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Structural Basis Of Adaptation And Integration Of The Small Intestine

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Abstract: This article examines the structural foundations underlying the processes of adaptation and integration in the small intestine. Particular attention is paid to the morphological and histological features of the intestinal wall that ensure functional adaptability to varying physiological conditions. The study analyzes the role of epithelial cells, villi, crypts, vascular and nervous components in maintaining integrative interactions between digestion, absorption, immune defense, and neurohumoral regulation. The adaptive capacity of the small intestine is considered in the context of structural plasticity, cellular renewal, and regulatory mechanisms that support homeostasis. The findings contribute to a deeper understanding of the structural–functional relationships essential for the integrative activity of the small intestine.

Keywords: Small intestine, structural adaptation, integration, morphology, histology, intestinal epithelium, villi and crypts, functional plasticity, homeostasis.

Introduction: The mucous membrane consists of four layers: a simple columnar border epithelium, the lamina propria, the muscularis mucosa, and the submucosa. Morphological and functional studies focused on the development of the digestive and excretory systems and the formation of a functional digestive system provide insight into the structural mechanisms of absorption in the small intestine and the regulation of blood homeostasis. This problem is of great interest because its solution is of significant importance for clinical medicine, particularly for elucidating the pathogenesis of atopic diseases in children and liver and kidney diseases in all age groups.

METHODS

The study was performed on rats aged 1, 3, 7, 14, and 21 days after birth. Samples for histological examination were collected by euthanizing anesthetized animals in the morning between 9:00 and 10:00 AM. The study timing was based on the structural and functional characteristics of small intestinal development during postnatal ontogenesis.

Jejunal tissue samples (2-3 cm below the ligament of Treitz) were used for general morphological, histochemical, morphometric, and electron microscopic studies. Paraffin sections 5-6 µm thick were stained with hematoxylin and eosin; semithin sections from Araldite - embedded blocks 1-2 µm thick were stained with methylene blue and basic fuchsin. Ultrathin tissue sections 600 Å thick were obtained on an LKB ultramicrotome. III. After contrasting with acetone and lead citrate, the samples were examined under a JEM -100 S electron microscope (Japan). Morphometric studies were performed on sections stained with hematoxylin and eosin using an Intral -211 semiautomated image analyzer (Russia).

Statistical processing was performed using Excel 2600. The arithmetic mean (M), its error (m) , and the degree of reliability (P) were determined. Values were considered reliable at $P < 0.05$.

RESULTS

The crypt-villus system is the structural and functional unit of the small intestinal mucosa. Throughout the organ, specific dynamic relationships between proliferating and differentiating epithelial cells in the

crypts, and functioning and extruding epithelial cells on the villi, allow for continuous, optimal architectural changes in response to the influencing factors. The spatiotemporal separation of enterocyte pools in the crypts and villi provides the intestine with high adaptive capacity. The height, width, and shape of the villi in apparently healthy individuals vary both within the specific section being studied and throughout the entire organ. In healthy individuals, their length ranges from 200 to 1000 µm, and their width from 90 to 130 µm. In the duodenum, jejunum, and ileum of the small intestine, the villus height is 570±35, 615±29, and 315±18 µm, respectively. In the proximal portion of the organ, villus height is more variable than in the distal portion. Thus, in the jejunum, villus height fluctuates between 700 and 1000 (35%), 550-700 (35%), and the remaining villi are approximately 500 µm. In the ileum, approximately 85% of the villi are 250-380 µm in height.

While villus parameters gradually decrease toward the end of the small intestine, crypt depth increases from 100-150 µm in the duodenum to 200-250 µm in the ileum. In each section of the organ, crypt depth and villus height decrease from the mesenteric to the antimesenteric border. While in the duodenum the villi are leaf-shaped and finger-shaped, in the jejunum they are mostly regular finger-shaped and protrude freely into the intestinal lumen. Mucoid secretions are present in the intervillous space and on the surface, yielding a positive PAS and Hale reaction. The ratio of the number of villi to the number of crypts is 1:6 - 1:9; the villus height to crypt depth ranges from 3:1 to 1.5:1. In sterile animals, in old age, or when the normal microbiocenosis in the intestinal lumen is disrupted, these ratios can vary significantly.

In order to establish the mechanisms of intestinal adaptation, most researchers study the cell cycle and the kinetics of enterocyte renewal in the crypt-villus system. As in any other stationary system, four pools of enterocytes are distinguished in it: stem, proliferating, differentiating and functioning. It should be noted that the first three are concentrated in the crypts and only the functional ones - on the surface of the villi. If the entire depth of the crypt is conditionally taken as one, then the following is established: the bottom (0.1 part) is lined with specialized Paneth cells; from the bottom upwards 0.1 part are stem and slowly proliferating, the next 0.4 of the crypt surface is occupied by intensively proliferating; 0.4 in the upper part of the crypt is lined by differentiating enterocytes.

of enterocyte migration from crypts on the surface of villi in the small intestine, it should be noted that only highly differentiated ones, which make up the functioning pool, move to the area of the base of the villi.

Considering that in mature animals, 60 to 75% of crypt epithelial cells in the zone of highest proliferation are labeled, while the upper 0.4 of its part loses the ability to proliferate and differentiates, we believe that the regulation of proliferative activity is carried out by changing the number of cells involved in reproduction. A reduction in the duration of the cell cycle and its synchronization in the majority of proliferating crypt cells allows for the maintenance of a dynamic equilibrium between proliferating, differentiating, functioning, and extruding cells. enterocytes in the crypt-villus system, characteristic architecture of the mucous membrane throughout the organ. The majority of proliferating cells have a short cell cycle duration – about 12-14 hours. Epithelial cells that have entered the DNA synthesis phase do not enter the resting phase either in G1 or G2 periods. They either enter the differentiation pathway through mitosis or re-enter the cell cycle. Individual labeled epithelial cells in the bottom part of the crypts even 3-4 days after pulse labeling with H3 – thymidine indicate the presence of enterocytes with a longer cell cycle (20 hours or more) in this zone. Stem cells are single, not labeled, and can be detected in the transition zone of the crypts to the bottom part, at the border with Paneth cells. Lysozymes, defensins, metalloproteases secreted by Paneth cells into the lumen of the crypts, They create a sterile microenvironment for the cell pools concentrated here. This is necessary to protect stem, proliferating, and differentiating cells from bacteria and their toxins. The constant secretion of mature, functionally active forms of defensins, as well as other antimicrobial substrates, at the very bottom of the crypts, during their movement through the crypt lumen, and into the intestinal lumen represents an evolutionarily ancient mechanism for the reliable protection of the pool of stem, proliferating, and specializing cells, and for optimal adaptation of these cells to the endoecology, which is subject to unpredictable qualitative and quantitative changes.

Increase in the proportion of heterochronic proliferating The crypt epithelial cells after various influences should be considered as a measure of the reliability of the functioning of the crypt-villus system.

The relatively large zone of enterocyte differentiation in the upper part of the crypts (0.4 of its total length) is explained by the need for complete cell specialization before entering the villus base. The first labeled enterocytes at the villus bases are detected 12 hours after a single administration of H3- thymidine. The time for complete renewal of the mucosal epithelium is approximately 3 days. Therefore, the epithelium in the crypt-villus system belongs to a rapidly renewing cell

population.

The surface of the villi and crypts is lined with a single-layer epithelium consisting of columnar, bordered, goblet, endocrine, Paneth, proliferating, and stem cells. Bordered (absorptive) enterocytes constitute the bulk of the villus cells. On the apical surface, they have microvilli with a typical ultrastructure and well-developed glycocalyx (Fig.). The plasma membrane between the bases of the microvilli has isolated endocytic formations. During the interdigestive period (approximately 6 hours after the last feeding), in a state of relative functional rest, SER profiles are detected primarily in the supranuclear cytoplasm, oriented along or around round or oval mitochondria. Smooth reticulum profiles are found near the Golgi complex. Mitochondria with a moderately dense matrix and a number of cristae are located supranuclear, less often subnuclear. The structures of the Golgi complex are located above the upper pole of the nucleus, vacuoles are single, 3-4 cisterns are flattened, vesicles are present in moderate quantities on both the cis- and trans-surface. Free ribosomes and polysomes are found everywhere. Occasionally, isolated small electron-dense lysosomes are observed in the supranuclear cytoplasm. Their number and size increase after each feeding or disruption of the microbiocenosis in the intestinal lumen. The contents of receptor-mediated enzymes are hydrolyzed in them. endocytic formations. The nuclei of the bordered enterocytes of the villi are oval, located basally, oriented along the cell. One or two dense nucleoli are located eccentrically. The ratio of euchromatin and heterochromatin is approximately equal. Heterochromatin is mainly concentrated under the nuclear envelope. The outer nuclear membrane in some areas is connected with the profiles of the SER, through single smooth membranes and vesicles - with the structures of the Golgi complex. Bordered enterocytes, like other types of epithelial cells, hermetically separate the external (intestinal) environment from the internal (interstitium) due to the formation of a junctional complex, desmosomes, interdigitations . Characteristically, desmosomes are observed up to the level of the upper pole of the nucleus; Interdigitations of the lateral plasma membranes with adjacent cells are numerous and deep, typically extending from the supranuclear cytoplasm to the base. The basal plasma membrane rarely forms folds or protrusions. The basement membrane beneath the epithelial cells is homogeneous, 50-100 nm thick, and uninterrupted. During periods of relative functional rest, the goblet cells of the villi have a characteristic shape, filled with secretion. Their proportion increases from 10-12% in the duodenum to 23-25% in the ileum. Within the section under consideration, their number increases from the apex of the villus to the crypt orifice. They are PAS- and Hale-positive, differentiating in the crypts and functioning on the surface of the villi. With the introduction of histamine, it was established that the secretory cycle in an individual cell lasts approximately 6 hours. Heterochronic functioning allows them to secrete mucus continuously throughout the day, increasing 10-15 minutes after a meal. During peristaltic movements of the small intestine, when the substrate comes into contact with the supraepithelial mucus layer (NESS), a certain proportion of goblet cells rupture the apical plasma membrane, ejecting their secretion in a stream. This secretion becomes reticular and coats the surface of nearby enterocytes in the villi. This formation and constant renewal of the NESS ensures perimembranous digestion, homeostasis, and sterility of membrane digestion and absorption, which occur in conjunction with the glycocalyx and plasma membrane of the microvilli. Degranulation of goblet cells after a single meal occurs sequentially from the duodenum to the end of the ileum and lasts approximately 3 hours. When histamine is administered, simultaneous secretion of all goblet cells in the villi and crypts throughout the entire organ is observed after 0.5 hours. Restoration of their original state and completion of the entire secretory cycle is completed within 6 hours. Therefore, under physiological conditions, goblet cells in the small intestine function asynchronously both on the surface of individual villi and along the entire organ. They have varying sensitivity to stimulators, and the entire secretory cycle lasts 6 hours.

In a differentiated goblet cell, the nucleus is oval or rounded, pushed toward the base by the secretion. Parallel profiles of the Golgi apparatus and isolated mitochondria are visible beneath and laterally. The Golgi apparatus is located beneath the upper pole of the nucleus and is fairly well developed: cisternae are dilated, and vacuoles and vesicles are numerous. Mature secretory granules detach from its trans-surface and accumulate in significant quantities in the supranuclear cytoplasm. They are round, multifaceted, and electron-clear; as they accumulate, they give the cell a goblet shape. A few short microvilli may be present on the narrow apical surface. During secretion, part of the apical membrane is destroyed. After secretion, isolated small secretory granules remain near the trans-Golgi surface. Upon completion of the rapid secretion release, fragments of the goblet cell's apical plasma membrane instantly rush toward each other, restoring the integrity of the membrane and the cell as a whole.

throughout the small intestinal mucosa on the surface of the villi and crypts. They have a characteristic ultrastructure of secretory granules and topography of cytoplasmic organelles. The cytoplasm of the cells is lighter than that of adjacent enterocytes. Their shape is cone-shaped: the narrowed apical surface in cross-section of some cells contacts the intestinal lumen and contains short, irregular microvilli. The other part does not communicate with the lumen and is usually surrounded by bordered Enterocytes. The broad basal portion of the endocrine cells does not form cytoplasmic islands or distinct folds. The basement membrane adjacent to the base of the endocrine cells is continuous. Free nerve endings with isolated light and dark secretory granules or a blood capillary with fenestrated endothelium may be located nearby, subepithelially.

Like all specialized cells of the small intestine, endocrine cells are polar. A moderately developed Golgi complex is located in the supranuclear region; a few SERS profiles are mainly detected in the supranuclear cytoplasm. Individual SERS profiles can be found in other parts of the cell, in contact with a few small to medium-sized mitochondria. The nucleus in the majority of endocrine cells is localized basally, rounded, with approximately equal amounts of euchromatin and heterochromatin. Secretory granules begin to be identified in the cisterns and vesicles of the Golgi complex, from where they move from the supranuclear zone along the lateral part of the cytoplasm to the base of the cell. Accumulating singly or in small groups in greater or lesser quantities, the secretory granules of endocrine cells occasionally contact the basal plasma membrane with their membrane. Exocytosis occurs upon fusion of the marked membranes. Secretory granules after Upon exiting the cell into the interstitial space, they immediately lose their electron density. Consequently, their subsequent fate is undetectable, although some exert paracrine effects, while others, after entering the bloodstream, exert a distant influence. Paracrine effects are exerted on nearby nerve endings, connective tissue cells, and the stromal capillaries of villi or crypts. All intestinal endocrine cells apparently exhibit a continuous, albeit heterochronic, secretion pattern due to their large number. Regardless of the endocrine cell type, during periods of relative functional rest and at the peak of active digestion and absorption (0.5-1 hour after feeding), a moderate number of secretory granules are present in the Golgi apparatus and basal portion of the cell.

If we examine the crypts of the small intestine, we see that they are located in the lamina propria of the mucosa of both the small and large intestines. In the small intestine, they are lined with low-prismatic epithelium. Their height increases from the base to the opening and averages 18 ±0.20 μm. In the lower and middle thirds of the crypts, the apical surface of the cells is formed by sparse short microvilli. As they differentiate in the upper part of the crypts and migrate to the base of the villi, the microvilli lengthen and assume a cylindrical shape. Simultaneously, the supramembrane layer of the glycocalyx thickens.

CONCLUSION

The period of natural feeding in newborn rats is characterized by the most intense histogenetic processes: the number of villi, the number and depth of crypts, and the thickness of all organ membranes progressively increase. Due to hypertrophy and hyperplasia of structural and functional units and an increase in the diameter and length of the small intestine, the absorptive surface area of the organ increases sharply from the time of transition to definitive feeding. During the period of final nutrition, structural and functional changes in the small intestinal membranes are stabilized and are characterized by certain proximo -distal gradients of the linear parameters of the villi: crypts, enterocytes, and the ratio of absorptive and goblet cells.

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