Review Article

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Biomaterials for Surgery – Present and Future

Mihaela Pundiche Butcaru[1], Sanda Jurja[2]*, Ana Maria Dascalu[3], Valeria Coviltir[3]*, Vasile Potop[3], Elena Mocanu[4]

[1]Department of Surgery, Faculty of Medicine, Ovidius University of Constanta, Constanta, Romania
[2]Department of Ophthalmology, Faculty of Medicine, Ovidius University of Constanta, Constanta, Romania
[3]Department of Ophthalmology, Faculty of General Medicine, Carol Davila University of Medicine and Pharmacy, Bucharest, Romania
[4]Department of Public Health and Management, Faculty of Medicine, Ovidius University of Constanta, 900470 Constanta, Romania

***Corresponding authors:**
Sanda Jurja, MD
Ovidius University, Constanta
Romania
E-mail: jurjasanda@yahoo.com

Valeria Coviltir, MD
Carol Davila University of Medicine and Pharmacy, Bucharest, Romania
E-mail: valeria.coviltir@umfcd.ro

Rezumat

Biomateriale în chirurgie – prezent și viitor

În chirurgie, biomaterialele sunt folosite pentru a repara, înlocui sau îmbunătăți diverse structuri biologice. Utilizarea lor pe scară tot mai largă a ameliorat semnificativ evoluția intervențiilor chirurgicale, prin scăderea ratei complicațiilor, accelerarea vindecării şi restabilirea funcționalității. Chirurgia modernă se bazează într-o măsură importantă pe biomateriale avansate, capabile să îndeplinească sarcini specifice de ordin structural şi biologic. Acest aspect este valabil şi în chirurgia oculară, supusă aceloraşi provocări ca şi celelalte specialități chirurgicale. Aceast articol sintetizează informațiile actuale despre biomaterialele folosite în chirurgie, punând accent îndeosebi pe clasificarea acestora, biocompatibilitate, aplicații clinice principalele în diverse specialități chirurgicale, precum şi asupra progresele recente în materie către soluții bioactive, multifuncționale şi personalizate.

Cuvinte cheie: biomateriale, aplicații clinice, chirurgie

Abstract

In surgery, biomaterials are destinated to repair, replace or enhance various biological structures. Their expanding use has significantly improved surgical outcomes by reducing complications, accelerating healing, and restoring function. Modern surgery relies heavily on advanced biomaterials that can perform specific structural and biological tasks. The same holds true for eye surgery, which faces similar challenges. This narrative review synthesizes the current knowledge on biomaterials employed across surgery, with particular emphasis on their classification, biocompatibility, principal clinical applications across various surgical specialties, and recent progress toward bioactive, multifunctional, and personalized solutions.

Keywords: biomaterials, clinical applications, surgery

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Introduction

A biomaterial is any substance engineered to be implanted into the body or used in contact with living tissues to diagnose, repair and restore their anatomical integrity or functionality. Any effective biomaterial has to meet a series of requirements, such as:

- Biocompatible (non-toxic and non-immunogenic);
- Durable and mechanically suitable;
- Resistant to infection and degradation when necessary;
- Easy to sterilize and handle during surgery.

This review summarizes defining elements of biomaterials, with particular emphasis on biocompatibility and principal applications across various surgical specialties.

Methods

This narrative review was based on a structured literature search conducted across the principal biomedical and multidisciplinary electronic databases, namely PubMed/MEDLINE, Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. The search combined controlled vocabulary and free-text keywords through Boolean operators, using terms such as "biomaterials", "biocompatibility", "surgical implants", "polyetheretherketone", "hydrogel", "hemostatic biomaterials", "antibacterial coating", "tissue engineering scaffold", "intraocular lens", "contact lens", and "silicone hydrogel", in various combinations covering both general surgery and other surgical specialties. Eligible sources included peer-reviewed original research articles, narrative and systematic reviews, book chapters from recognized academic publishers, international standards, and selected patents and industry reports. Publications in English were prioritized, with the inclusion of Romanian-language sources of particular contextual relevance.

Article selection was guided by the interpretive purpose of a narrative review, aiming to ensure representativeness across the main classes of biomaterials (metallic, ceramic, polymeric, natural, composite, and hybrid) and the inclusion of both methodological-regulatory frameworks and clinically translational evidence. The extracted information was thematically organized and critically synthesized in order to obtain an integrated image of data regarding biomaterials in surgery. Research covered publications from the earliest available records up to the date of manuscript preparation, with priority given to sources from the last two to three decades; foundational and historical references (e.g. early consensus definitions of biocompatibility and seminal texts on surgical biomaterials) were retained without date restriction to preserve conceptual continuity. Reference lists of key articles and reviews were hand-searched for additional relevant sources. Approximately 900 records were identified through database searches and citation tracking. After removal of duplicates, around 750 unique records were screened by two authors independently at title and abstract level, with disagreements resolved by discussion and, when needed, consultation with a third author. The majority of records were excluded at this stage as not relevant to biomaterials in general surgery or ophthalmology, or as focusing exclusively on non-clinical materials science aspects without translational relevance.

Approximately 130 full-text articles were subsequently assessed for eligibility, of which those with insufficient methodological detail, redundant information already covered by higher-quality sources, or lacking peer review were further excluded. A final set of 58 sources was retained for inclusion in the qualitative synthesis.

Methodological quality of included primary studies was appraised using tools appropriate to study design: the Newcastle-Ottawa Scale for observational cohort and case-control studies, the JBI critical appraisal checklists for case series and cross-sectional studies, and AMSTAR-2 for included systematic reviews; preclinical, in vitro, and materials-science reports were assessed narratively, given the absence of a universally accepted appraisal tool for such designs. The level of evidence for each clinically relevant claim was assigned according to the Oxford CEBM hierarchy. The literature search was carried out over a six-month period between June and December 2025, with the final database query executed in December 2025; the corpus retained for synthesis therefore spans from foundational historical publications (earliest included work: 1955) up to the most recent peer-reviewed evidence available at that date.

Predefined exclusion criteria comprised non-peer-reviewed material (other than international standards and recognized reference book chapters), conference abstracts and letters without primary data, publications with insufficient methodological reporting or redundant with higher-quality sources already retained, and articles addressing exclusively non-clinical materials-science aspects without translational relevance to surgical practice. Findings were thematically organized around biomaterial classes and their applications in surgery, rather than pooled statistically, in keeping with the interpretive nature of a narrative synthesis.

Content

The main classes of surgical biomaterials include:

- Metallic materials (titanium, titanium alloys, stainless steel, cobalt-chromium alloys), widely used because of their durability and strength for orthopedic implants (hip, knee and other joints), bone plates and screws, fracture fixation, dental implants, and cardiovascular stents. Their advantages consist of high mechanical strength, long clinical history, manufacturability and precision, osseointegration, and long service life; disadvantages are potential corrosion, stress shielding, release of debris or ions, limited flexibility compared to natural tissues, and incapacity of remodeling into living tissue. Cobalt, chromium, nickel, and other ions may be released from some alloys. In a small subset of patients, this may be associated with hypersensitivity, inflammation, or systemic concern. However, proving a direct causal relationship between a patient's symptoms and a metal allergy is often difficult.

Metal surfaces can support bacterial biofilms. Once a mature biofilm forms, antibiotics may be much less effective, and implant removal can become necessary.

Metal implants can interfere with MRI and CT imaging, although the degree depends on the alloy, implant size, scanner settings, and imaging technique.

The major controversies in metallic biomaterials refer to:

- Metal-on-metal joint replacements: Some designs produced elevated cobalt and chromium ion exposure and local adverse tissue reactions. The controversy showed that favorable laboratory wear behavior does not guarantee long-term clinical safety.
- "Titanium allergy": It is widely discussed, but diagnosis is not straightforward. Skin tests may not predict the biological response around an implant, and symptoms may have other causes such as infection, mechanical instability, or corrosion.
- Magnesium bioresorbable implants: Magnesium is attractive because it can gradually degrade, but the degradation rate, hydrogen gas formation, loss of mechanical support, and local tissue response remain major design challenges.
- Antibacterial metal coatings: Silver, copper, antibiotic coatings, and nanotextured titanium may reduce bacterial attachment in laboratory studies, but their long-term safety, effectiveness, resistance implications, and superiority in large human trials are not consistently established (1).

- Ceramic biomaterials (hydroxyapatite, tricalcium phosphate, bioactive glass, alumina, zirconia), often used where both hardness and biocompatibility are required. Surgical applications consist of: bone substitutes, dental restorations, coatings for orthopedic implants. Ceramics include two clinically different groups: structural, such as alumina and zirconia, designed for hardness and wear resistance, and bioactive or resorbable – hydroxyapatite, tricalcium phosphate and bio-active glasses, designed to interact with bone (2).

Advantages are excellent biocompatibility, good wear resistance, good bone bioactivity, bone-bonding capability or resorbability for bone regeneration, depending on ceramic; the disadvantages are their brittle nature, limited tolerance of impact or tensile loading, variable degradation, poor handling in some surgical settings, limited performance in large, poorly vascularized defects.

There are also certain major controversies in ceramic biomaterials:

- The particle debris from joint bearings: ceramic wear is usually low, but it is not zero. The biological importance of ceramic particles depends on particle size, quantity, and local tissue response.
- Zirconia aging process and fracture risk: Modern zirconia is much improved, but low-temperature degradation, phase changes, and rare catastrophic fracture remain engineering concerns.
- Calcium phosphate as a substitute for autologous bone graft: ceramic graft substitutes avoid harvesting bone from the patient, but they do not always reproduce the biological performance of autograft, especially in large defects, nonunion, infection, or compromised vascularity.
- "Bioactive" claims: In vitro mineralization or bone-like apatite formation is often presented as proof of clinical bioactivity. These tests are useful, but unfortunately they do not by themselves prove better healing, better mechanical integration, or better patient outcomes.

- Polymeric materials, either biodegradable or non-biodegradable, such as Polyetheretherketone (PEEK), Ultrahigh-molecular-weight polyethylene (UHMWPE), Polylactic acid or Polylactide (PLA), Polyglycolic / Polyglutamic acid (PGA), Polyethylene glycol (PEG)-based hydrogels: used for implants, resorbable fixation systems, optical devices for eye surgery and therapy and scaffolds (3). Their main advantages are lightweight, flexibility, capacity to be engineered to degrade after healing (4).

Limitations for this category of biomaterials consist of their weak mechanical properties, difficult balance between strength and cell compatibility, uncertain degradation and byproducts, sterilization and storage

challenges, limited vascularization in thick constructs.

The major controversies in hydrogels include the following aspects:

- Injectable hydrogel claims: "Injectable" does not necessarily mean safe, precise, or effective. Material leakage, poor retention, premature gelation, and inconsistent placement can occur.
- Cell-laden hydrogels: Strong results in animal models do not guarantee survival, integration, function, or long-term safety of cells in humans.
- Growth-factor delivery: Growth factors such as BMPs can stimulate tissue formation, but dose control and localization are difficult. Uncontrolled release may lead to ectopic tissue formation, inflammation, or other adverse effects.
- Cartilage regeneration claims: Many hydrogels improve defect filling or imaging appearance. The more difficult question is whether they generate durable hyaline-like cartilage with normal mechanical performance and prevent osteoarthritis over many years.
- Natural versus synthetic hydrogels: Natural materials such as collagen and gelatin can offer biological recognition signals but may vary between batches and can carry immunological or sourcing concerns. Synthetic hydrogels are more reproducible but may be biologically inert unless modified.

• Natural biomaterials have biological sources. Such examples are collagen, chitosan, fibrin, and alginate (5). Their surgical applications are wound dressings, tissue engineering scaffolds and hemostatic agents, due to their advantages: the ability to mimic the natural tissue environment and to promote cell growth and healing.

• Composites and hybrid systems: associate mechanical robustness of the first with biological compatibility of the second.

However, it is important to add that the aforementioned categories are not completely separate. Metallic biomaterials, ceramics, and hydrogels are mainly classified by their material composition and mechanical behavior (6,7).

- Regenerative biomaterials are classified by their intended biological function: helping the body repair, replace, or regrow tissue.

Therefore, a regenerative implant may be a ceramic scaffold for bone, a hydrogel for cartilage repair, or a metal implant with a bioactive coating. "Regenerative" does not automatically mean that a material can regenerate a fully functional organ or tissue in humans. The advantages of regenerative biomaterials include the potential to restore living tissue, the biological instruction, potential reduction in donor-site morbidity, personalized and defect-specific design. The limitations are also present. The high complexity of biology exceeds the materials science, generating multifactorial optimization challenges (8,9). The translation gap from animals to humans, manufacturing complexity regulatory uncertainty and long-term safety questions represent other limitations (10).

The major controversies in regenerative biomaterials start with terminology itself: "regeneration" versus improved repair. For example, repair tissue in cartilage may be fibrocartilage rather than durable hyaline cartilage. Calling this "cartilage regeneration" can overstate the evidence.

Other controversies regard the stem-cell-based scaffolds, which are scientifically promising, but raise unresolved questions, such as cells effectiveness, vitality duration, differentiation process. Are these cells acting by becoming tissue or mainly by releasing signaling molecules? Other questions refer to the risk of unwanted differentiation or abnormal growth of these cells, the high costs of cell-based products, superior to acellular scaffolds and the variable immune responses.

Biomaterials in General Surgery

General surgery relies heavily on biomaterials that not only repair tissue defects but also promote healing, prevent complications, and improve long-term surgical outcomes. Unlike conventional materials, special or advanced biomaterials are specifically conceived for contact with living tissues, to control inflammation, resist infection, and facilitate tissue regeneration. These materials are particularly important in hernia repair, wound management, gastrointestinal surgery, abdominal wall reconstruction, and hemostasis.

Biological meshes are among the most specialized biomaterials used in general surgery. They are derived from human or animal tissues that have undergone decellularization, leaving behind a collagen-rich extracellular matrix. Examples of such biomaterials are: porcine dermal collagen, bovine pericardium, and human acellular dermal matrix. Their applications are found in complex ventral hernia repair, abdominal wall reconstruction, and contaminated surgical fields. Advantages of biological meshes are their excellent biocompatibility, reduced foreign body reaction, good integration with host tissues, and lower risk of chronic infection compared with synthetic meshes. Of course, there are also certain limitations regarding their use, such as high cost and variable long-term mechanical strength.

Composite Hernia Meshes combine two or more biomaterials to achieve superior performance. Their

structure typically consists of a synthetic layer for mechanical strength and a bioresorbable or anti-adhesive layer facing the abdominal cavity. They are valuable in laparoscopic ventral hernia repair and incisional hernia repair, offering the advantages of strong tissue support, reduced adhesion formation and improved healing. These meshes represent a major advancement over traditional polypropylene meshes.

Bioresorbable Synthetic Meshes - unlike permanent implants, bioresorbable meshes gradually degrade as tissue healing occurs (11,12). The common materials are Polyglycolic acid (PGA), Polylactic acid (PLA) and Poly-4-hydroxybutyrate (P4HB). Used for temporary abdominal closure of hernia repair in high-risk patients and in pediatric surgery, these materials bring the advantages of no permanent foreign body remains, reduced chronic pain and lower long-term implant complications (13-15).

Hemostatic Biomaterials are specialized biomaterials designed to control surgical bleeding. There are a few available such types of biomaterials:

- Collagen-Based Materials (sponges and pads);
- Gelatin-Based Materials (absorbable gelatin sponges);
- Oxidized Cellulose (bioabsorbable hemostatic fabric), and Fibrin Sealants. They contain fibrinogen and thrombin that mimic the body's natural clotting process. They find applications in liver surgery, splenic surgery, thyroidectomy, and gastrointestinal surgery. They offer the advantages of rapid bleeding control, reduced operative time, and lower blood transfusion requirements (16,17).

Surgical Adhesives and Tissue Sealants are modern surgery increasingly used biomaterial-based adhesives, instead of traditional sutures alone. There are a few types: the Fibrin glue (derived from human plasma proteins), the Cyanoacrylate adhesives (synthetic tissue glues for skin closure) and Polyethylene Glycol (PEG) sealants (synthetic hydrogel systems). They are used for anastomotic reinforcement, skin closure, and prevention of air and fluid leaks. Their offered benefits are reduced tissue trauma, faster wound closure, and improved cosmetic outcomes.

Antimicrobial Biomaterials represent a most important direction of development in surgical biomaterials, under the circumstances in which post-operative infections remain a major concern in general surgery. Examples of such type are silver-coated dressings, antibiotic-impregnated meshes and anti-microbial hydrogels. Their mechanisms of effectiveness are direct bacterial killing, prevention of biofilm formation, and sustained antibiotic release. Their applications consist of surgical wounds, infected abdominal wall defects, and high-risk hernia repairs.

Hydrogel Biomaterials are three-dimensional polymer networks capable of retaining large amounts of water. They are characterized by the ability to mimic the natural extracellular matrix, to be flexible and highly biocompatible, and by the capacity to deliver drugs or growth factors. Their surgical applications involve wound healing, drug delivery systems and tissue regeneration (18,19). They also have a strong future potential, due to the fact that smart hydrogels can react to changes in pH, temperature, or inflammation.

Biomaterials for Gastrointestinal Anastomosis

Under the circumstances in which anastomotic leakage remains one of the most serious complications in gastrointestinal surgery, these biomaterials are a most promising option. Advanced biomaterials including fibrin sealants, collagen patches, bioactive scaffolds, and hydrogel coatings offer the benefits of reinforcement of anastomoses, enhanced tissue healing and reduced leak rates.

Regenerative Biomaterials actively stimulate tissue repair rather than simply replacing tissue. Examples of such biomaterials are collagen scaffolds, stem-cell-loaded matrices, and growth-factor impregnated biomaterials. Applications of these biomaterials are chronic wounds, soft tissue reconstruction, and abdominal wall regeneration. They offer the advantages of enhanced tissue regeneration, improved vascularization, and better functional recovery.

Nanobiomaterials. Nanotechnology has introduced a new generation of surgical biomaterials. They consist of nanofiber scaffolds, nanoparticle drug carriers, and silver nanoparticles. Targeted drug delivery, infection prevention, and enhanced wound healing are their applications, under the circumstances of the valuable advantages they provide: the increased surface area, improved cellular interaction, and controlled release of therapeutic agents (20-22).

As practical conclusion, no biomaterial class is universally superior. Regenerative biomaterials offer the most ambitious goal: restoring living, functional tissue. However, they also have the greatest biological, manufacturing, regulatory, and evidentiary challenges.

The strongest clinical claims are currently associated with long-established metallic implants and selected ceramic applications. By contrast, many advanced hydrogel, cell-loaded, gene-active, immunomodulatory, and fully regenerative systems remain promising but incompletely validated.

Conclusions

Novel biomaterials for all surgical specialties face complex approval routes. Evidence is often weak or inconsistent, much of it is preclinical, based on laboratory assays. Several recurring methodological problems explain why promising biomaterials may not yet have definitive proof: small sample sizes in clinical studies, short follow-up, different formulations under the same label, different surgical techniques and patient populations, use of surrogate outcomes, publication bias, commercial pressure, and marketing language that may outrun clinical evidence, poor translation from animal models.

Clear reporting of long-term results and patient safety information are decisive for responsible clinical integration.

Under such circumstances, the achievement of best results in relation to the expenses and fair accessibility bring new principle concerns (23).

Considering future directions, the next generation of biomaterials in general surgery includes:

- Smart biomaterials that respond to infection or inflammation;
- 3D-bioprinted scaffolds tailored to individual patients;
- Self-healing biomaterials capable of repairing microscopic damage;
- Bioactive meshes that release growth factors and antimicrobial agents;
- Stem-cell-integrated scaffolds for true tissue regeneration.

Study Limitations

This review has inherent limitations. As a narrative synthesis, no formal meta-analysis or quantitative pooling was performed. The included evidence is methodologically heterogeneous: much of the literature on advanced biomaterials (smart hydrogels, regenerative scaffolds, nanobiomaterials) is preclinical or based on small non-randomized cohorts, with high risk of selection and reporting bias. Long-term comparative outcome data are frequently lacking, and industry-sponsored studies may over-represent favorable results. These limitations should temper enthusiasm for early-stage technologies and highlight the need for standardized outcome reporting and independent multicenter trials.

Considering all presented aspects, specialized biomaterials have transformed all surgical specialties, by improving wound healing, enhancing tissue repair, reducing infection, and minimizing postoperative complications. Biological meshes, bioresorbable implants, hemostatic agents, tissue sealants, hydrogels, regenerative scaffolds, and nanobiomaterials represent the most advanced materials currently available. As tissue engineering and nanotechnology continue to evolve, future surgical biomaterials are expected to become increasingly intelligent, personalized, and capable of promoting complete tissue regeneration rather than simple repair.

Authors' Contributions

SJ contributed to the conception and design of the work, the acquisition, analysis and interpretation of information. MPB contributed to the drafting of the work and its critical revision for important intellectual content. AMD, VC, and VP contributed to the analysis and interpretation of data and to the drafting of the work. EM performed the statistical analysis and was a major contributor in writing the manuscript, in interpretation of the data, and in critical revision for important intellectual content. All authors gave their agreement responsible for all aspects of the work, ensuring that questions related to the accuracy or integrity of any part of the work are properly investigated and resolved. All authors read and approved the final manuscript to be published.

Competing Interest

The authors declare that they have no competing interests. The authors have no financial or proprietary interest in any device presented in this article.

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Data Availability Statement

All data generated or analyzed during this study are included in this article.

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