KOWALIK, Kinga, MICHALSKA, Maria, ZIELIŃSKA, Aleksandra, SZYPULSKI, Szymon, SKIBA, Jakub, TYLCZYŃSKA, Kinga, SKIBA, Zuzanna, TYLCZYŃSKA, Natalia, IWANIUK, Sebastian and MACIEJEWSKI, Ignacy. Optimizing Visual Quality in Keratoconus. Quality in Sport. 2025;39:59171. eISSN 2450-3118.
https://doi.org/10.12775/QS.2025.39.59171
https://apcz.umk.pl/QS/article/view/59171

The journal has been 20 points in the Ministry of Higher Education and Science of Poland parametric evaluation. Annex to the announcement of the Minister of Higher Education and Science of 05.01.2024. No. 32553.
Has a Journal's Unique Identifier: 201398. Scientific disciplines assigned: Economics and finance (Field of social sciences); Management and Quality Sciences (Field of social sciences).
Punkty Ministerialne z 2019 - aktualny rok 20 punktów. Załącznik do komunikatu Ministra Szkolnictwa Wyższego i Nauki z dnia 05.01.2024 r. Lp. 32553. Posiada Unikatowy Identyfikator Czasopisma: 201398.
Przypisane dyscypliny naukowe: Ekonomia i finanse (Dziedzina nauk społecznych); Nauki o zarządzaniu i jakości (Dziedzina nauk społecznych).

The authors declare that there is no conflict of interests regarding the publication of this paper.
Received: 03.03.2025. Revised: 15.03.2025. Accepted: 25.03.2025 Published: 28.03.2025.

Optimizing Visual Quality in Keratoconus: A Review of Recent Advances

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ABSTRACT

Keratoconus (KC) is a progressive, bilateral, and asymmetric corneal disorder that results in corneal thinning and conical protrusion, causing irregular astigmatism and reduced visual acuity. KC prevalence varies widely, with onset typically in the second or third decade and

progression stabilizing by the fourth decade. Although the exact etiology remains unclear, genetic and environmental factors, such as family history and eye rubbing, are associated with increased risk, and recent findings suggest inflammatory processes may contribute to pathogenesis. This study aims to evaluate the efficacy of treatment approaches for KC across varying disease stages. Methods include a review of the latest assessment of therapeutic options, from glasses and contact lenses to advanced surgical interventions, including corneal cross-linking and transplantation. Findings indicate that recent advancements in contact lens designs and surgical techniques enhance visual outcomes and slow disease progression. These improvements in KC management provide clinicians with a comprehensive approach for customizing treatment strategies according to disease severity.
Keywords: keratoconus, management, treatment, contact lenses, corneal cross-linking, corneal transplantation

INTRODUCTION

Keratoconus (KC) is a progressive bilateral and asymmetric eye disorder characterized by thinning and conical protrusion of the cornea, leading to irregular astigmatism and reduced visual acuity [1, 2]. The condition typically affects both eyes to varying degrees of severity, with well-established signs and symptoms; however, there is no clear consensus on the specific indicators for early-stage KC.

The prevalence of KC varies widely, from 0.2 to 4,790 per 100,000 individuals, with an incidence rate of 1.5 to 25 per 100,000 annually [1]. The typical age of onset for keratoconus is the second and third decades of life, with progression continuing until the fourth decade [1, 3].

Although the precise etiology of KC remains unclear, both genetic and environmental factors, such as family history, eye rubbing, eczema, asthma, and allergies, are associated with increased risk [3, 4, 5]. While traditionally viewed as a noninflammatory condition, new evidence suggests inflammatory mediators may play a role in disease pathogenesis [3, 6, 7].

Clinically, keratoconus is characterized by corneal protrusion and thinning, scissors reflex, Fleischer’s ring, and prominent corneal nerves [8, 9]. Advances in diagnostic technology, particularly corneal topography and tomography, have enabled earlier detection, likely accounting for recent increases in reported incidence. Some devices integrate these technologies with tear-film analysis, aberrometry, optical biometry, and anterior/posterior segment optical coherence tomography [1, 10].

The treatment of keratoconus varies according to disease severity, with early stages often managed using corrective glasses or contact lenses, and advanced or progressive cases requiring surgical interventions, such as corneal cross-linking or corneal transplantation. Recent advancements in contact lens technology and surgical techniques have further refined treatment options, offering improved visual outcomes and slowing disease progression in keratoconus patients [1].

MANAGEMENT AND TREATMENT

The treatment of keratoconus varies depending on the severity and progression of the disease. In the early stages of keratoconus, vision impairment may be managed with glasses or soft contact lenses. As the condition progresses, patients may require rigid gas-permeable contact lenses or alternative modalities, such as scleral lenses. In advanced cases, a corneal transplant may be indicated [1].

1. Mild and moderate keratoconus

Contact lenses are the primary method of visual correction for keratoconus patients. Advances in materials and design technology have significantly improved contact lenses for KC treatment, offering diverse options adapted to different stages of disease progression. Gas-permeable lenses (including corneal, corneoscleral, and scleral lenses), piggyback systems (rigid corneal lenses over soft lenses), soft contact lenses, and hybrid lenses are viable choices for managing mild to moderate keratoconus [1, 11, 12, 13].

1.1 Rigid corneal contact lenses and piggyback systems

There are three methods used for fitting rigid corneal contact lenses: apical clearance, apical touch and three-point touch [14]. The difference is in their points of support. Apical clearance (bears on the paracentral cornea) vaults the corneal apex. Apical touch (bears on the central cornea) provides good vision but may increase corneal scarring. The three-point touch technique, involving light apical touch with firmer contact on the paracentral cornea, offers better lens fit rates (83%) compared to apical touch fittings [14]. Currently, various rigid corneal contact lens designs, including multi-curve and aspherical options, are available to better manage KC.

Piggyback systems, which involve a rigid corneal lens fitted over a soft lens, improve comfort, lens centration, and stability, while optimizing oxygen transmission and reducing visual aberrations [15].

1.2 Corneoscleral and scleral lenses

Corneoscleral lenses are rigid lenses that rest on both the peripheral cornea and the conjunctiva overlying the sclera, regardless of the lens diameter [16]. Their primary benefits over traditional rigid corneal lenses include enhanced comfort due to reduced interaction with the eyelids, and improved stability and centration, providing consistent vision across various pupil sizes. These lenses are particularly beneficial for patients with inferiorly positioned cones or when other lens types do not achieve satisfactory visual results [17].

Corneoscleral lenses can be customized for better fit and centration using multicurve, aspheric, or toric designs [18]. They exhibit less movement during blinking (approximately 0.5 mm) compared to rigid corneal lenses (1–2 mm), yet more than scleral lenses, which settle into the conjunctival tissue [19]. This design allows for better oxygen transmission than sealed scleral lenses, thanks to tear exchange and a thinner post-lens fluid reservoir, which reduces corneal edema. Limbal compression must be avoided in corneoscleral designs, as it can trigger neovascularization [1, 20].

On the other hand, scleral lenses completely vault the cornea and limbus, resting upon the conjunctival tissue [21]. They are especially effective for advanced keratoconus, where other lenses may not fit well due to central bearing or decentration, and can postpone or eliminate the need for corneal grafts in minimally scarred corneas [22]. Scleral lens designs include both prolate and oblate (reverse geometry) profiles, with prolate profiles recommended for keratoconic eyes to match anterior corneal shape. Recent advances in anterior segment imaging have increased the use of scleral lenses, making them a first choice for patients with high regular astigmatism or ocular surface diseases [23].

While scleral lenses offer greater stability and comfort than rigid corneal or corneoscleral lenses, they pose a higher risk of corneal hypoxia in healthy eyes, keratoconics, and following penetrating keratoplasty [20, 24, 25]. This risk is attributed to reduced tear exchange and a thicker central post-lens fluid reservoir (approximately 200 μm compared to 20 μm in some corneoscleral designs). Additionally, patients often face a learning curve for lens handling in the first six months of use, with about 30% experiencing regular fogging from debris in the fluid reservoir, leading to frequent lens removal and reapplication [26, 27].

Recent randomized crossover trial showed no significant differences in visual acuity or contrast sensitivity between successful rigid corneal lens wearers and those using scleral lenses [28].

1.3 Soft contact lenses

Recent advancements in soft contact lens design for keratoconus have led to the development of high spherical and toric options suitable for early keratoconus, decentred cones, and patients intolerant of rigid lenses [29]. Although soft lenses offer greater initial comfort, they conform to the irregular corneal shape, leading to suboptimal visual correction. To address this, these lenses are designed with a thicker central thickness (0.2–0.6 mm) to mask corneal irregularities, though this reduces oxygen transmissibility. However, silicone hydrogel materials are now commonly used to improve oxygen permeability [1].

There is growing interest in aberration-controlled soft contact lenses designed to correct both lower- and higher-order ocular aberrations [30]. Despite theoretical improvements in vision, factors such as lens flexure, movement, rotation, and tear layer effects complicate the correction of higher-order aberration. Particularly, vertical coma is often the most elevated higher-order aberration in keratoconus, leading to focused research on lenses specifically targeting this issue [1, 31]. Recent prototypes, such as a soft lens fitting set with multiple vertically asymmetric powers and axes, have shown promise in correcting vertical coma and enhancing visual quality [32]. Further refinements in aligning the optic zone with the pupil center have led to better visual outcomes [33].

1.4 Hybrid contact lenses

Hybrid contact lenses combine a rigid corneal lens with a soft peripheral skirt, aiming to combine the optical advantages of rigid lenses with the comfort of soft lenses. Early hybrid designs often faced challenges such as reduced comfort, complications from low oxygen permeability, and durability issues at the GP/soft material interface [34]. Current hybrid lenses have addressed some limitations. Despite their comparable clinical performance in visual quality and comfort, their higher cost compared to GP lenses, limits their use in keratoconus management [35].

2. Severe keratoconus

In terms of methods primarily used in severe cases of the disease, the main options include corneal cross-linking, refractive surgery, corneal transplantation, and combinations of various refractive procedures.

2.1 Corneal cross-linking (CXL)

Corneal cross-linking (CXL) enhances corneal biomechanical stability and rigidity to prevent keratoconus progression. The procedure involves the removal of 6–7 mm of central corneal epithelium, followed by the application of 0.1% riboflavin solution and exposure to ultraviolet-A (UVA) light at 370 nm [1, 36, 37, 38]. UVA radiation activates riboflavin, leading to the formation of covalent bonds between collagen fibrils and the corneal stroma, along with significant keratocyte apoptosis in the anterior stroma. Radiation levels at the corneal endothelium, crystalline lens, and retina remain well below the damage threshold [39]. However, this technique is contraindicated in corneas thinner than 400 µm due to the risk of endothelial toxicity [40].

The conventional 'epi-off' method involves removing the epithelium before riboflavin application and ultraviolet-A (UVA) exposure. This technique effectively flattens the central cornea and reduces cone progression, particularly in progressive keratoconus [41]. It is widely used in both adults and children [42, 43]. Patients who undergo CXL often continue to require contact lens correction after the procedure [44]. ‘Epi-on' (transepithelial) CXL techniques (the corneal epithelium remains intact) are thought to reduce pain and minimize complications associated with the 'epi-off' method. Despite the growing popularity of transepithelial approaches, 'epi-off' CXL has demonstrated better corneal surface regularization and greater reduction in higher-order aberrations compared to 'epi-on' techniques [45]. CXL is also combined with other surgical techniques, such as corneal ring segments, to enhance treatment outcomes [46, 47, 48].

2.2 Refractive surgery

Various refractive surgery approaches are used in keratoconus management like phakic lens implantation and photorefractive keratectomy (PRK). These procedures are indicated only in stable keratoconus and can be classified into: (1) corneal, including excimer laser, intracorneal ring segments, radial keratotomy, and thermal therapy; (2) intraocular, with phakic and pseudophakic lenses; and (3) combined methods.

2.2.1 Corneal

Photorefractive keratectomy (PRK), using an excimer laser to reshape the anterior central cornea by removing a small section of stromal tissue by vaporisation, has shown moderate success in keratoconus. It reduces cone progression, enhances visual acuity, and decreases higher-order aberrations [49]. PRK is commonly combined with corneal cross-linking (CXL) for added benefit [50].

Intracorneal ring segments (ICRS), initially developed for myopia correction, are now used in the management of mild to moderate keratoconus. This procedure is proper for transparent corneas with a minimum thickness of 450 µm and involves implanting one or two polymethacrylate segments into the corneal stroma to alter the irregular surface [51]. ICRS improve both uncorrected and corrected visual acuity, corneal regularity, and ease contact lens fitting [52, 53]. ICRS implantation may delay the need for corneal transplantation, though it does not consistently stabilize aggressive keratoconus, particularly in younger patients [53, 54].

Radial keratotomy and thermal therapy are now rarely used due to limited efficacy [55, 56].

2.2.2 Toric intraocular lens implantation (IOL)

Phakic and pseudophakic toric IOLs often combined with ICRS or keratoplasty, improve visual acuity. Toric IOLs are recommended only in mild to moderate cases of stable keratoconus with manageable astigmatism and adequate spectacle-corrected vision [57].

2.3 Corneal transplantation and implantation

Corneal transplantation is a primary treatment for advanced keratoconus. Keratoconus is the cause of 18% of penetrating keratoplasty (PK) cases and 40% of deep anterior lamellar keratoplasty (DALK) cases [1, 58]. In cases of extreme corneal thinning, anterior limiting lamina transplantation may offer benefits, though further research is required to refine this approach [59]. Additionally, intrastromal stem cell implantation has been investigated as a potential method for partial stroma replacement or regeneration in advanced keratoconus [60].

2.3.1 Keratoplasty

Penetrating Keratoplasty (PK): This full-thickness corneal transplant is often performed in advanced keratoconus for which contact lenses are an ineffective treatment choice [61, 62].

Deep Anterior Lamellar Keratoplasty (DALK) involves replacing diseased stroma while preserving the recipient's corneal endothelium and posterior limiting lamina, leading to faster recovery, fewer healing complications, and reduced rejection risk [63].

Although PK can yield higher visual acuity than DALK, it carries increased risks of endothelial cell loss and graft rejection [62, 64].

2.3.2 Anterior Limiting Lamina Transplantation

This innovative technique is currently being evaluated for advanced cases of keratoconus that are not suitable for CXL or ICRS [65]. It has the potential to stabilize vision and delay the necessity for more invasive corneal transplants. A new technique involves the transplantation of an isolated anterior limiting lamina layer, placed either as a corneal stromal inlay or onlay, into a manually dissected mid-stromal pocket for patients with advanced keratoconus. It may effectively halt the progression of keratoconus and support contact lens tolerance [1, 65].

2.3.3 Intrastromal implantation of stem cells

Innovative approaches for stromal regeneration in keratoconus include stem cell therapies such as intrastromal injection alone, the use of biodegradable or nonbiodegradable scaffolds, and implantation with a decellularized corneal stromal scaffold, all of which have shown promise in preclinical studies [67].

CONCLUSIONS

Keratoconus is a progressive, bilateral, and asymmetric corneal disease that often manifests in the second or third decade of life and stabilizes by the fourth decade. Genetic factors, along with environmental risks such as eye rubbing and allergies, contribute to disease susceptibility. Recent advances in corneal imaging, wavefront aberrometry and machine learning have refined the understanding of keratoconus, improving detection of optical, anatomical, and biomechanical changes, particularly in subclinical cases. Current diagnostic standards include corneal tomography, pachymetry, and topography. The specific treatment plan depends on several factors, including the severity and progression of the disease. Spectacles and contact lenses are used for treating mild to moderate cases. Corneoscleral and scleral lenses have gained popularity due to their effectiveness in cases where other lens options are unsuccessful. Surgical interventions, particularly corneal cross-linking, have become a common treatment for progressive cases of keratoconus. Although extensive research over the past decade has significantly advanced the understanding of keratoconus, larger, long-term studies are still needed to optimize treatment selection.

Disclosures

Author's contribution

Conceptualization - Kinga Kowalik and Maria Michalska; methodology - Jakub Skiba; software - Kinga Tylczyńska and Sebastian Iwaniuk; check - Aleksandra Zielińska, Maria Michalska and Ignacy Maciejewski; formal analysis - Ignacy Maciejewski and Natalia Tylczyńska; investigation - Szymon Szypulski; resources - Maria Michalska; data curation - Kinga Tylczyńska and Jakub Skiba; writing - rough preparation - Sebastian Iwaniuk and Zuzanna Skiba; writing - review and editing, Szymon Szypulski and Aleksandra Zielińska; visualization, Natalia Tylczyńska; supervision - Kinga Kowalik; project administration – Kinga Kowalik; receiving funding not applicable, All authors have read and agreed with the published version of the manuscript.

Financing Statement:

This research received no external funding.

Institutional Review Board Statement:

Not applicable.

Informed Consent Statement:

Not applicable.

Data Availability Statement:

The authors confirm that the data supporting the findings of this study are available within the article’s bibliography.

Conflict of Interest:

Authors declare no conflict of interest.

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