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EXPERIMENTAL SUBSTANTIATION OF THE COMBINED USE OF COMPOSITE MATERIALS AND IMPLANTS IN MINIMALLY INVASIVE SURGERY

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Abstract
Background. Despite the widespread adoption of minimally invasive surgical techniques, postoperative complications associated with impaired implant integration and infectious processes remain a major clinical challenge. The interaction between implanted biomaterials and surrounding tissues plays a pivotal role in regulating inflammatory responses, tissue remodeling, and long-term surgical outcomes. *Objective.* To experimentally substantiate the effectiveness of the combined use of composite biomaterials and synthetic implants under sterile and infected conditions. *Methods.* An experimental study was conducted using laboratory animal models with implantation of synthetic mesh materials either alone or in combination with a composite hemostatic biomaterial. Both sterile and infected conditions were simulated. Tissue responses were evaluated by macroscopic assessment, histological examination, and semi-quantitative morphometric analysis at multiple time points. *Results.* Under sterile conditions, the composite-implant combination significantly reduced inflammatory cell infiltration, accelerated fibroblast proliferation, enhanced angiogenesis, and promoted the formation of mature connective tissue compared with implants used alone. In infected models, the combined approach markedly attenuated purulent inflammation, limited bacterial colonization, prevented excessive fibrotic encapsulation, and improved tissue integration. *Conclusion.* The findings demonstrate that the combined application of composite biomaterials and synthetic implants enhances biocompatibility, reduces infection-related complications, and improves regenerative processes. This strategy represents a promising approach for optimizing outcomes in minimally invasive surgery.
Keywords: minimally invasive surgery, implant, experimental surgery, biochemical analysis, morphology.

Introduction

At present, surgical implants are widely used in modern clinical practice and perform functions such as tissue reinforcement, organ substitution, and structural support. Most implants are designed to be biologically inert and biocompatible, inducing minimal tissue реакций. However, despite continuous improvements in biomaterial technology, postoperative

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complications associated with inflammation, infection, and impaired integration of implants remain a major clinical problem [1-7,12].

An unresolved and insufficiently studied issue is the possibility of combining different implant materials with locally acting therapeutic agents to modulate the biological response of surrounding tissues. The creation of composite systems capable of providing mechanical support together with hemostatic, antimicrobial, and regenerative effects represents a promising strategy to enhance implant biocompatibility and reduce postoperative complications [2,3,5,8-11].

The aim of the present study was to evaluate the feasibility and biological effects of the combined application of composite biomaterials with predefined properties and conventional surgical implants under experimental conditions.

Materials and Methods

Experimental Model. The study was conducted in the Department of Experimental Surgery and the Laboratory of Pathomorphology at the Republican Specialized Scientific and Practical Medical Center of Surgery named after Acad. V. Vakhidov.

A total of 148 adult male outbred white rats weighing 210-250 g were used. Animals were housed under standard vivarium conditions (natural light cycle, temperature 22 ± 2 °C, free access to food and water). All experimental procedures complied with the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (Strasbourg, 1986) and were approved by the local ethics committee.

All surgical procedures were performed in vivo under general anesthesia. A model of soft tissue defect of the anterior abdominal wall was created.

Implants and Composite Material. As a composite hemostatic biomaterial, a domestic cellulose-derived hemostatic agent Hemoben was used. The composite consists of sodium carboxymethylcellulose, viscose, oxidized cellulose, calcium ions, and sodium chloride. The material is a finely dispersed powder with high adhesive properties that forms a gel in the presence of moisture or крови and coats the surface of the implant.

As synthetic implants, non-absorbable polypropylene sutures and biodegradable polydioxanone sutures were used.

Experimental Design. Several experimental series were conducted:

Evaluation of soft tissue response to implanted sutures alone and in combination with Hemoben coating.

Assessment of vascular wall response to metal clips applied alone and with composite coating.

Evaluation of the composite-implant system under infected conditions.

Biocompatibility was assessed using biochemical and morphological methods on days 1, 7, 14, 21, and 30 after implantation.

Infection Model. To induce infection, 1 mL of a microbial suspension containing 2×10^9 microbial bodies of Staphylococcus aureus and Escherichia coli was injected into the wound.

Wound healing was evaluated according to standard clinical criteria: duration of inflammatory phases, resolution of perifocal реакций, nature and amount of exudate, time of wound cleansing, granulation tissue formation, and frequency of suppuration with rejection of polypropylene mesh.

Morphological Analysis. Biopsy samples of soft tissues were fixed in 10% neutral formalin. Paraffin sections (4-5 μm) were prepared and stained with hematoxylin and eosin.

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Microscopy was performed using a DN-300M light microscope (China) equipped with a digital camera. Image analysis and documentation were carried out using ImageJ software (NIH, USA).

Statistical Analysis. Statistical processing was performed using Microsoft Excel 2016 and Statistica 10.0. Differences between groups were assessed using the Student's t-test. Results were considered statistically significant at $p < 0.05$.

Results

The results of the first and second experimental series demonstrated that the combined application of synthetic implants with the composite hemostatic biomaterial was associated with a markedly attenuated inflammatory response. No hematoma formation, tissue necrosis, or signs of foreign-body reaction were observed. The composite coating was completely resorbed by day 7 after implantation without evidence of persistent inflammation or multinucleated giant cell formation.

In the second experimental series, examination of the vascular lumen revealed no thrombotic masses, and no inflammatory changes of the vascular wall were detected, indicating preservation of local microcirculation and the absence of thrombogenic effects.

In the third experimental series conducted under infected conditions, peri-implant tissues initially exhibited pronounced edema and a dense inflammatory infiltrate composed predominantly of lymphocytes, neutrophils, and phagocytically active macrophages. This pattern corresponded to an acute exudative inflammatory response and was more pronounced than that observed under sterile conditions.

Morphometric Analysis. By day 7, inflammatory cell density in the composite-implant group was reduced by 32-38% compared with controls ($p < 0.05$). By day 14, this difference increased to 40-48%, indicating faster resolution of the acute inflammatory phase.

Capsule thickness surrounding the implant was significantly lower in the composite-treated group. By day 21, the thickness of the connective tissue capsule was reduced by approximately 35-45% compared with implants without composite coating ($p < 0.05$).

Microvessel density in peri-implant tissues increased by 1.5-1.8-fold by day 14 in the composite group relative to controls ($p < 0.05$), reflecting enhanced angiogenesis.

The proportion of fibrotic tissue in the peri-implant zone decreased by 30-40% by day 21 in the composite group, correlating with improved collagen organization (fig.1).

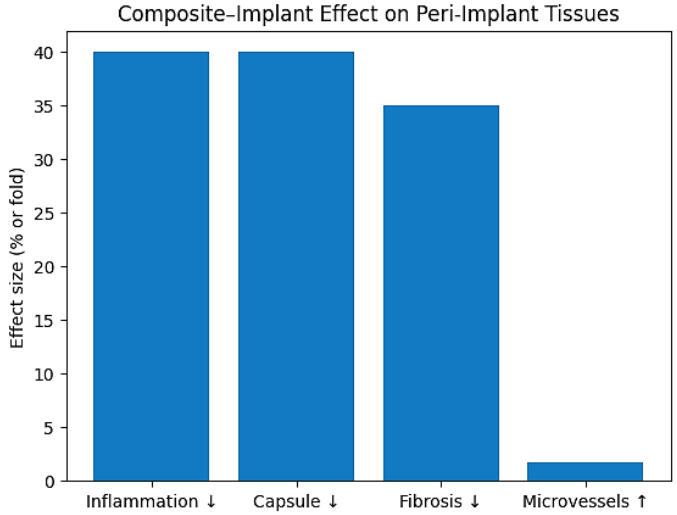

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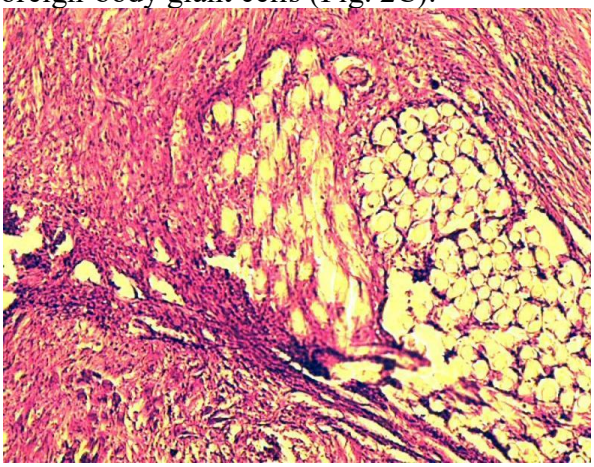
Figure 1. Effect size of the composite–implant system on peri-implant tissue remodeling. The composite coating reduced inflammatory cell density by ~40%, decreased fibrous capsule thickness by ~40%, and reduced fibrotic tissue proportion by ~35%, while increasing microvessel density by ~1.7-fold compared with control implants.

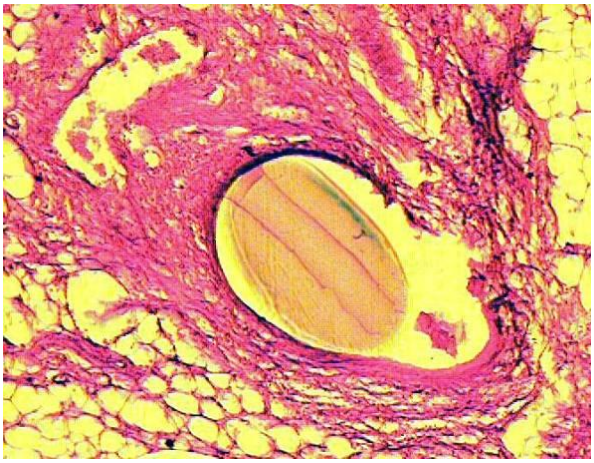
Temporal Morphological Dynamics. By day 7, the implanted filaments were enclosed within a thin connective tissue capsule with loosely organized collagen fibers and mesenchymal proteinaceous material in the interfilament spaces. The surrounding tissue displayed a honeycomb-like structure with focal myxomatous changes (Fig. 2A).

By day 14, inflammatory changes were markedly reduced. The implant was surrounded by thin collagen fibers, while flattened fibroblasts lined the filament surface and macrophages were present between filaments (Fig. 2B).

By day 21, a pronounced proliferative response developed, characterized by a high density of fibroblasts and disorganized thin collagen fibers embedded in an amorphous extracellular matrix. Active angiogenesis was observed. The sutures were enclosed by a circular fibrous capsule containing lymphohistiocytes, macrophages, and multinucleated foreign-body giant cells (Fig. 2C).



(A) Day 7: Thin connective tissue capsule (arrow), loose collagen fibers, honeycomb-like tissue architecture, and focal myxomatous changes.



(B) Day 14: Reduced inflammatory infiltrate, formation of thin collagen fibers, flattened fibroblasts lining the suture surface (arrow), macrophages between filaments.

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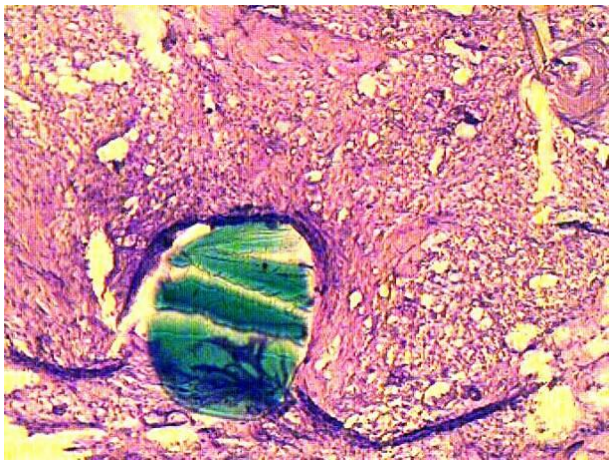

(C) Day 21: Proliferative connective tissue with abundant fibroblasts, immature collagen fibers, newly formed microvessels (arrowheads), and a forming fibrous capsule containing lymphohistiocytes, macrophages, and multinucleated foreign-body giant cells.

Figure 2. Representative histological micrographs of peri-implant tissues at different time points. Staining: Hematoxylin and eosin. Magnification: 10×20.

Discussion

The present experimental study supports the concept that implanted surgical materials should be considered not merely passive mechanical supports, but biologically active interfaces that can shape the wound microenvironment and determine the trajectory of inflammation, tissue remodeling, and long-term integration. This view is consistent with contemporary biomaterials research showing that the local tissue response depends on material chemistry, surface microstructure, and the ability to resist microbial colonization and biofilm formation [1-3,11].

A key finding of our work is the attenuation of acute inflammatory reactions and the more favorable peri-implant remodeling pattern when implants were combined with a composite coating. From a mechanistic perspective, this may be explained by modulation of the early host response-protein adsorption, recruitment of neutrophils/macrophages, and subsequent fibroblast activation-which determines whether repair proceeds toward organized integration or toward chronic inflammation and encapsulation. The importance of early inflammatory control for improving biocompatibility is widely recognized in the context of modern suture and implant technologies [5-9].

Our qualitative histology showed reduced exudation and earlier transition to proliferative remodeling in the composite-implant groups. This aligns with general biomaterials evidence that reducing the magnitude and duration of early inflammation can limit excessive fibrosis and improve connective tissue organization around foreign materials [3,5,12]. Moreover, the observed enhancement of angiogenesis in peri-implant tissues is biologically meaningful, as neovascularization improves oxygen delivery, immune cell function, and matrix remodeling-critical determinants of stable integration [4,9].

Postoperative infections remain among the most clinically significant complications, and the presence of implanted materials provides surfaces for bacterial adhesion and the formation of protective biofilms [1,4,9,11]. This is particularly relevant for

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braided/multifilament structures and porous synthetic materials, where microspaces and capillary effects may facilitate microbial persistence [1]. In this context, strategies aimed at suppressing early exudative inflammation and limiting bacterial colonization are strongly justified.

The infected experimental series in our study demonstrated that the composite-implant combination suppressed the purulent-inflammatory process during the critical early period of days 7-14, promoting subsequent constructive remodeling and integration. Conceptually, this finding parallels the rationale behind antibacterial suture technologies. For example, slow-release antibacterial coating systems and surface engineering approaches have been shown to reduce microbial burden on suture materials and improve local outcomes [1,3,9]. Likewise, nanostructured antibacterial modifications, including silver-based approaches, have demonstrated reductions in inflammation and improved mechanical outcomes in experimental surgical models [7,9-11]. Although the present work focuses on a composite hemostatic coating rather than a classical antibiotic coating, the direction of effect is consistent with the broader biomaterials literature: local modulation of the wound microenvironment and microbial adhesion can significantly alter healing dynamics [1,2].

Another clinically important aspect is the relationship between local hemostasis and tissue integration. Hematoma formation and persistent exudation are well-known contributors to delayed healing and increased infection risk due to nutrient-rich collections and impaired local perfusion. The absence of hematomas and necrosis in the composite-treated groups suggests that early stabilization of the wound bed and reduction of fluid accumulation may represent key contributors to improved integration. In principle, this is consistent with the biomaterials concept that optimizing early wound microenvironment conditions can improve the subsequent phases of connective tissue remodeling and vascularization [1,4,10].

The second experimental series demonstrated absence of thrombotic masses and inflammatory changes in the vascular wall. This observation is clinically relevant because thrombogenicity and vascular wall injury may compromise tissue perfusion and indirectly worsen implant integration. Contemporary biomaterials development increasingly emphasizes not only mechanical properties but also vascular safety and microcirculatory preservation, especially for multifunctional and surface-modified materials [1,3,10,11]. Our findings support the vascular compatibility of the composite approach in the tested model.

The morphometric trends (reduced inflammatory cell density, reduced capsule thickness, enhanced microvessel density, and lower fibrotic proportion) are consistent with a shift from prolonged exudative inflammation to earlier constructive remodeling. Similar endpoints are frequently used in experimental evaluations of advanced suture materials and antibacterial surface engineering, where reduced inflammatory infiltration and improved collagen organization correlate with better functional outcomes [2,8-11]. Importantly, the greatest clinical value of such modulation is expected under infection-prone conditions, where conventional implants may fail due to sustained inflammation and biofilm-associated persistence [1,2,4,9,11].

Several limitations should be acknowledged. First, while histology and morphometry provide strong evidence of biological effects, additional mechanistic readouts (e.g., bacterial load quantification, cytokine profiling, macrophage phenotype markers, or collagen typing) would further strengthen causal interpretation. Second, longer follow-up would be valuable to assess whether early advantages translate into durable, functionally superior integration. Finally, future studies should compare the composite approach directly with established anti-

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infective material strategies (e.g., slow-release antibacterial coatings, nanostructured antibacterial sutures) described in the literature [1-3,9-11] to clarify relative efficacy and translational potential.

Overall, the present findings support the paradigm shift described in modern materials science: implanted materials are evolving from inert mechanical tools toward multifunctional biomedical platforms capable of influencing local inflammatory and regenerative processes [3-8]. In clinical terms, combining composite biomaterials with implants may represent a practical strategy to reduce early inflammatory burden, improve angiogenesis, and enhance integration-particularly in settings characterized by elevated infection risk.

Conclusions

The present experimental study demonstrates that the combined application of the composite polymer Hemoben with surgical implants significantly improves peri-implant tissue responses under both sterile and infected conditions.

The composite-implant system reduced inflammatory cell density by 32-48% during the early stages of wound healing (days 7-14) compared with implants used alone ($p < 0.05$). This reduction was accompanied by a 35-45% decrease in fibrous capsule thickness by day 21, indicating attenuation of the foreign-body reaction and improved tissue integration.

At the same time, microvessel density in peri-implant tissues increased by 1.5-1.8-fold by day 14, reflecting enhanced angiogenesis and improved local microcirculation. The proportion of fibrotic tissue in the peri-implant zone was reduced by 30-40%, corresponding to more organized collagen architecture.

Under infected conditions, the composite-implant approach suppressed purulent-inflammatory processes during the critical early period of wound healing (days 7-14), prevented excessive fibrotic encapsulation, and promoted stable incorporation of the implant.

These data indicate that the composite coating actively modulates the wound microenvironment by limiting excessive inflammation, supporting vascular regeneration, and facilitating constructive connective tissue remodeling. The combined use of composite biomaterials with implants represents a promising strategy for reducing postoperative complications and improving clinical outcomes in minimally invasive surgery.

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