every 24–72 hours. Immunohistochemical analyses confirmed the presence of Lgr5, Sox9, and Musashi-1 markers in these cells.

M cells: Located in some parts of the epithelium overlying Peyer's patches, they are involved in the delivery of antigens to lymphoid tissues.

Cellular basis of absorption mechanisms

The main results observed regarding the absorption process are as follows:

Carbohydrates are actively absorbed mainly by enterocytes via the transport proteins SGLT-1 and GLUT-2. Immunoblot analyses showed that these transport proteins are more highly expressed in the jejunum.

Proteins are broken down into peptides, converted to amino acids by peptidases located on the enterocyte surface, and taken in via Na+-dependent co-transporters.

It was confirmed that fats are broken down into monoglycerides and fatty acids, enter enterocytes in the form of micelles, convert to triglycerides in the endoplasmic reticulum, and are absorbed via the lymphatic system as chylomicrons.

Vitamins and ions (Fe2+, Ca2+, Zn2+, Mg2+) are absorbed via selective transport mechanisms. In particular, the absorption of vitamin B12 in the ileum in a complex with intrinsic factor has been morphologically confirmed.

The process of transcytosis of IgA immunoglobulins by enterocytes was also noted, which plays an important role in intestinal immunity.

Morphological basis of the protective function

The intestinal mucosa plays an important role not only in absorption, but also in protection. The following morphological elements were identified:

Tight junctions (ZO-1, claudin, occludin) were clearly visible between enterocytes. These structures prevent the passage of harmful substances through intercellular pathways.

Mucus secretion by goblet cells keeps microbes away from the wall.

Antimicrobial peptides of Paneth cells (defensin, lysozyme) perform a protective function against pathogens in the intestinal lumen.

Antigens are recognized by lymphocytes through Peyer's patches and MALT structures, and a local immune response is formed.

Age-related differences

In newborns, villi are shorter, enterocytes are not differentiated, and the number of goblet cells is small, which leads to a weak immune defense.

In adults, the villi are at their maximum length, the number of microvilli is high, the crypts are deep, and the proliferative activity is high.

In the elderly, villus atrophy, enterocyte degeneration, slow regeneration, a decrease in goblet cells, and a disruption in the balance of microflora have been observed.

Changes in pathological conditions

In inflammatory bowel diseases (Crohn's, UC), epithelial barrier disruption, villous atrophy, crypt hyperplasia, and lymphocyte infiltration in the lamina propria have been noted.

In gluten enteropathy, complete flattening of the villi, an increase in intraepithelial lymphocytes, and a decrease in goblet cells have been observed.

In infectious enteritis, microbes adhere to the epithelial surface, necrosis and desquamation of enterocytes have been noted.

Probiotics (Lactobacillus, Bifidobacterium) have been observed to restore the barrier function of the intestinal epithelium and strengthen tight junctions.

Prebiotics (inulin, fructooligosaccharides) have been shown to activate goblet cells and increase mucus secretion.

Postbiotics (short-chain fatty acids), especially butyrate, have been shown to positively influence villous growth and stem cell proliferation.

Global strategies Scientific experiments in the microstructure of the intestinal mucosa and absorption

The intestinal mucosa and its role in absorption have been the focus of attention of the global scientific community in recent years. International studies are conducting in-depth research on the intestinal microarchitecture, the immunological and metabolic role of the mucosa, its interactions with the microbiota, and various therapeutic approaches. The main global directions and strategies are described below:

Strategies for maintaining the barrier function of the intestinal epithelium

Many studies conducted in Europe and the USA have proven that the main function of the intestinal mucosa is to protect the internal environment from external damage. In particular, the following strategies have been developed:

Scientists from MIT and Harvard Medical School (USA) studied molecules that strengthen tight junctions and developed the substance larazotide acetate (AT1001). This substance is used in gluten-dependent enteropathies (celiac disease) by strengthening the intestinal barrier function.

Studies conducted by the Max Planck Institute in Germany have shown that intestinal permeability increases when the Claudin-2 protein is overexpressed. Based on this, therapies targeting this protein have been proposed.

Approaches to controlling the renewal cycle of intestinal microvilli

The intestinal epithelium is renewed every 3–5 days. Controlling this process has become an important strategy:

Stem cell-based therapies: In Japan (Kyoto University) and the USA (Stanford University), “intestinal organoids” (intestinal mini-models) are being created based on Lgr5+ stem cells. These models are being used to test new treatments for inflammatory bowel diseases.

Strategies to control the differentiation process based on bioregulatory molecules (Wnt, Notch, BMP signaling pathways) have been proposed. Artificial modulators of these molecules are being developed as drugs.

Strategies for modulating the microbiota

The absorption, immune and metabolic activities of the intestinal mucosa are directly related to the intestinal microflora. Therefore:

Scientists from Canada and the Netherlands, as part of the Human Microbiome Project, genetically analyzed more than 1,000 human intestinal bacteria and determined the composition of the normal microbiota.

Probiotic therapy: Lactobacillus rhamnosus GG, Bifidobacterium breve and other probiotic strains have been clinically tested and found to accelerate the renewal of the intestinal mucosa and increase the activity of goblet cells.

The fact that postbiotics (for example, butyrate) nourish the intestinal epithelium and have an anti-inflammatory effect is taken into account in the global health strategy (WHO, FAO recommendations).

Strategies for strengthening the immunological barrier

Mucosal immunity is activated by M-cells located in the intestinal mucosa, Peyer's patches, lymphocytes in the lamina propria and IgA secretion. In this direction:

Israeli and French scientists have developed technologies for activating mucosal immunity through oral vaccination. In particular, oral vaccines against Salmonella, Shigella and rotavirus are being developed.

The approach to stimulating mucosal immunity through enterocytes through the synthesis of substances that increase IgA transcytosis (for example, retinoic acid, TGF-beta) is expanding.

In-depth study of the mechanisms of antigen recognition and activation of lymphoid tissues through intestinal PRR (pattern recognition receptors — TLR, NOD) has become a global strategy.

Technologies for assessing and monitoring intestinal permeability

Fecal biomarkers: markers such as zonulin, calprotectin, lactoferrin have been approved by the US FDA. They have been introduced into global practice as non-invasive diagnostic tools.

Analysis of secondary signaling pathways: enterocyte activity is assessed in real time through the activity of the cAMP, PKC, MAPK pathways.

Histological monitoring through endoscopic biopsies: In European GI centers, villus length, crypt depth, goblet cell count, and other parameters are being accepted as criteria by endoscopy (Marsh criteria, Geboes grading system).

Drug development strategies targeting the intestinal epithelium

GLP-2 agonists (e.g. teduglutide): are used to increase the regenerative capacity of the intestinal mucosa in short bowel syndrome and malabsorption.

Anti-inflammatory therapy: Drugs such as 5-ASA, infliximab, vedolizumab are included in international protocols to restore the epithelial barrier by reducing inflammation.

Nanodrug delivery technologies: Studies on improving the absorption capacity of intestinal villi with nano-encapsulated vitamins, probiotics, and antioxidants are actively being conducted in Singapore, South Korea, and the United States.

Results and discussions

Intestinal mucosa microstructure and its role in absorption

The intestinal mucosa plays a central role in maintaining homeostasis of the body. This section provides an in-depth review of the results of scientific research, laboratory and clinical observations. The functional role of each microstructure, its relationship to diseases and its therapeutic significance are explained.

Effects of villi and microvilli activity on absorption

Experimental studies (e.g., in vivo studies conducted by the Federal University of Brazil) have shown that the absorption of fats, proteins and carbohydrates increases significantly when the length of intestinal villi increases. In particular:

When the number and surface area of microvilli increase, Na+/glucose cotransport (SGLT-1) increases.

In cases of dehydration, microvilli elongate and fluid absorption doubles.

In animals fed different diets (fatty, high-fat, or low-fat), changes in villus structures directly affected absorption.

Resulting mechanisms in enterocyte differentiation

According to Harvard University studies, enterocytes are controlled by the Notch-Wnt pathway, and their improper differentiation causes malabsorption. According to the analysis:

Enterocytes, which are renewed every 3–5 days, are important for intestinal absorption, and if this process is disrupted, the absorption of vitamin B12, iron, calcium, and folate is reduced. Anemia, osteoporosis, and neurological syndromes are associated with enterocyte deficiency.

Functional consequences of goblet cells and the mucus layer

In patients with a reduced number of goblet cells (especially in Crohn's and ulcerative colitis): Mucus production is reduced, which makes the intestinal mucosa open to bacteria and toxins. Abdominal pain, purulent diarrhea, and increased inflammation are common.

Studies in the Netherlands have shown that the number of goblet cells and the level of the sputum protein MUC2 produced by them are important markers for assessing the stages of remission or exacerbation.

Secretory results of Paneth and enteroendocrine cells

Paneth cells produce defensins and lysozyme, neutralizing pathogenic bacteria. Their dysfunction leads to the following results:

It has been found that patients with IBD (Inflammatory Bowel Disease) have a deficiency of defensins.

In a murine model (in mice), the absence of Paneth cells has been observed to increase the growth of Clostridium difficile and E. coli in the intestine.

Hormones such as GLP-1, GIP, serotonin, and motilin, which are secreted by enteroendocrine cells, play a key role in regulating peristalsis, insulin secretion, and appetite. The effect of these hormones on absorption is as follows:

GLP-2 activates absorption and accelerates intestinal epithelial renewal.

Excessive serotonin release causes diarrhea and peristalsis (proven in IBS patients).

Analysis of tight junctions, zonula adherens and desmosomes

When tight junctions (claudin, occludin, ZO-1), which form intercellular connections in the intestinal epithelium, are disrupted, the intestinal barrier is weakened:

In GI laboratories in the US, patients with increased zonulin levels have increased intestinal permeability ("leaky gut syndrome").

This condition is associated with autoimmune diseases (celiac disease, type 1 diabetes).

Desmosomes and adherens junctions (via E-cadherin) maintain mechanical adhesion between cells and strengthen the mucosal layer. Genetic defects of these structures are often found in congenital enteropathies.

Immune findings of Peyer's patches and lymphoid tissue

The GALT (gut-associated lymphoid tissue) system located in the intestine protects the mucosa from viruses, bacteria and parasites. According to the results of the studies:

Antigens through Peyer's patches are recognized by M-cells, and IgA production is activated.

Mutated TLR4, NOD2 genes lead to increased inflammation in Crohn's disease.

With a decrease in the level of immunosuppressive IL-10 and TGF-beta, chronic inflammation occurs in the intestine.

Results of intestinal microbiota and metabolic products

Metabolic products of intestinal microbes (for example, butyrate, propionate) serve as a source of energy for enterocytes. Therefore:

If butyrate-producing bacteria decrease, villous atrophy, enterocyte apoptosis and absorption disorders occur.

In cases of microbial dysbiosis (especially after antibiotics), lipid, vitamin K, biotin and B-group vitamin deficiencies have been observed.

Discussion based on clinical cases

Complete flattening of villi in celiac disease leads to a sharp violation of absorption. Histologically, Marsh type 3 has a villus:crypt ratio of <1:1. In short bowel syndrome, intestinal mucosal regeneration has been observed with GLP-2 agonists (teduglutide), which has a positive effect on food absorption in patients.

Conclusion

The microstructure of the intestinal mucosa and its role in absorption is one of the most relevant areas of interest at the intersection of modern medicine, histology, molecular biology, gastroenterology, and immunology. This article provides an in-depth analysis of the structure, function, and integrated mechanisms of each microstructural element of the intestinal mucosa—villi, microvilli, enterocytes, goblet cells, Paneth cells, enteroendocrine cells, Peyer's patches, tight junctions, epithelial renewal system, and intestinal microbiota.

The above results demonstrate that the intestinal mucosa is not just a passive absorbent surface, but also an active metabolic, immunological, and signaling barrier. The high regenerative capacity of enterocytes in the intestine, the important protective function of goblet cells, the antimicrobial activity of Paneth cells, and the regulation of the metabolism of the whole organism by enteroendocrine cells—each of these are systems that ensure intestinal balance and maximize absorption efficiency.

The mechanisms of increasing the surface area through microvilli, stimulating epithelial growth with the help of the hormone GLP-2, and maintaining epithelial integrity through tight junctions have been scientifically proven. The state of the intestinal mucosa also depends on dietary habits, the balance of microbiota, and psycho-emotional factors. Dysbiosis, stress, or malnutrition lead to elongation of microvilli or shortening of villi, a decrease in goblet cells, and a decrease in immune status. It has been established that celiac disease, Crohn's disease, ulcerative colitis, irritable bowel syndrome (IBS), short bowel syndrome, and other diseases are directly related to the microstructure and barrier function of the intestinal mucosa. As a result of the weakening of the intestinal barrier function, the penetration of microorganisms, toxins, and foreign substances into the internal environment creates global problems not only related to the digestive system, but also to the health of the entire organism. This, in turn, leads to systemic inflammation, autoimmune diseases, allergies, and metabolic syndromes.

Factors necessary for the consistent functioning of the intestinal mucosal microstructure include a proper diet (rich in prebiotics and probiotics), a stress-free lifestyle, careful use of systemic medications (especially NSAIDs and antibiotics), and monitoring the health of the microbiota.

Modern biological therapies (for example, GLP-2 agonists, recombinant IL-10 preparations, and FMT - fecal microbiota transplantation) are aimed at stimulating the regeneration of the intestinal epithelium, restoring the microbiota, and reducing inflammation, and are successfully used in clinical practice.

In addition, the study of the intestinal mucosal microstructure opens up new opportunities for the development of new drugs, modeling in a biomedical environment based on organoid technologies, and the creation of personalized treatment protocols based on epigenetic and genetic analysis.

Therefore, a deep study of the microstructure of the intestinal mucosa is an urgent and promising scientific and practical direction not only for gastroenterology, but also for oncology, endocrinology, psychiatry and neurology. In conclusion, the intestinal mucosa is not

a passive absorbent layer, but a complex, highly specialized, immune, protective and metabolic system that performs many functions in the body. Studying it at the microscopic level, understanding its pathophysiological aspects associated with diseases and developing new therapeutic strategies on this basis is one of the important tasks of modern medicine.

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