FUNDAMENTAL OF DENTAL IMPLANTS OSSEOINTEGRATION (LITERATURE REVIEW)

ОСНОВЫ ОСТЕОИНТЕГРАЦИИ ДЕНТАЛЬНЫХ ИМПЛАНТАТОВ (ОБЗОР ЛИТЕРАТУРЫ)

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Annotation: *The extensive use of dental implants in oral rehabilitation has increased scientific interest in how implants integrate with bone tissue. This study aims to review and organize both domestic and international research on the osseointegration of titanium implants.*

Recent literature shows that advances in research methods and interdisciplinary approaches have significantly altered traditional understanding of this process. Current data summarize the physiological

mechanisms and cellular interactions occurring at the implant-bone interface during different stages of integration. The findings suggest the need to reconsider the long-held view of titanium as bioinert and to evaluate osseointegration from an immunological perspective.

Effective bone regeneration in maxillofacial diseases, traumatic injuries, and implant procedures depends on a balanced interaction of neural, endocrine, and immune mechanisms that regulate osteogenesis. This process involves several biologically active mediators, including beta-endorphin, serotonin, and others.

Currently, dental implantation is widely used for orthopedic rehabilitation in patients with various dental defects. International experience demonstrates that implant-based prosthetics can be applied in a wide range of clinical scenarios — for both fixed prostheses and to enhance the stability of removable ones — providing predictable and stable treatment outcomes [1,8].

Key words:*osteointegration, osteoconduction phase, alkaline phosphatase*

In recent decades, the growing popularity of dental implants has stimulated increased research interest in the mechanisms governing the interaction between implants and bone tissue. Osseointegration is traditionally regarded as the most favorable outcome of this process. P.-I. Branemark, the pioneer of modern dental implantology, defined it as “the apparent direct connection of living bone tissue to the implant surface without any intervening connective tissue” [2]. Successful osseointegration is widely considered essential for the long-term stability and effectiveness of implant-supported prosthetics [1,6].

The phenomenon of osseointegration was serendipitously discovered by P.-I. Branemark during studies of bone microcirculation using a miniature optical device implanted in a rabbit's tibia. Over more than forty years since this discovery, an extensive body of research has accumulated, providing insights into the mechanisms of implant integration with bone tissue, which continues to expand [3–6].

According to A. A. Kulakov, implant integration should be understood as a dynamic interaction between biological and inert components, in which a balance of compensatory-adaptive and homeostatic mechanisms is established. This equilibrium allows living and non-living components to coexist within a unified system. The criteria for successful integration include the absence of inflammatory, necrotic, or allergic reactions in the peri-implant tissues, the formation of morphofunctional characteristics (such as bone-like tissue) at the implant-bone interface, and the long-term preservation of these characteristics [7,10].

The literature describes several types of tissue organization at the implant-bone interface. Classic osseointegration, as defined by Branemark, involves direct bone-to-implant contact. Fibro-osseointegration is distinguished by a connective tissue layer, composed of collagen fibers and coarse fibrous tissue, between the bone and implant. Connective tissue integration occurs when the implant is completely encased in fibrous connective tissue. While the first two patterns are considered normal bone responses to the implant, the latter is interpreted as a sign of implant rejection.

For many years, the blood clot retraction theory was widely accepted [10,16]. According to this model, osseointegration begins with the osteoconduction phase, during which mesenchymal cells and osteoblasts

migrate to and adhere to the implant surface via the residual thrombus. Osteoinduction follows, characterized by new bone formation and deposition of mineral salts within the developing matrix. The final stage, remodeling, involves a prolonged cycle of bone resorption and formation surrounding the implant. The implantation itself is considered a surgical trauma, accompanied by inflammation, initial signs of resorption, and the initiation of a cascade of vascular-tissue reactions leading to regeneration. The condition of the vascular bed and the level of blood supply in the area of intervention are important in this process: ischemia increases the likelihood of fibrous or cartilaginous tissue forming instead of normal bone structure [1,5,11,8].

It has been established that even when the implant is twisted at high speed and high primary stability is achieved during its installation, a gap of up to 60 μm remains between the implant surface and the adjacent bone. Depending on the traumatic nature of the operation, this gap can increase locally to 100–500 μm. The space is filled with blood and tissue fluid, which serve as a source of biologically active substances and proteins necessary to initiate osseointegration. Although the characteristics of the implant surface can modify the composition and spatial organization of adsorbed proteins, cell membrane receptors interact with the titanium surface, ensuring their initial attachment [19, 20].

In the early stages of osseointegration, the extracellular protein fibronectin and transmembrane heterodimers—integrins—are actively involved in the process of cell recognition and adhesion to the implant surface [21, 22]. Blood from the bone bed vessels forms a clot containing platelets, fibrin, vascular growth factors, transforming growth factor, insulin-like growth

factor, and other mediators. These components stimulate neoangiogenesis and bone tissue healing [13,18, 23].

The fibrin network ensures the migration of osteogenic cells to the implant surface under the action of growth factors produced by platelets. The latter attract fibroblasts and other undifferentiated cells to the fibrin matrix zone and stimulate their differentiation [15]. The characteristics of this stage largely determine the further course of implant integration. The tight attachment of the blood clot to the surface and the formation of fibrin "bridges" between the implant and viable bone create conditions for the proliferation of osteogenic cells along the fibrin strands to the implant and the subsequent formation of bone tissue.

It is now clear that in the early stages of dental implant integration, the area and density of attachment of bone tissue cell elements and blood components to its surface are of key importance. In this regard, there is no doubt about the need to create a pronounced topography and developed micro-relief of the intraosseous part of the implant. Various technologies are used to create a complex relief with optimal roughness for , which are conditionally divided into two main groups:

1. Physicochemical surface treatment — sandblasting, acid etching, laser modification, etc.;

2. Application of biologically active coatings that stimulate bone formation processes (hydroxyapatite, tricalcium phosphate, amino acids, etc.) [3,9,19].

At the same time, implant integration solely due to contact osteogenesis is rather an idealized model. Most likely, both contact and distant osteogenesis processes occur simultaneously in different areas of the "bone-implant" zone.

The latter is characterized by the formation of bone tissue not on the surface of the implant, but on the surface of the surrounding bone: osteogenic cells of the implant bed synthesize bone matrix towards the surface of the implant.

Already in the first days after implant placement, osteoblasts attach to its surface. These cells synthesize osteogenesis marker proteins — osteopontin, osteocalcin, sialoprotein — which promote the adhesion of osteogenic cells to the implant and the fixation of mineral compounds in the newly formed organic bone matrix. The next stage is the formation of a collagen matrix directly on the implant surface, followed by the deposition of an osteoid substance that transforms into bone tissue [19].

Mineralization of the bone matrix is associated with the accumulation of calcium and phosphorus ions and is ensured not only by calcium-binding proteins, but also by the participation of phospholipids and chondroitin sulfate of the ground substance [4,17]. Subsequently, young bone tissue undergoes a long-term structural reorganization. This stage—remodeling—combines two opposing processes: bone resorption and new bone formation. Resorption of immature bone tissue is mainly carried out under the action of matrix metalloproteinases secreted by osteoclasts, which is accompanied by an increase in acid phosphatase activity. At the same time, the formation of new bone in the direction of the implant surface is ensured by the high functional activity of osteoblastic cells and is accompanied by the expression of alkaline phosphatase [22]. The remodeling process is closely dependent on the load

conditions on the implant and ultimately leads to the replacement of immature bone with a more mature and functionally complete structure.

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