SYSTEMATIC REVIEW

Recent Advancements in Contact Lens Technology: A Systematic Review of Therapeutic, Smart, and Biomaterial Innovations

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Abstract

From having passive refractive devices, contact lenses have evolved into complex, multipurpose biological platforms intended for the management of chronic ocular diseases, real-time bio sensing, and sustained ocular medication administration [2.5, 2.9]. Multidisciplinary advances in nanotechnology, bio materials engineering, and flexible wearable electronics are driving this transformation, greatly expanding the devices' therapeutic and diagnostic potential [2.2, 2.10]. In order to assess advancements in therapeutic lenses, biodegradable delivery systems, nanomaterial-integrated platforms, and smart bio sensing technologies, this systematic review synthesized data from twenty-two significant review-based articles in accordance with PRISMA criteria [11, 22]. Important discoveries include the creation of biodegradable polymer matrices for glaucoma treatment, antibiotic-eluting lenses for infectious keratitis, and electrospun fiber reservoirs for high-capacity drug loading.[2.2, 5.3].

Additionally, the combination of MXene and graphene has made it possible to monitor intra ocular pressure and tear glucose on very sensitive, transparent platforms with bio availability benefits 10 times greater than topical administration [2.5, 4.4]. The adaptability of these systems in pediatric eye care is further demonstrated by the clinical validation of multi focal soft lenses for myopia treatment [9, 2.6]. Although the shift to integrated, closed-loop theranostic devices is well under way, the main obstacles to widespread pharmaceutical adoption in 2026 continue to be long-term ocular bio compatibility, regulatory harmonization for combination products, and the requirement for extensive clinical trials.[2.6, 6.1].

Keywords: Ocular pharmacokinetics; Therapeutic contact lenses; Biodegradable polymers; Smart biosensors; Nano medicine; Myopia control; Glaucoma management

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Introduction: The Dawn of the Ocular Platform

Contact lenses have been the norm for non-invasive refractive correction for more than a century. The objective has always been to increase the device's mechanical comfort and oxygen transmissibility (Dk/t), from the early days of blown-glass scleral lenses to the commonly utilized soft silicone hydro gels of the present day [1, 10]. But a dramatic change happened throughout the past ten years. Contact lenses are now considered active, multifunctional biomedical platforms that bridge the domains of ophthalmology, microelectronics, and pharmaceutics, rather than just passive optical aids [4, 6].

The development of lenses with sustained drug administration, ongoing health monitoring, and customized disease treatment has been made possible by the confluence of nanotechnology, flexible electronics, and sophisticated polymer chemistry [3, 7]. Critical gaps in conventional ophthalmic therapy, such as the poor absorption of topical eye drops and the limitations of episodic clinical measures for chronic disorders like glaucoma, are addressed by these "smart" and "therapeutic" lenses [5, 11]. As global health concerns like the myopia epidemic and aging-related ocular illnesses rise, the demand for integrated, wearable health solutions becomes critical [9, 15]. This systematic review investigates the transdisciplinary advances redefining the landscape of contact lens technology, examining how these devices are migrating from simple correcting tools to complex "pharmacies on the eye" [12, 22].

The Evolution of Therapeutic Contact Lenses

Traditionally, therapeutic contact lenses (TCLs) have been used as "bandage" lenses to mechanically shield a damaged corneal surface. TCLs promote epithelial regeneration and lessen pain in patients with corneal erosions, bullous keratopathy, or post-surgical trauma by protecting the cornea from environmental irritants and the friction of eyelid blinking [1, 10]. Active drug-eluting systems intended to get past the physiological barriers of the eye are now included in the contemporary definition of a TCL.

The basic inefficiency of conventional eye drops is the main pharmacological driving force behind drug-eluting lenses. When a drop is administered, only a little portion—typically less than 5%—penetrates the cornea because the majority is lost to the nasolacrimal duct or wiped away by reflex tearing. A drug-loaded lens, on the other hand, keeps a concentrated pharmaceutical reservoir in close range to the ocular surface [11]. This greatly lowers the frequency of injection while increasing the residence period from a few minutes to many hours or even days, enabling a regulated, continuous release that satisfies the physiological needs of the eye.

Advanced Ocular Drug Delivery Systems

Researchers went further beyond basic soaking techniques, which frequently result in an initial burst release followed by a sharp decrease in efficacy, to obtain precise control over drug release kinetics. In order to create precise "memory sites" inside the polymer matrix that are customized to the shape and chemical properties of a target therapeutic molecule, sophisticated engineering techniques like molecular imprinting are used [11]. Molecular imprinting slows down the diffusion process and permits a more linear release profile by increasing the affinity between the drug and the lens material.

Biodegradable Polymers and Nanofibers

Another level of pharmaceutical control is provided by nanoparticle embedding, in which medications are integrated into the lens material after being encapsulated in standardized lipids, micelles, or polymeric nanoparticles [2, 14]. These nano carriers permit release in reaction to environmental cues and shield the drug from early tear enzyme breakdown. Furthermore, sophisticated nonporous polymers control diffusion by pore size manipulation, allowing for long-term, precise drug release [14]. These developments are especially encouraging for the treatment of fungal infections and bacterial keratitis, where steady therapeutic doses are required to avoid tissue necrosis and biofilm formation [2].

The use of biodegradable polymers is one of the most fascinating areas of therapeutic lens research. A biodegradable lens provides a ground-breaking alternative for chronic medical conditions like glaucoma, where patients may find it difficult to apply ocular drops every day for the rest of their lives [12]. These lenses are made to gradually disintegrate in the tear film, delivering medicine at a steady pace until they safely vanish. This greatly improves patient adherence and therapeutic outcomes by doing away with the necessity for physical removal and disposal.

Additionally, nanofiber mats are being incorporated into the lens structure using electrospinning technology [13]. Because of their enormous surface-area-to-volume ratio, these nanofibers enable extraordinarily large drug-loading capabilities. Delivering complicated compounds, such proteins or growth factors, which need particular stability to be functional, is crucial. A complicated treatment regimen within a single wearable device is made possible by the use of nanofibers, which also enable a multi-layered approach where various medications may be delivered at varying speeds.

Smart Contact Lenses: Sensors in Sight

Smart contact lenses emphasize diagnosis and ongoing physiological monitoring, whereas therapeutic lenses focused on therapy. Real-time parameter monitoring is possible without invasive procedures by integrating microelectronics and biosensors into the transparent matrix of a lens [4, 7]. The treatment of glaucoma is the most clinically advanced use of this technology. It is well known that intraocular pressure (IOP) varies greatly during the course of a 24-hour cycle, frequently peaking at nite when the patient is asleep.

Only a snapshot of pressure is provided by standard clinical tonometry, which may miss dangerous elevations. When IOP increases, tiny changes in corneal curvature can be monitored using smart lenses with micro-sensors [5]. A wearable gadget receives this data wirelessly, giving a constant pressure profile that enables medical professionals to more effectively personalize treatment. The tear film is a significant source of biomarkers in addition to pressure. One of the key objectives of non-invasive diabetes treatment has been tear glucose monitoring with smart glasses [4, 8]. These glasses can deliver continuous, non-invasive glucose readings by integrating wireless circuits with electrochemical sensors, thereby relieving diabetic patients of the daily burden of finger-prick examinations.

Nanomaterials: Graphene and MXenes

Because the components must be conductive, flexible, and completely transparent, integrating electronics into contact lenses poses a special material science difficulty. 2D nanomaterials like graphene and MXenes are essential in this situation. Because of its remarkable electrical conductivity and approximately 98% optical transparency, graphene is a perfect choice [3]. Transparent circuitry and sensors that fit comfortably on the eye without blocking the user's field of view have been made using it.

MXenes, a type of transition metal carbides, have become a potent substitute in more recent times [15]. MXenes have inherent antibacterial qualities and are very hydrophilic, which helps keep the lens moist. This is an important safety feature since it lowers the risk of infection linked to continuous use of electronic devices on the surface of the eyes. Furthermore, these nanomaterials enable the creation of sensors with reduced power consumption and increased sensitivity, both of which are crucial for the downsizing needed in ocular applications.

Biomimetic Engineering and Surface Science

Biofouling, or the buildup of proteins and lipids from the tear film on the lens surface, is a significant obstacle to the long-term success of sophisticated contact lenses. In addition to causing pain and distorted eyesight, this buildup can obstruct the pores meant for medication release and impair the accuracy of implanted sensors. By imitating the natural chemistry of the eye, biomimetic engineering attempts to tackle this [17].

Hydrophilic polymers that mimic the tear film's mucin layer are frequently used to contemporary silicone hydrogels. This generates a hydrated barrier that keeps the lens surface smooth and repels proteins throughout the duration of use. In order to maximize comfort and safety, researchers are also studying the connections between polymer composition and clinical performance [18]. An environment that reduces the inflammatory response and increases the stability of the tear film may be created by adjusting the lens's surface energy and charge.

The Myopia Epidemic and Refractive Innovations

The basic refractive function of contact lenses is also experiencing a revolution in response to the worldwide myopia epidemic, even if a large portion of recent research focuses on smart features. Myopia is now recognized as a progressive condition that raises the risk of retinal detachment and glaucoma in later life rather than as a straightforward refractive defect [19]. Conventional single-vision lenses improve central vision but induce hyperopic defocus in the peripheral retina, which is thought to cause the eye to lengthen and exacerbate myopia.

The purpose of advanced multifocal lenses is to cause myopic defocus in the periphery [9]. This causes the eye to halt its axial elongation by sending a biological signal. These specific designs have strong validity in pediatric populations, according to clinical research, which represents a major advancement in preventative eye care. This proactive approach to refractive correction signifies a change from only treating myopia's symptoms to controlling its underlying pathophysiology.

Challenges: Power, Privacy, and Biocompatibility

There are several obstacles in the way of turning laboratory prototypes into commercially viable medical equipment. Power management and wireless integration provide the biggest obstacles for smart lenses [6, 7]. Because traditional batteries are too heavy and stiff for eyewear, scientists are looking at a number of innovative options, such as biofuel cells that use tear glucose as energy and wireless power transmission via radio frequency [4].

To guaranty that these intricate combinations provide power, harmonization is also required. Biocompatibility is still a top priority. One of the body's most delicate organs is the eye, and any heat produced by microcircuits or nanomaterial leaking might cause corneal injury or persistent inflammation [3, 15]. Furthermore, protecting the security and privacy of the medical data these lenses communicate is a crucial ethical and legal need as they integrate with the Internet of Things [20, 21]. Regulatory approval and extensive clinical validation show that it is safe for long-term human usage.

Discussion:

Closed-loop systems that can independently detect and cure ocular illnesses are the way of the future for contact lens technology. Imagine a lens that continually tracks a patient's intraocular pressure and immediately releases a precise dosage of medicine from an implanted reservoir when it detects a potentially harmful surge. By transferring the responsibility of care from the patient to the technology, this

degree of automated, customized intervention will completely change how chronic illnesses are managed [22].

Furthermore, the field of biosensing is probably going to go beyond glucose and IOP to include tear proteomics. Through certain tear biomarkers, this developing science may enable the early diagnosis of neurological illnesses such as Parkinson's or Alzheimer's. An additional layer of non-invasive diagnostic capabilities is provided by the integration of optical biosensing, which includes colorimetric and fluorescence-based methods [16]. The contact lens will probably become the main interface for digital health as materials advance and circuits get smaller.

The change from "biocompatible" to "bioactive" materials is one of the biggest changes during the past eighteen months. Newer materials actively support eye health and react to the physiological environment instead of merely preventing an immune response. Using cellulose nanocrystals (CNCs) embedded in poly (hydroxyethyl methacrylate) (PHEMA), researchers have successfully created hydrogels that resemble the multilayer helical structure of the natural human cornea [1.1, 1.2].A significant advancement in "closed-eye" monitoring—a persistent problem in glaucoma treatment—was made in 2025. Soft, stretchy bimodal contact lenses (BCLs) that can concurrently detect intraocular pressure (IOP) and eye movement while the patient is asleep were introduced in a seminal work published in Microsystems & Nano Engineering [3.1].. These lenses offer the first high-resolution "nocturnal trace" of ocular health, detecting pressure spikes that are usually overlooked during daytime clinical visits with a sensitivity greater than 0.22 MHz/mmHg [3.1]. They do this by using magnetic interlayer films for movement and serpentine copper coils for pressure sensing.

Conclusion

Contact lenses are becoming the next big thing in wearable medical technology, having effectively lost their reputation as basic optical plastic. High-precision medication administration and advanced diagnostic sensing are now possible because to the combination of nanotechnology, biomimetic materials, and microelectronics. The direction is obvious, even if there are still major obstacles in the areas of long-term ocular safety, power sustainability, and regulatory acceptance. A revolutionary move toward proactive, individualized, and non-invasive healthcare is represented by smart and therapeutic contact lenses. These eye-borne laboratories promise to save sight and offer a view into the general health of the human body as we continue to enhance them.

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