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COMPREHENSIVE NARRATIVE REVIEW ON NANOTECHNOLOGY FOR THE TREATMENT OF GLAUCOMA

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ABSTRACT

Glaucoma, characterized by its asymptomatic nature, particularly in the later stages, is globally acknowledged as a leading cause of irreversible vision impairment. The intricate and highly sensitive nature of the human eye poses a formidable challenge in the context of drug delivery. Glaucoma, characterized by an elevation in intraocular pressure within the aqueous humor, is not only elusive in its presentation but can also result in irreversible blindness for many individuals. Existing formulations of anti-glaucoma drugs available in the market encounter challenges related to either difficulty in traversing the blood-retinal barrier or exhibiting lower systemic bioavailability. Consequently, drugs with a lower therapeutic index necessitate frequent administration, leading to the accumulation of concentrated solutions at the ocular site. This, in turn, gives rise to potential toxic effects and cellular damage within the eye. Nanotechnology-based interventions hold the potential to overcome the constraints associated with existing glaucoma treatments by offering refined targeted drug delivery, enhanced bioavailability, and controlled release mechanisms. This review comprehensively explores recent advancements in strategies for glaucoma treatment employing nanotechnology.

KEYWORDS: Glaucoma, Treatment, Ocular drug delivery, Nanotechnology, Application.

INTRODUCTION

glaucoma stands as the second most prevalent cause of global blindness, holding a prioritized position on the World Health Organization's list of crucial eye diseases. According to current World Health Organization data, approximately 4.5 million instances of blindness are attributed to glaucoma, constituting over 12% of total global blindness cases.[1] The pathophysiology of glaucoma is characterized by heightened intraocular pressure (IOP), primarily stemming from impediments in the eye's drainage system. This obstruction results in the degeneration of retinal ganglion cells (RGCs) and subsequent optic neuropathy. Glaucoma manifests as a multifactorial ailment, shaped by a intricate interplay of risk factors encompassing intraocular pressure (IOP), aging, genetic predisposition, ethnic considerations, and structural ocular variations.[2] These factors collectively contribute to the progressive degeneration of retinal ganglion cells and their axons. Notably, prevailing therapeutic interventions predominantly focus on the reduction of intraocular pressure. This emphasis on IOP stems from its status as the singular modifiable parameter in the glaucoma equation, aiming to attenuate the advancement of the disease. glaucoma represents a collective designation for a spectrum of ocular diseases marked by gradual impairment of the optic nerve. This impairment culminates in a decline in visual acuity, and if left untreated, there exists the potential for the condition to advance to complete blindness. glaucoma is colloquially referred to as "the silent thief of sight" due to the absence of discernible symptoms in the early phases of the disease.[3] Glaucoma instigates a gradual visual decline, affecting both the central and peripheral fields of vision. Consequently, delays in both diagnosis and treatment are commonplace, often resulting in the identification of glaucoma only when the condition has advanced to a moderate or severe stage, precipitating substantial visual impairment.[4]

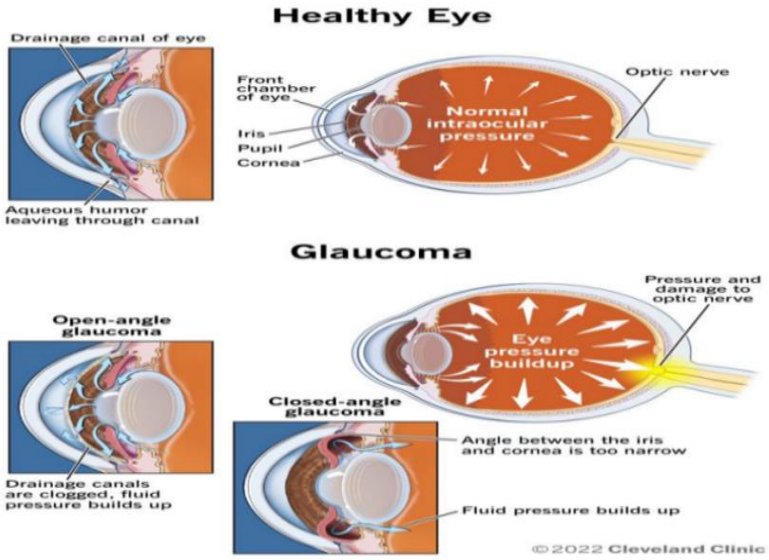

Figure 1: Aqueous Humor Drainage Pathways of Healthy and Glaucomatous Eyes.[5]

Causes of glaucoma

- Genetics
- Intraocular pressure
- Ageing
- Ocular hypertension
- Severe myopia
- Eye trauma
- Ocular surgery
- Migraine
- Prolonged use of local or systemic corticosteroids.[6]

Symptoms of Glaucoma

- No symptoms in early stages
- Patchy blind spots in peripheral vision
- In later stages, difficulty in central vision
- Severe headache
- Severe eye pain
- Blurred vision
- Eye redness.[7]

Diagnosis criteria for Glaucoma

Health care provider will review medical history of patient and conduct comprehensive eye examination.

They may perform several tests, including.

- Measuring intraocular pressure, also called tonometry.
- Testing for optic nerve damage with a dilated eye examination and imaging tests.
- Checking for areas of vision loss, also known as a visual field test.
- Measuring corneal thickness with an exam called pachymetry.
- Inspecting the drainage angle, also known as gonioscopy.[8]

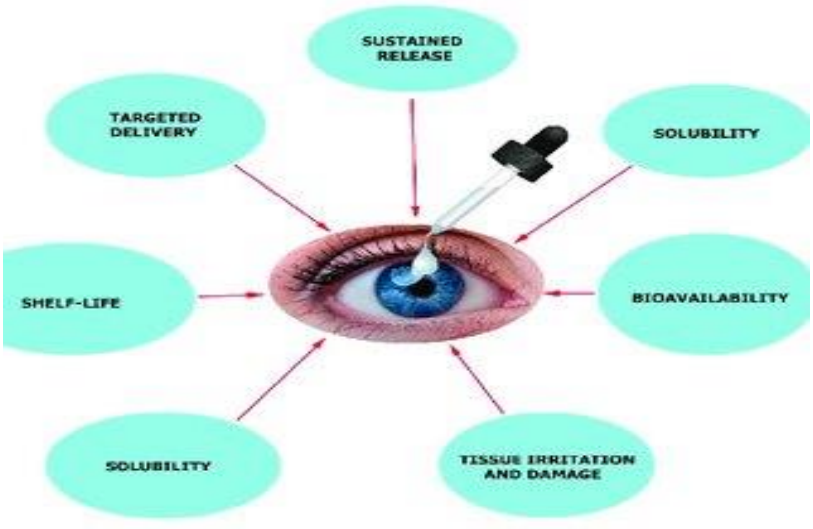

Figure 2: Major challenges in ocular disease treatment with eye drop formulations.[9]

Treatment of Glaucoma[10]

Sr. No.	Name of Drug	Class of Drugs	Mechanism of Action
1	Latanoprost, travoprost bimatoprost	Prostaglandin analogues	Increase in uveoscleral outflow of aqueous humor.
2	Timolol, levobunolol, carteolol, Betaxolol	β-Adrenergic- blockers	Reduction of aqueous humor production.
3	Brimonidine, apraclonidine	α-Adrenergic agonists	Initial reduction of aqueous humor production with subsequent effect of increase in outflow.
4	Dorzolamide, brinzolamide	Carbonic anhydrase inhibitors	Reduction of aqueous humor production.
5	Pilocarpine, Physostigmine	Cholinergic agonists	Increase in aqueous humor outflow.

Nanotechnology: Nanotechnology, derived from the Greek word nano, which means dwarf, applies engineering, electronics, physical and material science, and manufacturing processes at the molecular or submicron level. Nanomaterials can be devices or systems, or they can be supramolecular structures, complexes, or composites. Albert Franks, a founder of nanotechnology, characterized it as a branch of science and technology with dimensions and tolerances ranging from 0.1 to 100 nm.[11] The eye represents a distinctive organ, characterized by both physical and physiological uniqueness, encompassing diverse and autonomously functioning components that confer a high degree of impermeability to external chemical agents. Notably, the cornea and crystalline lens, with the exception of cartilage, stand as the sole tissues in the body devoid of a vascular network. Given the intricacies of the ocular structure, pharmaceutical scientists encounter specific challenges in devising effective drug delivery systems for ocular medications.[12] The diverse nanotechnology-based ophthalmic formulations are outlined as follows in scientific terminology.

1) Liposomes: Liposomes are microparticulate or colloidal carriers characterized by a diameter spanning 0.05 to 5.0 micrometers, emerging spontaneously through the hydration of specific lipids in aqueous environments. Comprising natural or synthetic lipids, including phospho- and sphingolipids, liposomes may additionally incorporate cholesterol and lipids linked to hydrophilic polymers. Classification of liposomes is based on their composition and intracellular mechanism, resulting in categories such as ordinary liposomes, cationic liposomes, immunoliposomes, and long-circulating liposomes. In the context of drug delivery, liposomes are typically unilamellar, exhibiting diameters ranging from 50 to 150 nanometers.[13] Liposome properties exhibit significant variation based on factors such as lipid composition, size, surface charge, and the method of preparation. The observed behavior of liposomes as an ocular drug delivery system is in part attributable to their surface charge. Positively charged liposomes display a preferential affinity for capture at the negatively charged corneal surface compared to neutral or negatively charged liposomes. According to findings by Felt cationic liposomes are anticipated to impede drug elimination through lacrymal flow by enhancing solution viscosity and interacting with the negative charges of the mucus. The binding affinity of liposomes to the cornea suggests that corneal uptake is highest for positively charged liposomes, lower for negatively charged liposomes, and least for neutral liposomes. This implies that the initial interaction between the corneal surface and liposomes is predominantly electrostatic in nature.[14] A novel and stable glaucoma medication with sustained drug release properties for timolol maleate was developed using gelatinized core liposomes. This innovative liposomal modification aimed to address challenges commonly associated with traditional liposomal preparations, including low drug loading, inadequate physical stability, and limited corneal penetration of water-soluble molecules. The investigated formulation demonstrated enhanced compatibility with the corneal layers, exerted potent and sustained reduction in intraocular pressure (IOP) in the eyes of rabbits, and exhibited a safe histological profile.[15]

Nanomicelles: Nanomicelles are nanocarriers characterized by a core–shell structure, generated through the spontaneous assembly of amphiphilic copolymers. The core is comprised of hydrophobic groups, while the outer shell consists of hydrophilic groups. Typically, the particle size of nanomicelles falls within the range of 10 to 100 nanometers.[16] Positive micelles are employed for the encapsulation, solubilization, and delivery of hydrophobic drugs, while reverse nanomicelles are utilized for encapsulating and delivering hydrophilic drugs. The distinctive chemical structure of nanomicelles enables the internal solubilization of drugs, leading to reduced adverse reactions, enhanced drug stability, and a sustained release effect. This makes nanomicelles considered safe alternatives for ocular drug delivery.[17] Nanomicelles investigated for Ocular Drug Delivery (ODD) are classified into three fundamental categories: polymeric, surfactant, and polyionic complex micelles. The majority of polymeric micelles utilized in drug delivery comprise amphiphilic di-block (hydrophilic-hydrophobic) polymers, tri-block (hydrophilic-hydrophobic-hydrophilic) polymers, graft (hydrophilic-hydrophobic) polymers, and ionic (hydrophilic-ionic) copolymers.

Poly(ethylene glycol) (PEG) serves as the principal hydrophilic component in the majority of these systems.[18] For topical application of eye drops, the anticipated route for a drug to reach posterior segment tissues involves the corneal or conjunctival-scleral pathway. The encapsulation of Dorzolamide, a marginal augmentation in micellar sizes was observed. Utilizing dynamic light scattering, it was empirically substantiated that both unladen and drug-laden polymeric micelles (PMs) remain stable over a 30-day storage period at 4 °C. Furthermore, in vitro biological assessments demonstrated the hemocompatibility and cytocompatibility of the synthesized PMs, supporting their suitability for subsequent in vivo investigations. The engineered micellar system exhibited proficiency in in vitro drug release studies, and the findings were corroborated through in vivo experiments conducted on experimental animals. These in vivo tests underscored the micellar system's notable efficacy in diminishing intraocular pressure.[19]

2) Nanoparticles: Nanoparticles present a promising solution to overcome existing challenges in drug delivery by safeguarding drugs against degradation and preserving their structural integrity. Their capability to transport adequate drug quantities to specific tissues within the eye addresses difficulties posed by the natural protective and filtration mechanisms of ocular barriers. As a result, there is considerable potential for the implementation of nanoparticle-based drug delivery systems in the treatment of glaucoma.[20]

Polymeric nanoparticles[51]: Polymeric nanoparticles consist of polymers derived from either synthetic or natural sources. Among the commonly employed synthetic polymers for ocular applications are polylactide, polycaprolactones, polylactide–polyglycolide copolymers, and polyacrylates. Notably, lactide–glycolide copolymer (PLGA) has garnered increased attention in the last decade. In addition to synthetic polymers, natural polymers such as chitosan, alginate, gelatin, and albumin are extensively utilized in ocular drug delivery. The polymeric systems relevant to ocular drug delivery can be classified as either biodegradable or nonbiodegradable.[21] Biodegradable systems have the capacity to undergo degradation over time, while nonbiodegradable systems maintain their structural integrity without undergoing significant breakdown. The researchers prepared poly(lactic-co-glycolic acid) (PLGA) nanoparticles encapsulating brinzolamide (BRN) designed for subconjunctival injection. Their investigation in Albino rabbits demonstrated that BRN-PLGA nanoparticles with a particle size of 193 ± 0.40 nm exhibited superior bioavailability and prolonged reduction of intraocular pressure (IOP) compared to those with a larger particle size of 660.75 ± 51.61 nm.[22] The researchers developed polymeric nanoparticles loaded with timolol maleate, utilizing flax seed gum and chitosan for ocular delivery through the ionic gelation method. Their findings indicated that the formulated nanoparticles exhibited notable bioadhesive strength, a heightened capacity to penetrate deeper layers of the cornea, and a substantial and prolonged reduction in intraocular pressure (IOP) compared to conventional eye drops.[23]

Solid Lipid Nanoparticles[50]: The introduction of Solid Lipid Nanoparticles in 1991 signifies an alternative carrier system in comparison to conventional colloidal carriers. This system comprises nanometer-sized spherical solid lipid particles dispersed in water or an aqueous surfactant solution. Structurally resembling an oil-in-water emulsion used in parenteral nutrition, Solid Lipid Nanoparticles differ in that the liquid lipid (oil) in the emulsion is replaced by a solid lipid, giving rise to Solid Lipid Nanoparticles. Due to their non irritant and nontoxic properties, Solid Lipid Nanoparticles have been regarded as highly suitable carriers for ocular drugs.[24] The sustained and controlled drug release characteristics of SolidLipid Nanoparticles offer potential advantages in ocular formulations.Positive - potential of the formulations suggested that the Solid Lipid Nanoparticles were dispersive and would promote corneal retention of the lipid nanoparticles, hence increasing ocular bioavailability of the drug.[25] Moreover, formulations comprising bimatoprost loaded in solid lipid nanoparticles dcomposed of glyceryl monostearate and Tween 80, and incorporated into a pH-sensitive in-situ gelling Carbopol 941 solution, were developed with the goal of utilizing them in the treatment of glaucoma. The optimized formulation demonstrated non-irritant characteristics upon instillation in the eye and did not induce tissue damage, as confirmed by histopathological examination.[26]

3) Niosomes: Niosomes are self-assembled vesicles created through the hydration of non-ionic surfactants, cholesterol, or other amphiphilic molecules. Structurally resembling liposomes, niosomes have been devised as an alternative drug delivery system to liposomes. Noteworthy advantages of niosomes over liposomes encompass enhanced chemical stability, extended storage duration, and the potential for sustained drug administration. In an effort to enhance the treatment of glaucoma.[27] Allam et al. incorporated betaxolol-loaded niosomes into pH-responsive in situ gels to extend the precorneal retention of the drug. The optimized niosomes exhibited a high encapsulation efficiency, a negative surface charge, and a nanoscale hydrodynamic diameter. Following the instillation of the niosomal gel containing betaxolol into rabbit eyes, a consistent reduction in intraocular pressure (IOP) was observed, and the relative bioavailability of betaxolol was significantly increased when compared to commercially available eye drops. Consequently, the utilization of niosomal pH-triggered in situ gel for ophthalmic drug delivery emerges as a promising technique for the treatment of glaucoma.[28]

4) Nanosuspension[53]: Nanosuspensions are formulations comprising undiluted, inadequately water-

soluble pharmaceutical substances that are dispersed within a suitable medium. This technology proves advantageous, particularly for drug compounds that undergo crystallization characterized by high energy content, resulting in their insolubility in both organic (lipophilic) and hydrophilic media. polymeric nanoparticle suspensions, derived from inert polymeric resins, serve as significant vehicles for drug delivery, effectively extending drug release duration and augmenting bioavailability. These carriers are particularly advantageous in ophthalmic applications, as they do not induce irritation in the cornea, iris, or conjunctiva. In this context, they function as inert carriers for ophthalmic drugs.[29] polymeric nanoparticle suspensions containing Flurbiprofen (FLU) and prepared from Eudragit RS 1001 and RL 1001 polymer resins have been documented for their ability to prevent myosis induced during extracapsular cataract surgery. Flurbiprofen, classified as a non-steroidal anti-inflammatory drug (NSAID), functions by inhibiting the activity of cyclooxygenase. Consequently, it acts as an antagonist to papillary constriction during intraocular surgery. This mechanism of action implies that Flurbiprofen, when encapsulated in polymeric nanoparticles, exhibits potential utility in mitigating the constriction of the pupil during extracapsular cataract surgery.The positive charge present on the surface of nanoparticles promotes their adherence to the corneal surface. Consequently, it is reasonable to infer that the incorporation of nanosuspensions into ophthalmic pharmaceutical formulations represents an appealing avenue. This approach holds significant promise in addressing the inherent challenges associated with delivering drugs to the eye, thus presenting an opportunity for overcoming obstacles related to ocular drug delivery.[30] The investigator has developed Brimonidine Tartarate loaded a nanosuspension incorporated into an in situ gel-based formulation, which could serve as a promising delivery system for the sustained management of glaucoma with a once-daily dosing regimen.[31]

5) Nanosponges: The "Nanosponges" strategy involves the use of a nanoparticle-sized system capable of encapsulating both hydrophilic and hydrophobic compounds. These nanosponge particles exhibit solubility in water, allowing for encapsulation through the addition of an adjuvant reagent. This chemical serves to mitigate undesirable flavors and transform liquids into solids with reduced adverse effects.[32] The nanosponges act as encapsulating nanoparticles, housing therapeutic molecules within their core. The nature of drug attachment to the nanoparticle can be characterized as encapsulating, complexing, or conjugating. Crucial components in nanosponge manufacture include polymers and crosslinking agents. Polymers like cyclodextrin and its derivatives (e.g., Methyl B-cyclodextrin, alkyloxy carbonyl cyclodextrins) and crosslinking agents such as diphenyl carbonate, diaryl carbonates, epichlorohydrin, and glutaraldehyde play essential roles.[33] The emulsion solvent diffusion method is commonly employed in nanosponge production. In nanosponge formulations, careful consideration is required to prevent dose dumping. In a specific instance, Besifloxacin HCL was loaded into nanosponges by Mousumi Pillai using ethyl cellulose as a polymer and polyvinyl alcohol as a surfactant. This formulation aimed to enhance ocular retention and permeability.[34] The researcher conducted an investigation involving the preparation of brinzolamide nanosponges using the emulsion solvent evaporation technique. Brinzolamide in-situgel an efficient and scalable drug delivery system with significant potential as the targeted therapy of posterior segment eye diseases.[35]

6) Dendrimers: dendrimers are macromolecular compounds characterized by a central core surrounded by a series of branches. These structures are appealing for drug delivery applications due to their nanometer size, facile preparation and functionalization, as well as their capacity to present multiple copies of surface groups for biological recognition processes. The inherent properties of dendrimers make them effective candidates for serving as vehicles in ophthalmic drug delivery systems.[36] he corneal epithelium of the eyes is characterized by a quasi-impermeable nature. To enhance the bioavailability and effectiveness of drugs, an extended residence time is essential. The corneal epithelium is susceptible to damage from bacteria, viruses, fungi, and mechanical injuries. In the treatment of certain conditions like glaucoma or diabetic retinopathy, achieving adequate therapeutic drug concentrations becomes challenging due to difficulties in lachrymal drainage from the eye. Therefore, there is a pressing need to enhance bioavailability. This can be achieved by utilizing water-soluble polymers, which, by increasing viscosity, facilitate the bioadhesion of the instilled drug.[37] poly(amidoamine) (PAMAM) is among the frequently employed polymers in the synthesis of dendrimers. PAMAM dendrimers can be described as polymer structures that exist in either a liquid or semi-solid state, featuring multiple functional groups including carboxylic, amine, and hydroxyl groups. These dendrimers exhibit the ability to solubilize even poorly water-soluble drugs within their structure, which comprises cascading tiers in the inner region and terminal moieties on the surface. The unique characteristics of PAMAM dendrimers make them proficient in enhancing the solubility of drugs, especially those with limited water solubility, by providing specific zones within their structure. PAMAM dendrimers have demonstrated significant potential in the field of ocular drug delivery through various studies and applications.[38] brimonidine tartrate-loaded dendrimers were prepared and subsequently integrated into nanofibers through the electrospinning technique to create a nanomat. This drug-dendrimer-loaded nanomat was then evaluated in vivo using normal tension rabbits and compared with conventional eye drops. The findings indicated that the drug-dendrimer-loaded nanomat exhibited non-irritant

properties and was well-tolerated by the animals. The study data further suggested that the nanofibers loaded with dendrimers effectively reduced intraocular pressure (IOP) for an entire day following a single dose.[39]

7) Hydrogel: Hydrogels are three-dimensional, hydrophilic polymer frameworks with a significant water content. This unique structure facilitates the effective diffusion of drug molecules throughout the gel, allowing the hydrogel to function as a reservoir for drugs. Hydrogels possess distinctive physicochemical properties, including transparency, high water content, and mechanical flexibility. Notably, they exhibit viscoelastic properties that make them less prone to expulsion from the eye through blinking, resulting in enhanced ocular residence time. This increased residence time is attributed to the difficulty of hydrogels being expelled from the eye, leading to longer contact time compared to conventional eye drops. This property makes hydrogels particularly valuable in treating various ocular diseases, especially those affecting the anterior segment of the eye. Additionally, the prolonged contact time allows for reduced dosing frequency, contributing to improved patient compliance. Overall, the unique properties of hydrogels make them promising candidates for ocular drug delivery systems, offering enhanced therapeutic benefits and patient adherence.[40] Researchers have explored modifications to conventional hydrogels, such as the development of bioadhesive hydrogels like poloxamers and Carbopol hydrogels. These are frequently employed as carriers for macromolecules with the goal of maximizing their ocular residence time by enhancing formulation adhesiveness, ultimately increasing overall bioavailability. This strategy was applied in the topical delivery of brimonidine, and the prepared hydrogels demonstrated a moderate level of non-cytotoxicity and non-irritation, coupled with excellent cytocompatibility. These findings suggest that the modified hydrogels, specifically those incorporating poloxamers and Carbopol, exhibit promising characteristics for ocular drug delivery.[41] The observed non-cytotoxic and non-irritant properties, along with excellent cytocompatibility, underscore their potential suitability for use in ocular formulations. Pharmacodynamically, gels formulated with lower concentrations (0.05% and 0.1%, w/v) exhibited an enhanced intraocular pressure (IOP) lowering effect of the drug by extending its duration of action.In the context of glaucoma treatment, traditional medications such as timolol maleate, pilocarpine, and Xalatan exhibit suboptimal bioavailability and brief retention periods. Consequently, integrating these therapeutic agents into a hydrogel matrix has the potential to extend their retention duration by enhancing bioavailability.[42]

8) Nanoemulsion: Nanoemulsions are colloidal dispersions characterized by multiple phases, and their droplet sizes fall within the nanometer range. The essential constituents of nanoemulsions include oil, water, and surfactant. They are usually prepared by homogenization which results in emulsion having droplet size 20-500nm. Due to their small size, nanoemulsions have the capability to traverse the cell membrane, thereby optimizing the therapeutic effectiveness of a drug component. Furthermore, these systems demonstrate minimal side effects and toxic interactions. Microscopic analyses of certain nanoemulsions revealed a spherical morphology characterized by amorphous and lipophilic surfaces with a negative charge.[43] The investigation focused on the corneal penetration of brinzolamide incorporated into water-in-oil nanoemulsions. The findings indicated a substantial enhancement in its penetration through excised corneal tissue compared to the commercially available product. This suggests that the optimized nanoemulsion systems hold considerable promise as an effective ocular drug delivery system for brinzolamide.[44]

9) Microneedles: Microneedles are drug delivery devices manufactured using metals or polymers with dimensions between 10 and 200µm. The ultradimensions of these devices make the drug delivery less invasive and more targeted to the sites of drug action. Jiang and colleagues used 500- to 750-µm-long coated stainless steel microneedles delivering pilocarpine into the anterior chamber via the intrascleral route.[45] The authors reported a 45-fold increase in drug absorption compared with conventional eye drops. The researchers explored the potential of microneedles coated with pilocarpine, conducting both in vitro and in vivo evaluations on postmortem human eyes. The evaluation study of these coated solid microneedles demonstrated exceptional penetration into the sclera, with rapid dissolution of the coated drug upon insertion into the eye. A comparative analysis with conventional eye drops revealed that microneedles were capable of delivering a greater quantity of the drug to the eye compared to traditional eye drop administration.[46]

11) Microemulsion: Microemulsions are colloidal dispersions characterized by specific proportions of various phases, including an aqueous phase, oil phase, cosurfactant, and surfactant. Their droplet sizes fall within the range of 10 to 100 nm. Depending on the types and quantities of surfactants present in the formulation, microemulsions can be categorized into three structures: oil-in-water (o/w), water-in-oil (w/o), and bi-continuous. Typically, o/w microemulsions have a higher water content, while w/o microemulsions have a higher oil content. Microemulsions have been extensively investigated as drug delivery vehicles for ocular preparations. This research aims to overcome various challenges associated with ocular drug delivery and reduce the need for frequent administration of daily eye drops. The researcher developed pilocarpine microemulsions, demonstrating enhanced absorption and reduced dosing frequency in comparison to conventional eye drops. The formulated microemulsion systems exhibited varied morphological structures of crystalline

fluid with rheological behavior, resulting in increased viscosity that prolonged the retention of the formulation on the corneal surface. Despite these advantageous features, the applicability of microemulsions in ocular drug delivery is constrained by a limited range of surfactants and oils with biocompatibility, restricting their utilization.[47]

12) Nanofibers: Nanofibers, characterized by diameters ranging from 1 to 100 nm, can be synthesized using diverse materials, including natural polymers such as chitosan, fibronectin, gelatin, collagen, silk, and ethyl cellulose, as well as synthetic polymers like PLA, PLGA, and PCL, either individually or in combinations, employing the electrospinning technique. Nanofibers exhibit notable advantages, including a heightened surface-to-volume ratio, substantial porosity, customizable mechanical properties, robust drug-loading capabilities, high encapsulation efficiency, and the simultaneous delivery of multiple therapeutic agents. Furthermore, nanofibers facilitate the traversing of physiological barriers by drugs, enabling targeted delivery to specific tissues. This property supports prolonged, controlled drug release, thereby minimizing systemic drug distribution to non-target areas. These inherent characteristics position nanofibers as distinctive candidates for applications in drug delivery, as well as the diagnosis and treatment of various diseases. Notably, they prove particularly promising for addressing chronic eye diseases that necessitate frequent administration.[48]

Novel advanced nanotechnological methodologies present a plethora of advantages over traditional pharmacotherapies in the realm of drug delivery.[49]

Enhanced Patient Adherence: Improved patient compliance with prescribed regimens, signifying a higher likelihood of adhering to the recommended treatment protocols.

Facile Insertion for Ocular Inserts: Simplified application of ocular inserts, ensuring ease of insertion and placement within the ocular environment.

Minimized Tissue Irritation and Damage: Reduction in ocular tissue irritation and damage, indicative of formulations with minimal adverse effects on ocular tissues.

Optimal Bioavailability and Ocular Tissue Compatibility: Attainment of sufficient drug bioavailability and compatibility with ocular tissues, reflecting formulations that optimize drug delivery and are well-tolerated by ocular structures.

Augmented Solubility of Specific Drugs (e.g., Dexamethasone, Budesonide, Ganciclovir): Improved dissolution characteristics for specific drugs such as dexamethasone, budesonide, and ganciclovir, indicative of enhanced drug solubility in the formulated nanotechnological approach.

Optimal Preservation of Encapsulated Drug: Maximum protection of the encapsulated drug within the formulation, ensuring stability and integrity of the therapeutic agent.

Efficient Penetration of Membrane Barriers (e.g., Blood–Retinal Barrier): Successful traversal of membrane barriers, such as the blood–retinal barrier, showcasing the formulation's ability to efficiently overcome physiological barriers for enhanced drug delivery.

Controlled and Sustained Drug Release: Precise regulation and prolonged release of the drug over time, highlighting the formulation's capacity for controlled and sustained drug delivery.

Superior Targetability and Stability: Exceptional ability to target specific sites and maintain structural integrity over time, demonstrating the formulation's superior targetability and stability in the ocular environment.

CONCLUSION

Glaucoma is a pathological condition characterized by elevated intraocular pressure (IOP) within the eye, resulting in irreversible damage to the optic nerves. Untreated glaucoma poses a significant risk for permanent vision impairment. Nanotechnology presents innovative avenues for the advancement of strategies in glaucoma treatment. Notably, enhanced nanodelivery systems for antiglaucoma medications currently take precedence due to the distinctive properties and adjustability of nanoparticles. Highly customizable liposomes, polymers, and dendrimers contribute to the solubilization of lipophilic drugs, offering control over bioavailability and sustained release owing to their biodegradable characteristics. These advancements in drug delivery vehicles facilitate the effective and secure administration of pharmaceutical agents. The current review comprehensively elucidates the pharmacological attributes of various conventional drugs employed in glaucoma treatment, emphasizing their potential for enhanced efficacy when formulated using advanced drug delivery systems. Over time, diverse endeavors have been undertaken to achieve sustained or controlled release of drugs targeted at the eye. These sophisticated drug delivery systems exhibit promising prospects in enhancing patient adherence, augmenting drug efficacy and effectiveness, mitigating side effects, ultimately contributing to the preservation of vision in individuals afflicted with glaucoma.

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