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BIOMATERIALS IN OPHTHALMOLOGY: CURRENT APPLICATIONS AND FUTURE PERSPECTIVES IN EYE SURGERY

Doina MOALEȘ [1,2], Irinel LUNGU [3,*]

[1] „Dimitrie Cantemir" University, Faculty of Medicine, Târgu Mureș, România
[2] Bacau County Emergency Hospital
[3] Faculty of Medicine and Pharmacy, "Dunarea de Jos" University, Galati, Romania

Abstract

Biomaterials play a key role in ophthalmology, providing innovative solutions for eye surgery and regenerative treatments. The development of biocompatible materials, including flexible polymers, hydrogels, and nanobiomaterials, has enabled improvements in surgical outcomes and a reduction in postoperative complications. In corneal surgery, keratoprostheses and amniotic membrane have revolutionized treatments for severe injuries, while advanced artificial lens has optimized cataract surgery. Drainage devices for glaucoma, injectable hydrogels for vitreous body replacement, and controlled drug delivery systems contribute to more effective and personalized therapies. Despite significant advances, biomaterials present challenges, including high costs, risks of complications, and limitations in complete tissue regeneration. Future research focuses on intelligent biomaterials capable of responding to biological stimuli and promoting the regeneration of ocular structures. The integration of nanotechnology and artificial intelligence could optimize the personalization of treatments and their accessibility. Thus, biomaterials represent an essential component of progress in ophthalmology, with promising prospects in the development of minimally invasive and effective solutions for complex eye conditions..
Keywords: Biomaterials, ophthalmology, eye surgery, nanotechnology, tissue regeneration, controlled release, artificial lens.

Introduction

Biomaterials are an essential component of modern medicine, being used to replace, repair, or regenerate damaged tissues and organs. In ophthalmology, the development of biomaterials has had a significant impact on surgical treatments, offering innovative solutions for eye conditions that, in the past, were difficult to manage. From synthetic materials for intraocular implants to bioengineered structures for corneal regeneration, biomaterials contribute to improving patients' prognosis and quality of life.

Eye surgery imposes strict requirements on the biocompatibility, transparency, and strength of the materials used. The eyes are delicate structures, and any intervention on them must minimize the risk of inflammation, infection, or rejection. Therefore, biomaterials intended for ophthalmology must be perfectly integrated into the ocular environment, without inducing immunological reactions or toxicity. Their development has been possible thanks to progress in the field of biocompatible polymers, nanotechnology, and tissue engineering, which have allowed the creation of materials adapted to the needs of each eye segment [1-3].

Corresponding author: lun_iri@yahoo.com

In corneal surgery, biomaterials have revolutionized treatments for conditions such as keratoconus or severe lesions of the corneal epithelium. Keratoprostheses, made of synthetic or biocomposite materials, offer a viable alternative for patients for whom classic corneal transplantation is not an option. In addition, the use of the amniotic membrane, a natural biomaterial with regenerative properties, has become standard practice for ocular reconstruction. It promotes healing and reduces inflammation, being used in cases of corneal ulcers, chemical burns, or recurrent pterygium [2-4].

In cataract surgery, biomaterials have allowed the development of an artificial lens (IOL – intraocular lens), an implant that replaces the opaque natural lens. Originally made of PMMA (polymethylmethacrylate), modern intraocular lenses are made of flexible materials, such as silicone or hydrophilic acrylate, which allow implantation through small incisions, thus reducing surgical trauma and speeding up recovery. In addition, some IOLs are coated with biomimetic layers that prevent the formation of capsular opacity, a common postoperative complication [2-5].

Glaucoma, an eye disease that affects the optic nerve and can lead to blindness, has benefited from significant advances thanks to the biomaterials used in drainage devices. They regulate intraocular pressure by facilitating the elimination of watery humor, thus preventing progressive deterioration of vision. The materials used must be biocompatible and resist fibrosis that can obstruct drainage. Among the most widely used are polydimethylsiloxane (PDMS), a type of inert silicone, and hydrogelic polymers that can be adapted for the controlled release of antiglaucomatous drugs [4,5].

Vitreoretinal surgery has also been improved by the use of biomaterials, especially silicone oils and special gases, which stabilize the retina after detachment. In addition, the development of injectable hydrogels, capable of gelling in situ, offers a promising alternative for the treatment of macular degeneration and other retinal conditions. These biomaterials may contain growth factors or controlled-release drugs, thus helping to protect and regenerate retinal tissue [5-10].

Currently, biomaterials are also used in the regeneration of eye tissues through tissue engineering. Scaffolds (matrices) made of collagen, biodegradable polymers, or nanofibers serve as a support for the growth of epithelial cells, fibroblasts, or even stem cells, opening up new possibilities for the restoration of the damaged cornea or retina. These technologies, still in the experimental phase, could revolutionize ophthalmological treatments, offering personalized solutions based on regenerative medicine [3,4].

Despite significant advances, the use of biomaterials in ophthalmology is not without its challenges. One of the main limitations is the risk of rejection or chronic inflammation, which can compromise the success of the intervention. In addition, the high costs of advanced biomaterials limit access to these technologies in many regions of the world. Also, the integration of biomaterials with native tissues remains a challenge, especially in the case of complex structures such as the retina [10-13].

In the future, research focuses on the development of smart biomaterials capable of responding to eye stimuli and releasing drugs in a controlled manner. Nanotechnology plays a key role in this process, enabling the creation of multifunctional biomaterials that not only replace damaged structures but also support cell regeneration. Also, the integration of artificial intelligence into the design of biomaterials could facilitate the identification of the most effective combinations of materials for each patient [13].

Biomaterials are an essential field in ophthalmology, with various applications in eye surgery. From corneal prostheses and artificial lenses to drainage devices and regenerative therapies, biomaterials have transformed the way ophthalmological conditions are treated. Although there are still challenges related to biocompatibility and accessibility, technological advances continue to improve their performance, opening up new prospects for treating complex eye diseases [13-16].

Current Applications of Biomaterials in Eye Surgery

The use of biomaterials in ophthalmology has revolutionized surgical treatments, offering innovative solutions for eye conditions that previously had an unfavorable prognosis. Due to advances in materials engineering, biomaterials are now essential in corneal surgery, cataracts, glaucoma, and vitreoretinal pathologies [2-4].

Table 1. This table provides an overview of ophthalmic biomaterials, detailing their applications, advantages, and challenges. Biocompatible polymers are widely used in intraocular implants, while hydrogels enhance corneal repair. Ceramic materials aid orbital reconstruction, nano-biomaterials improve drug delivery, and smart biomaterials enable real-time monitoring and adaptive therapeutic responses [1-4,8-16].

Biomaterial type	Ophthalmic applications	Advantages	Challenges
Biocompatible polymers	Intraocular lenses, glaucoma drainage devices, keratoprostheses	High biocompatibility, durability, and flexibility	Fibrosis risk, long-term stability concerns
Hydrogels	Corneal repair, vitreous substitutes, drug delivery systems	Hydration properties, transparency, and drug delivery capability	Limited mechanical strength, potential for degradation
Ceramic materials	Orbital implants, corneal scaffolds, and bone integration	Mechanical strength, biointegration, osteoconductivity	Brittleness, complex manufacturing processes
Nano-biomaterials	Antimicrobial coatings, drug-loaded nanoparticles, and regenerative medicine	Enhanced drug bioavailability, antimicrobial properties, and improved cell adhesion	High production costs, regulatory barriers
Smart biomaterials	Stimuli-responsive implants, biosensors, personalized treatments	Adaptive responses, real-time monitoring, optimized therapeutic outcomes	Complex implementation, high research and development costs

Biomaterials used in corneal surgery

The cornea is constantly exposed to external aggressions, and severe damage or progressive degeneration requires surgery to restore vision. Keratoprostheses are synthetic implants used when corneal transplantation is not a viable option. They are made of polymethyl methacrylate (PMMA) or advanced hydrogels, having the advantage of good integration into the ocular structure. Another important biomaterial is the amniotic membrane, used for ocular reconstruction due to its anti-inflammatory and regenerative properties. It is applied in the treatment of corneal ulcers, pterygium, and severe keratitis, accelerating healing and preventing complications [8-12].

Biomaterials used in cataract and refractive surgery

Replacing the opaque natural lens with a synthetic implant is the standard of therapy in cataract surgery. Originally made of PMMA, modern artificial lens (IOL - intraocular lens) is made of silicone, hydrophilic or hydrophobic acrylate, materials that allow implantation through small incisions and reduce postoperative complications. Some IOLs are coated with biomimetic layers to prevent secondary capsular opacity. In refractive surgery, biomaterials are used in fakične lenses and customized implants for the correction of myopia, farsightedness, and astigmatism. Flexible and biocompatible polymers allow these lenses to be adapted to the ocular structure, ensuring superior visual results [13-16].

Biomaterials in Glaucoma Surgery

Glaucoma is a condition characterized by increased intraocular pressure, which leads to damage to the optic nerve. In cases resistant to drug treatment, surgery is necessary to facilitate the drainage of the aqueous humor. Drainage devices, such as Ahmed or Baerveldt shunts, are made of biocompatible materials such as polydimethylsiloxane (PDMS) or fluoropolymers. These devices prevent fibrosis and ensure constant drainage of intraocular fluid. Biodegradable hydrogels are also used for the controlled release of antiglaucomatous drugs, reducing dependence on topical treatment and preventing disease progression [6,14-16].

Biomaterials used in vitreoretinal surgery

Retinal pathologies, such as retinal detachment and macular degeneration, require advanced surgical solutions to prevent vision loss. Silicone oils and special gases, such as sulfur hexafluoride or perfluoropropane, are used to stabilize the retina during surgery. These biomaterials allow the retina to be fixed and adequate intraocular pressure to be maintained until complete healing [16-22].

Injectable hydrogels are a recent innovation, being used as substitutes for the vitreous body or as controlled drug delivery systems for the treatment of chronic retinal diseases. These hydrogels may contain growth factors and nanoparticles with regenerative properties, contributing to the protection and regeneration of retinal tissue. Also, cell matrices made from collagen or biodegradable polymers are used to support retinal and choroid regeneration in cell therapy and stem cell transplants [13-16].

Types of biomaterials used and their properties

The development of biomaterials for eye surgery was driven by the need for biocompatible, transparent, mechanically and chemically stable materials, capable of predictably interacting with sensitive ocular structures. In ophthalmology, biomaterials are used for corneal implants, artificial lenses, glaucomatous drainage devices, vitreous substitutes, and controlled drug delivery systems. These include polymers, hydrogels, ceramic materials, nanobiomaterials, and smart biomaterials, each category having properties tailored to specific clinical applications [7,13].

Polymers are the most widely used class of ophthalmological biomaterials due to their structural versatility, biocompatibility, and functionalization. Polymethyl methacrylate (PMMA) was the first material used in intraocular lenses, providing optical stability and excellent durability, but its rigidity required wide surgical incisions and an increased risk of tissue trauma [2,13].

Modern materials, such as medical silicone and hydrophilic or hydrophobic acrylates, have allowed the development of foldable intraocular lenses, which can be implanted through self-sealing microincisions. These materials reduce postoperative inflammation, accelerate visual recovery, and improve patient comfort [1,3].

Polydimethylsiloxane (PDMS) is extensively used in drainage devices for glaucoma and silicone oils in vitreoretinal surgery, due to its chemical inertia and long-term stability, which minimizes inflammatory and fibrotic reactions [6,17]. Biodegradable polymers, such as polylactic acid (PLA) and its copolymers (PLGA), are used in cell matrices and controlled drug delivery systems, facilitating tissue regeneration and reducing the need for frequent topical administration [19,21].

Hydrogels are hydrophilic polymer networks capable of retaining large amounts of water, having biomechanical properties similar to eye tissues. In ophthalmology, they are used in therapeutic contact lenses, corneal patches, tear substitutes, and controlled drug delivery systems [8,13].

Hydrogels based on sodium hyaluronate, collagen, or gelatin are used to maintain hydration of the cornea, protect the epithelium, and accelerate the healing of eye injuries [5,11].

An important application is represented by the use of injectable hydrogels as substitutes for the vitreous body, where they provide mechanical support to the retina and reduce the risk of post-vitrectomy detachment [14,15].

The combination of hydrogels with nanoparticles allows for the controlled release of growth factors or anti-inflammatory agents, contributing to retinal regeneration and slowing the progression of degenerative diseases [10,16].

Ceramic materials, such as calcium phosphate and hydroxyapatite, are used in eye implants for patients with anophthalmia. These biomaterials exhibit high biocompatibility and porous structure, favoring vascular integration and reducing the risk of implant migration or rejection [9].

Due to their rigidity and stability, ceramic materials are mainly used as a structural support and not in applications that require flexibility or optical transparency [7].

Composite materials combine polymers with ceramic or metal nanoparticles to improve mechanical, optical, and biological properties. For example, the integration of titanium or silver oxide nanoparticles into ophthalmological biomaterials confers antimicrobial and antifibrotic properties, reducing the risk of postoperative infections and opacity of the posterior capsule [11,12].

These materials are investigated for use in advanced intraocular lenses, corneal patches, and multifunctional implantable systems [7,10].

Nanotechnology has significantly expanded the potential of ophthalmological biomaterials through the development of structures with controlled dimensions and advanced biological functionality. Gold and silver nanoparticles are used for their antimicrobial and anti-inflammatory properties, being integrated into contact lenses and corneal dressings for infection prevention [11,17].

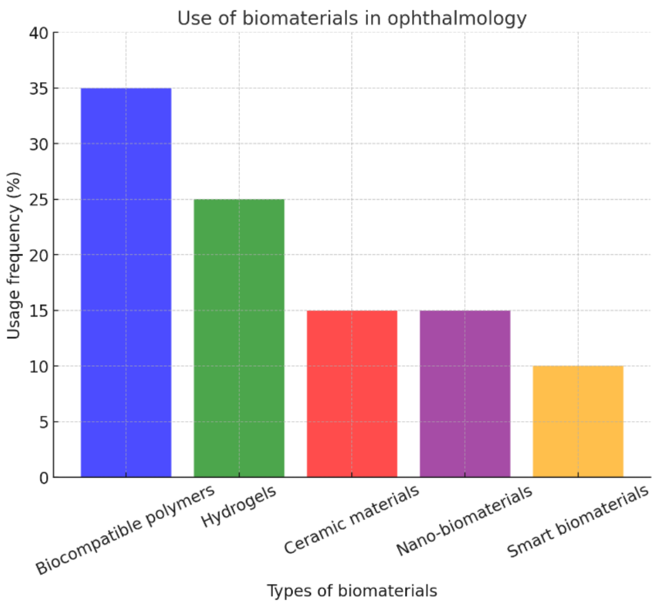

Figure 1. This chart illustrates the usage frequency of different biomaterials in ophthalmology. Biocompatible polymers lead in application, followed by hydrogels, ceramic materials, nano-biomaterials, and smart biomaterials. These materials enhance surgical outcomes, ensuring better biocompatibility, controlled drug release, and improved regenerative potential in ocular treatments.

Nano-hydrogels allow the controlled and targeted release of drugs in the treatment of glaucoma, uveitis, and retinal diseases, increasing therapeutic efficacy and reducing systemic adverse effects [10,21]. Carbon nanotubes and graphene are experimentally evaluated for retinal regeneration, due to electrical conductivity, which can facilitate neuronal communication between retinal cells and the optic nerve [16].

An emerging field is smart biomaterials, capable of responding to biological stimuli such as pH, temperature, or glucose concentration in the aqueous humor. Temperature-sensitive hydrogels alter their physical state depending on temperature, being used for injectable implants with controlled drug release [10,22].

These systems reduce the need for repeated intraocular injections and open up new perspectives for the treatment of chronic eye diseases such as glaucoma and macular degeneration [14–16].

A promising example is the use of shape-memory polymeric biomaterials, capable of modifying their conformation according to local physicochemical stimuli, allowing the dynamic regulation of drainage flow and intraocular pressure in glaucoma. These materials provide more precise control of intraocular pressure and may reduce the risk of hypotonia or peridrainage fibrosis [10,21]. Also, smart bioelectric implants, integrated with micro-sensors, allow real-time monitoring of eye parameters (intraocular pressure, inflammation, metabolic status) and automatic adjustment of drug delivery according to the individual needs of the patient. This personalized approach opens up new perspectives in the management of chronic eye diseases, especially glaucoma and retinal diseases, by increasing therapeutic efficiency and reducing repeated interventions [16,22].

Advantages and disadvantages of using biomaterials in ophthalmology

The use of biomaterials in eye surgery has led to major advances in the management of ophthalmological conditions, allowing the development of effective therapeutic solutions to restore visual function and improve patients' quality of life. Their integration into clinical practice has been facilitated by advances in materials science, nanotechnology, and bioengineering. However, biomaterials have both significant benefits and limitations that influence clinical indications and outcomes [7,9].

Advantages of biomaterials in ophthalmology

A fundamental advantage of modern biomaterials is their increased biocompatibility, which reduces the risk of inflammation, foreign body reactions, and ocular toxicity. Polymers commonly used in ophthalmology, such as hydrophilic acrylates, medical silicone, or fluorinated polymers, are well tolerated by ocular structures and provide long-term stability [1,3,13]. Hydrogels and bioactive materials additionally contribute to the protection of the corneal epithelium and the stimulation of tissue regeneration processes [8,15].

Modern artificial lenses, made of flexible materials and with optimized refractive index, allow the restoration of visual function after cataract surgery, with a reduction in dependence on postoperative optical correction [2]. Also, synthetic corneal implants and keratoprostheses are viable alternatives in cases of severe corneal opacities or corneal transplant failure, where biological grafts are not feasible [9,11]. In refractive surgery, the biomaterials used in fakične intraocular lenses and intracorneal rings allow stable corrections of ametropia, with predictable results [4].

Advances in 3D printing and nanotechnology have allowed the development of personalized biomaterials, adapted to the anatomical and pathological particularities of each patient. Bioengineered corneal implants and drainage devices for glaucoma are designed to minimize periprocedural fibrosis and improve tissue integration [7,16]. In addition, smart biomaterials, capable of controlled release of active substances, reduce the need for repeated administration of topical or injectable treatments [10,21].

The use of soft and foldable biomaterials has facilitated the development of minimally invasive surgical techniques, with the reduction of surgical trauma and the acceleration of visual recovery. Foldable artificial lenses can be implanted through self-sealing, sutureless microincisions, and modern glaucomatous drainage devices made of biocompatible polymers decrease the rate of resurgeries [3,6].

Disadvantages and limitations of biomaterials in ophthalmology

A major limitation of the use of ophthalmological biomaterials is the high costs associated with state-of-the-art technologies. Premium artificial lenses, keratoprostheses, and controlled drug delivery systems are inaccessible to a significant part of patients, especially in health systems with limited resources [2,5]. In addition, the implementation of these solutions requires advanced infrastructure and specialized medical personnel, restricting their use to reference eye centers [6].

Although biomaterials are designed for optimal biological tolerance, specific complications can occur. Intraocular lenses can cause opacity of the posterior capsule, requiring YAG laser capsulotomy [2]. Synthetic corneal implants are associated with an increased risk of infection, extrusion, or chronic inflammation, and drainage devices for glaucoma may be compromised by fibrotic obstruction [6,9].

Despite advances in the field of regenerative biomaterials, they cannot fully reproduce the structure and function of native tissues. Bioartificial corneal substitutes still raise issues related to long-term transparency and mechanical stability [9]. In retinal surgery, injectable hydrogels and cell carriers cannot completely replace the functional complexity of the retina, limiting therapeutic efficacy in conditions such as macular degeneration [14–16].

Another significant obstacle is the rigorous regulatory and clinical validation process. Biomaterials need to go through extensive in vitro, ex vivo, and in vivo testing stages to demonstrate safety and efficacy, which entails high costs and long development times [18–20]. As a result, patients' access to innovative biomaterials may be delayed, despite promising results achieved in preclinical studies [7,22].

Conclusion

The use of biomaterials in ophthalmology has revolutionized eye surgery, providing innovative solutions for treating conditions that, in the past, had limited treatment options. From the artificial lens used in cataract surgery to corneal implants, drainage devices for glaucoma, and biomaterials for retinal regeneration, technological advances have significantly improved patients' prognosis.

One of the biggest advantages of biomaterials is their biocompatibility, which allows harmonious integration into eye structures and reduces the risk of side effects. Modern materials, such as flexible polymers, hydrogels, and nanobiomaterials, have enabled the development of minimally invasive solutions that accelerate recovery and improve visual function. In addition, the integration of nanotechnology and controlled drug delivery systems has opened up new possibilities for more effective and personalised treatments.

However, biomaterials are not without their challenges. The high costs of advanced devices and implants limit the accessibility of these technologies for all patients. Also, postoperative risks, such as fibrosis, infections, or rejection of implants, remain a problem in some cases. In addition, complete tissue regeneration is still difficult to achieve, and existing biomaterials cannot perfectly reproduce the natural structures and functions of the eye.

Prospects in ophthalmology include the development of smart biomaterials capable of reacting to biological stimuli and providing personalized treatments. Research focuses on the use of bioactive stem cells and scaffolds for corneal and retinal regeneration, as well as ocular implants that monitor and regulate ocular parameters in real time. In addition, integrating artificial intelligence into the design and customization of biomaterials could further improve their efficiency.

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