EARLY DETECTION AND MODERN MANAGEMENT OF KERATOCONUS: ADVANCES IN CORNEAL TOMOGRAPHY, ARTIFICIAL INTELLIGENCE, AND SURGICAL INTERVENTIONS

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Abstract. Keratoconus is a progressive ectatic disorder of the cornea characterized by stromal thinning, irregular corneal shape, and the development of irregular astigmatism. In advanced cases, these changes may result in a substantial reduction in visual function. Early diagnosis has become increasingly important because the detection of subclinical disease and early progression allows treatment to be initiated before significant structural damage develops. Modern corneal tomography provides detailed information about anterior and posterior corneal elevation, pachymetric distribution, and changes in corneal shape that may not be detected by conventional examination alone. Anterior segment optical coherence tomography and assessment of corneal biomechanics can provide additional information in patients with suspected early disease. In recent years, artificial intelligence has also been increasingly investigated for the analysis of corneal imaging and the identification of subtle patterns associated with keratoconus. Modern management includes optical correction, corneal cross-linking, intrastromal corneal ring segments, and keratoplasty in advanced disease. The choice of treatment depends on disease stage, documented progression, corneal characteristics, and the visual needs of the patient. This review discusses current advances in the early detection of keratoconus, the growing role of artificial intelligence, and contemporary surgical approaches to disease management.

Keywords: keratoconus; corneal tomography; corneal topography; artificial intelligence; corneal cross-linking; intrastromal corneal ring segments; keratoplasty.

РАННЯЯ ДИАГНОСТИКА И СОВРЕМЕННЫЕ ПОДХОДЫ К ЛЕЧЕНИЮ КЕРАТОКОНУСА: ДОСТИЖЕНИЯ ТОМОГРАФИИ РОГОВИЦЫ, ИСКУССТВЕННОГО ИНТЕЛЛЕКТА И ХИРУРГИЧЕСКИХ ВМЕШАТЕЛЬСТВ

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Аннотация. Кератоконус представляет собой прогрессирующее эктазийное заболевание роговицы, характеризующееся истончением стромы, изменением формы роговицы и развитием неправильного астигматизма. На поздних стадиях эти изменения могут приводить к значительному снижению зрительных функций. Ранняя диагностика приобретает все большее значение, поскольку выявление субклинических форм заболевания и начальных признаков прогрессирования позволяет своевременно начать лечение до развития выраженных структурных изменений роговицы. Современная томография роговицы позволяет получать подробную информацию о передней и задней элевации роговицы, распределении ее толщины и изменениях формы, которые могут не выявляться при стандартном офтальмологическом обследовании. Оптическая когерентная томография переднего отрезка глаза и оценка биомеханических свойств роговицы могут предоставлять дополнительную информацию у пациентов с подозрением на ранний кератоконус. В последние годы активно изучаются возможности применения искусственного интеллекта для анализа изображений роговицы и выявления малозаметных признаков, характерных для кератоконуса. Современное лечение включает оптическую коррекцию, кросслинкинг роговичного коллагена, имплантацию интрастромальных роговичных сегментов и кератопластику при далеко зашедших стадиях заболевания. Выбор метода лечения зависит от стадии заболевания, наличия документированного прогрессирования, состояния роговицы и зрительных потребностей пациента. В настоящем обзоре рассматриваются современные достижения в ранней диагностике кератоконуса,

возрастающая роль искусственного интеллекта и современные хирургические подходы к лечению заболевания.

Ключевые слова: кератоконус; томография роговицы; топография роговицы; искусственный интеллект; кросслинкинг роговичного коллагена; интрастромальные роговичные сегменты; кератопластика.

Introduction

Keratoconus is a bilateral, usually asymmetric ectatic disorder in which progressive thinning and structural weakening of the cornea lead to localized protrusion and increasing optical irregularity. The disease commonly begins during adolescence or early adulthood, although its clinical course is highly variable. Some patients remain relatively stable for many years, whereas others demonstrate rapid progression and significant visual deterioration.

The clinical consequences of keratoconus are mainly related to progressive irregular astigmatism, myopia, higher-order aberrations, and reduced quality of vision. In advanced stages, corneal scarring or acute corneal hydrops may further impair visual function. For this reason, the current approach to keratoconus is no longer limited to correcting refractive error. Greater attention is now given to detecting the disease at an early stage, recognizing progression, and providing timely treatment aimed at maintaining corneal stability [1, 2].

Several factors have been associated with keratoconus, including family history, allergic or atopic disease, and habitual eye rubbing. Current evidence also supports careful evaluation of patients with suspicious corneal findings before refractive surgery, because subtle or subclinical ectatic changes may increase the risk of postoperative corneal instability [1, 3].

The development of corneal tomography, anterior segment optical coherence tomography (OCT), biomechanical assessment, and artificial intelligence (AI) has significantly expanded the possibilities for early diagnosis. At the same time, advances in corneal cross-linking and other surgical techniques have changed the prognosis of patients with progressive disease.

Early Detection of Keratoconus

The diagnosis of established keratoconus is often straightforward when characteristic clinical and topographic changes are present. Early and subclinical disease is more difficult to recognize. Patients may have good corrected visual acuity and only minor refractive changes, while structural abnormalities are already beginning to develop.

Traditional Placido-based corneal topography remains useful for evaluating the curvature of the anterior corneal surface. Typical findings include inferior or inferotemporal steepening, asymmetric bow-tie patterns, irregular astigmatism, and increased corneal power. However, topography evaluates primarily the anterior surface and may therefore be insufficient for detecting some of the earliest ectatic changes [3, 4].

Corneal tomography has become particularly important in this setting. Scheimpflug-based systems provide three-dimensional information about the anterior and posterior corneal surfaces as well as corneal thickness. Evaluation of posterior elevation, the location of the thinnest point, and the pattern of pachymetric progression may reveal abnormalities before obvious changes become visible on conventional anterior surface topography [3].

The importance of combining several diagnostic parameters has been increasingly recognized. No single tomographic value should be considered sufficient for establishing early keratoconus in every patient. Interpretation should include corneal shape, anterior and posterior elevation, pachymetric distribution, refractive findings, and changes observed during follow-up.

Anterior segment OCT provides another useful approach to the assessment of early disease. High-resolution imaging allows detailed evaluation of corneal thickness and epithelial distribution. The corneal epithelium may partly compensate for irregular stromal shape by becoming thinner over the cone and relatively thicker in surrounding areas. This remodeling can mask early ectatic changes on anterior surface measurements. Epithelial thickness mapping may therefore provide additional diagnostic information when standard tomography is inconclusive [3, 4].

Corneal biomechanical assessment is also receiving increasing attention. Keratoconus is not only a geometric abnormality but also a disorder associated with altered corneal mechanical properties.

Combining biomechanical parameters with tomography may improve the identification of eyes with early structural weakness. Nevertheless, interpretation remains device-dependent, and these measurements should currently be considered complementary to rather than replacements for established clinical and tomographic assessment [1, 4].

Early diagnosis is especially important in younger patients because disease progression can be more rapid in this group. Serial examinations remain essential when progression is suspected. Comparison of corneal curvature, thickness, elevation, refraction, and visual function over time can help determine whether intervention is required.

Artificial Intelligence in Keratoconus Diagnosis

Artificial intelligence has become one of the most actively investigated areas in keratoconus diagnostics. The large amount of quantitative data generated by modern corneal imaging systems makes the disease particularly suitable for machine-learning applications.

Machine-learning and deep-learning algorithms can process multiple parameters simultaneously and identify complex patterns that may not be evident when individual measurements are evaluated separately. These approaches have been applied to corneal topography, Scheimpflug tomography, anterior segment OCT, biomechanical measurements, and combinations of different imaging modalities [5, 6].

A systematic review by Goodman and Zhu showed that a substantial proportion of AI studies in keratoconus have focused on diagnosis and the recognition of subclinical disease. Neural networks, support vector machines, random forests, and other classification methods have been evaluated for distinguishing normal corneas from keratoconic or suspicious corneas [5].

A systematic review and meta-analysis by Hashemi et al. also demonstrated that AI-assisted analysis of corneal imaging can achieve high diagnostic performance. In particular, combinations of Scheimpflug imaging with Placido-based topography have shown promising results for the recognition of subclinical and forme fruste keratoconus [6].

The potential clinical value of AI extends beyond simple classification. Future models may assist with progression prediction, identification of patients who require closer follow-up, and selection of appropriate treatment strategies. Integration of demographic factors, tomography, epithelial thickness, biomechanics, and longitudinal measurements may eventually provide a more individualized assessment of disease risk.

Despite these advantages, several limitations remain. Many AI models have been developed using retrospective datasets obtained from single centers or specific imaging devices. Differences in patient populations, definitions of subclinical disease, image acquisition protocols, and diagnostic platforms may affect model performance. External validation is therefore necessary before an algorithm can be considered reliable for routine clinical use [4–6].

Another important issue is interpretability. A highly accurate model may still have limited clinical value if the physician cannot understand which parameters influenced the result. For this reason, AI should currently be viewed as a decision-support tool rather than an independent diagnostic system.

Modern Management of Keratoconus

Management of keratoconus has changed considerably during the past two decades. The main objectives are to provide adequate visual rehabilitation and, when progression is present, to prevent further structural deterioration.

In mild and stable disease, spectacles may provide satisfactory vision. With increasing irregular astigmatism, soft toric lenses may become insufficient, and rigid gas-permeable, hybrid, or scleral contact lenses can provide better optical correction. Contact lenses, however, do not prevent disease progression.

Corneal Cross-Linking

Corneal collagen cross-linking (CXL) is currently the main treatment used to stabilize progressive keratoconus. The procedure combines riboflavin with ultraviolet-A irradiation to produce additional cross-links within the corneal stromal collagen, thereby increasing biomechanical resistance.

The principal indication for CXL is documented or strongly suspected progression, particularly in young patients who have a higher risk of continued ectatic change. Current international consensus and clinical practice guidance recognize CXL as an important intervention for reducing or stopping progression in suitable patients [1, 2].

The conventional epithelium-off protocol remains the most extensively studied approach. Accelerated protocols and transepithelial techniques have also been developed in an attempt to reduce treatment time or improve postoperative comfort. However, differences in depth of effect and long-term evidence should be considered when selecting a protocol.

It is important to explain to patients that the primary purpose of CXL is disease stabilization rather than refractive correction. Some flattening of the cornea and improvement in visual acuity may occur, but these outcomes are not guaranteed.

Intrastromal Corneal Ring Segments

Intrastromal corneal ring segments (ICRS) can be considered in selected patients with keratoconus who have significant corneal irregularity and reduced visual function but retain adequate corneal clarity and thickness.

The segments are implanted into the peripheral corneal stroma and modify corneal geometry by flattening the central or paracentral cornea. This may reduce irregular astigmatism and improve uncorrected or corrected visual acuity in appropriately selected patients.

ICRS primarily provide optical and geometric rehabilitation and should not be considered a substitute for CXL when progression is present. In some patients, a combined or staged approach using ICRS and CXL may be appropriate [1, 2].

Patient selection is critical because outcomes depend on cone location, corneal thickness, refractive characteristics, and the type and position of the implanted segments. The procedure may improve corneal regularity, but complete normalization of the cornea should not be expected.

Keratoplasty

Corneal transplantation remains necessary in a relatively small group of patients with advanced keratoconus, particularly when significant stromal scarring is present or when satisfactory visual rehabilitation cannot be achieved with contact lenses or less invasive interventions.

Deep anterior lamellar keratoplasty (DALK) is an important option when the corneal endothelium remains healthy. In DALK, the diseased anterior stroma is replaced while the patient's own Descemet membrane and endothelium are preserved. This reduces the risk of endothelial rejection and may provide advantages for long-term graft survival.

Penetrating keratoplasty remains appropriate in selected advanced cases, including situations in which deep stromal or Descemet membrane abnormalities make lamellar surgery unsuitable. Although visual outcomes can be good, penetrating keratoplasty carries risks related to endothelial rejection, graft failure, postoperative astigmatism, and prolonged visual rehabilitation [1, 2].

The availability of CXL and improved methods of visual rehabilitation has reduced the need to proceed directly to transplantation in many patients. Modern management therefore follows a stepwise and individualized approach, with the least invasive effective intervention selected according to disease stage and progression.

Discussion

The development of modern corneal imaging has changed the clinical understanding of keratoconus. Diagnosis is now based less on isolated curvature values and more on an integrated assessment of corneal morphology, thickness, posterior elevation, biomechanics, and longitudinal change.

This shift is clinically important because structural changes may be detectable before major visual symptoms develop. Early identification creates an opportunity to monitor patients more closely and, when progression is confirmed, to perform CXL before advanced irregular astigmatism or scarring develops.

Artificial intelligence may further improve this process by integrating large numbers of measurements that are difficult to interpret simultaneously during routine examination. Current evidence is encouraging, particularly for the differentiation of normal, subclinical, and established keratoconus. However, reported diagnostic accuracy should be interpreted in the context of the datasets on which individual algorithms were trained. Prospective multicenter validation and greater standardization are still required before widespread autonomous clinical application can be recommended [5, 6].

The same principle of individualization applies to treatment. CXL addresses progression, while contact lenses and ICRS primarily address visual rehabilitation and corneal regularity. Keratoplasty remains an effective option for advanced disease but is generally reserved for patients in whom less invasive methods cannot provide an acceptable functional result.

Thus, the modern management of keratoconus requires a distinction between three clinical questions: whether the diagnosis is established, whether the disease is progressing, and whether the patient's current visual function is satisfactory. Treatment should be selected according to the answer to each of these questions rather than on disease stage alone.

Conclusion

Early detection is one of the main priorities in contemporary keratoconus management. Corneal tomography has improved the recognition of subtle ectatic changes by providing information about posterior corneal elevation, pachymetric distribution, and the overall three-dimensional structure of the cornea. Anterior segment OCT and biomechanical assessment can provide additional information in suspicious or subclinical cases.

Artificial intelligence offers promising opportunities for combining multiple imaging parameters and identifying complex diagnostic patterns. However, current AI systems require further external validation, standardization, and assessment across different populations and imaging platforms before they can be routinely used as independent diagnostic tools.

Modern treatment should be individualized according to disease progression, corneal characteristics, and visual requirements. Corneal cross-linking remains the principal method for stabilizing progressive keratoconus, while intrastromal corneal ring segments may improve corneal regularity and visual function in selected patients. Keratoplasty continues to play an important role in advanced disease.

The combination of earlier diagnosis, careful monitoring, and timely intervention has made it possible to shift the management of keratoconus from treatment of advanced visual impairment toward preservation of corneal structure and long-term visual function.

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