



Impact of anterior segment parameters on corneal higher-order aberrations in keratoconus: a retrospective study

Early eGFR decline in IgA nephropathy

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Abstract

Aim: The purpose of this study is to evaluate the impact of anterior chamber and corneal parameters on higher-order aberrations in healthy eyes and in eyes with keratoconus.

Methods: A retrospective case-control study, comprising 50 keratoconus eyes and 50 healthy eyes that were matched for age and astigmatism. All measurements were obtained using the Sirius Scheimpflug-Placido system. Recorded parameters included corneal volume (CV), thinnest corneal thickness (TCT), apical corneal thickness (ACT), anterior chamber depth (ACD), anterior chamber volume (ACV), corneal curvature (CC), symmetry indices (ASI, PSI), and Baiocchi-Calossi-Versaci anterior/posterior indices. Higher-order aberrations (HOAs) were analyzed using Zernike polynomials (coma root mean square [RMS], spherical aberration RMS, total HOA RMS). Non-parametric tests (Mann-Whitney U) and Spearman correlation coefficients were applied. Statistical significance was set at $P < .001$.

Results: Keratoconus eyes demonstrated markedly reduced TCT and ACT, and significantly increased ACD, ACV, CC, symmetry indices, and Baiocchi-Calossi-Versaci index (BCV) indices compared with the control group ($P < .001$). Coma RMS and total HOA RMS were substantially elevated in the keratoconus group. Coma showed strong correlations with BCV anterior and BCV posterior, CC, and strong negative correlations with TCT and ACT.

Conclusion: This study demonstrates that structural alterations in both the cornea and anterior chamber strongly influence HOA profiles in keratoconus. The robust associations between coma/total HOAs and parameters reflecting corneal irregularity and anterior chamber enlargement highlight the importance of integrating HOA analysis into keratoconus diagnosis, staging, and treatment planning.

Keywords

keratoconus, corneal aberrations, corneal topography, anterior chamber, tomography

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Introduction

The cornea is a major refractive component of the human eye, and its morphological and biomechanical properties play a crucial role in maintaining visual quality. Advances in optical imaging and wavefront analysis have increased the clinical relevance of higher-order aberrations (HOAs), which may lead to visual disturbances such as glare, halos, reduced contrast sensitivity, and impaired night vision even at low levels. Therefore, understanding the mechanisms underlying HOAs and identifying their biometric determinants are essential for diagnostic evaluation and preoperative planning in refractive surgery.¹⁻³

Keratoconus is a progressive ectatic disease characterized by stromal thinning and anterior corneal protrusion, resulting in irregular corneal surfaces and a significant increase in optical aberrations. Previous studies have demonstrated that total HOAs, particularly coma-like aberrations, are markedly higher in keratoconic eyes compared with healthy eyes.⁴ Vertical coma is a characteristic feature of keratoconus and is strongly associated with impaired visual quality, especially under low-light conditions.⁵

Advances in Scheimpflug-based tomography and wavefront aberrometry have enabled comprehensive evaluation of both corneal morphology and optical aberration patterns. Emerging evidence highlights the diagnostic value of corneal HOAs in detecting early keratoconus. Darwish et al.⁵ reported that anterior corneal coma demonstrates high discriminative accuracy even in subclinical cases, while Yekta et al.⁶ showed that both lower- and higher-order aberrations correlate with disease severity and may aid in staging.^{5,6}

In addition to corneal geometry, anterior segment parameters such as anterior chamber depth (ACD), anterior chamber volume (ACV), and angle metrics may influence intraocular light propagation and contribute to aberration formation. Even subtle variations in these parameters may alter optical pathways and exacerbate visual dysfunction.⁷ Furthermore, biomechanical alterations, including stromal weakening and changes in corneal elasticity, play a key role in the development of conical deformation and associated aberration patterns in keratoconus.⁸

The generation of corneal aberrations is multifactorial, involving the interaction of corneal curvature, asphericity, thickness, biomechanical stability, and anterior chamber morphology. Evaluating parameters such as ACD, ACV, and angle width alongside corneal geometry may provide a more comprehensive understanding of the ocular optical system.⁹ This integrated approach is increasingly relevant in refractive and cataract surgery, where variations in anterior segment architecture have been associated with postoperative increases in HOAs.¹⁰

Despite these advances, most studies have evaluated corneal aberrations or anterior segment parameters separately, and data on their combined effects remain limited. In particular, there is a lack of comprehensive analyses comparing the contributions of anterior chamber parameters to HOAs across different stages of keratoconus. Therefore, this retrospective study aimed to evaluate the relationship between anterior chamber parameters and corneal higher-order aberrations in keratoconic and healthy eyes, in order to provide a more integrated understanding of the optical and biomechanical determinants of keratoconus.

Materials and Methods

Ethical approval for this retrospective case-control study was obtained from the Institutional Ethics Committee (Approval No:

2016/06, dated 30 March 2016) prior to the initiation of the research protocol. The approval permitted the retrospective evaluation of patient records. Following this approval, patients who presented to the Cornea Clinic of the Department of Ophthalmology, Çanakkale Onsekiz Mart University School of Medicine, between January 2018 and December 2020 and who had available Scheimpflug corneal topography records (Sirius, CSO, Italy) were retrospectively reviewed. Consecutive sampling was used to include all eligible patients. Sample size estimation was performed using G*Power 3.1.9.2 with an alpha error of 0.01 and a statistical power of 95%, resulting in a required sample size of 100 eyes. The study included 50 eyes of 50 patients diagnosed with keratoconus (Group 1) and 50 eyes of 50 healthy individuals (Group 2), matched for age, sex, and keratometric astigmatism.

Inclusion Criteria

Group 1 included eyes with keratoconus diagnosed according to clinical, topographic, and tomographic findings. Group 2 consisted of healthy eyes with normal corneal topography and no ocular pathology other than refractive error.

Exclusion Criteria

Eyes with a history of corneal refractive surgery or corneal transplantation, traumatic corneal scarring, ocular infection, severe dry eye disease, inflammatory ocular surface disorders, or systemic connective tissue diseases were excluded. Additionally, measurements obtained before adequate contact lens washout (4 weeks for rigid lenses and 2 weeks for soft lenses) were not included.¹¹

Imaging Protocol

All measurements were performed using the Sirius Scheimpflug-Placido tomographer. This system simultaneously provides anterior and posterior corneal elevation maps, pachymetry distribution, anterior chamber measurements, and corneal aberration data.

Recorded Parameters

The following parameters were recorded: ACD, ACV, corneal volume (CV), thinnest corneal thickness (TCT), apical corneal thickness (ACT), mean keratometry (Kmean), corneal curvature (CC), anterior symmetry index (ASI), posterior symmetry index (PSI), and Baiocchi-Calossi-Versaci indices. Higher-order aberration components, including coma root mean square (RMS), spherical aberration RMS, total HOA RMS, and astigmatic RMS, were calculated using the device's Zernike polynomial analysis module.

Ethical Approval

Ethical approval was obtained from the Clinical Research Ethics Committee of Çanakkale Onsekiz Mart University, Faculty of Medicine (Date: 30.03.2016, Decision No: 2016/06).

Statistical Analysis

Statistical analyses were performed using SPSS version 25. Continuous variables were expressed as mean $\pm$ standard deviation. Normality was assessed with the Kolmogorov-Smirnov test. Because the variables were not normally distributed, the Mann-Whitney *U* test was used for group comparisons, and Spearman's rho correlation coefficient was used to analyze associations. Statistical significance was set at $P \leq .001$.

Reporting Guidelines

This study is reported in accordance with the STROBE guidelines.

Results

Demographic and Baseline Characteristics

A total of 100 eyes were included in the study, comprising 50 eyes with keratoconus (Group 1) and 50 healthy control eyes (Group

2). The mean age of the keratoconus group was 31.4 ± 9.7 years, while that of the control group was 30.2 ± 7.8 years, with no statistically significant difference between the groups ($P = .70$). Similarly, keratometric astigmatism did not differ significantly between groups ($P = .50$).

In contrast, marked differences were observed in corneal and anterior segment parameters. Keratoconic eyes exhibited significantly lower CV, TCT, and ACT, whereas ACD, ACV, CC, ASI, PSI, and Baiocchi–Calossi–Versaci indices were significantly higher compared with healthy controls ($P < .001$). These findings reflect the characteristic pattern of corneal thinning, increased curvature, and anterior chamber enlargement in keratoconus.

The detailed demographic, corneal, and anterior chamber parameters are presented in Supplementary Table 1.

Representative Scheimpflug tomography maps demonstrating corneal thickness distribution, anterior and posterior curvature patterns, and ectasia indices in a keratoconic eye are shown in Supplementary Figure 1.

Corneal Higher-Order Aberrations

A significant increase in higher-order aberrations (HOAs) was observed in keratoconic eyes compared with healthy controls. Coma RMS, spherical aberration RMS, total HOA RMS, and residual RMS values were all significantly higher in the keratoconus group ($P < .001$), whereas astigmatic RMS values did not differ significantly between groups ($P > .05$). Notably, coma RMS demonstrated the most pronounced elevation, consistent with the well-established optical signature of keratoconus.

Detailed HOA comparisons between groups are presented in Supplementary Table 2.

Correlation analysis revealed distinct patterns among aberration components. Coma aberration showed strong positive correlations with corneal structural parameters, particularly Baiocchi–Calossi–Versaci index (BCV) anterior ($\rho = 0.862$), BCV posterior ($\rho = 0.851$), and corneal curvature ($\rho = 0.833$), while demonstrating significant negative correlations with TCT and ACT. These findings indicate that progressive corneal thinning and surface irregularity are closely associated with increasing coma aberration.

In contrast, spherical aberration exhibited weaker correlations with corneal parameters ($\rho = 0.17$ – 0.47), suggesting a more limited structural dependence. Astigmatic HOA showed no significant correlations, indicating minimal association with corneal morphology.

Total HOA displayed a correlation profile similar to coma, with strong positive associations with corneal curvature and BCV indices ($\rho = 0.692$ – 0.872 , $P < .001$), highlighting the dominant role of corneal shape irregularity in overall optical degradation.

With respect to anterior chamber parameters, coma and total HOA demonstrated moderate positive correlations with ACD and ACV, whereas corneal volume showed a negative association with coma. These findings suggest that both corneal morphology and anterior chamber configuration contribute to the development of optical aberrations in keratoconus.

The relationships between HOAs and structural parameters are illustrated in Supplementary Figure 2.

Overall, the results demonstrate that keratoconus is associated with significant structural alterations characterized by corneal thinning and increased curvature, accompanied by enlargement of anterior chamber parameters. These morphological changes are strongly associated with increased higher-order aberrations, particularly coma, which appears to be the most sensitive optical

marker of disease severity.

Discussion

In this study, the relationship between corneal and anterior chamber structural parameters and higher-order corneal aberrations (HOAs) in eyes with keratoconus was comprehensively evaluated. The findings demonstrated that corneal thickness was significantly reduced in the keratoconus group, with the TCT and ACT being the most affected. Meanwhile, CC, ACD, ACV, anterior and posterior symmetry indices (ASI and PSI), and Baiocchi–Calossi–Versaci indices (BCVf and BCVb) were all markedly increased. These structural alterations closely paralleled the substantial elevation in coma and total HOA RMS values. Our results are consistent with previous studies reporting significantly increased HOAs, particularly coma-like aberrations, in keratoconic eyes compared with healthy controls.^{12–15}

The strong and statistically significant correlations observed between coma and total HOAs and both corneal and anterior chamber parameters suggest that corneal irregularities and alterations in anterior segment geometry are the primary determinants of the optical profile in keratoconus. Previous studies have demonstrated that coma-related aberrations increase progressively with disease severity and are detectable even in early stages.^{12,13} In agreement with these findings, our results showed strong correlations between coma RMS and increased corneal curvature as well as deterioration in symmetry indices, indicating that both the magnitude and spatial distribution of corneal deformation directly influence optical quality.

Spherical aberration exhibited only weak to moderate correlations with structural parameters, supporting the concept that coma is the predominant contributor to visual degradation in keratoconus. Previous studies have shown that increased HOAs, particularly coma and total HOA values, are associated with reduced contrast sensitivity even when visual acuity is relatively preserved.^{16,17} Although functional visual outcomes were not evaluated in the present study, the strong associations between HOAs and corneal structural indices indirectly support this mechanism.

The absence of significant correlations between astigmatic HOA and both corneal and anterior chamber parameters indicates that conventional refractive astigmatism alone does not adequately explain visual impairment in keratoconus. Instead, irregular astigmatism and higher-order optical distortions appear to be the principal drivers of visual dysfunction. Previous studies have also reported that anterior and posterior corneal HOAs can differentiate keratoconus from normal eyes with high diagnostic accuracy.^{13,14} In this context, the strong associations observed between total HOA and BCV indices highlight the importance of evaluating both anterior and posterior corneal surfaces.

Our findings also demonstrated significant associations between anterior chamber parameters and HOAs. Increases in ACD and ACV were positively correlated with coma and total HOAs, suggesting that anterior segment configuration contributes to the overall optical behavior of keratoconus. Previous studies using advanced anterior segment imaging techniques have similarly reported significant differences in anterior chamber parameters between keratoconic and normal eyes.^{18,19} These findings support the concept that keratoconus involves not only corneal alterations but also changes in anterior segment architecture.

The relationship between corneal volume and HOAs observed in this study further emphasizes the importance of volumetric

assessment in keratoconus. Decreased corneal volume was significantly associated with increased coma and total HOAs, indicating that volumetric loss contributes to optical irregularity. Previous studies have reported that progressive reductions in corneal volume are associated with disease progression^{20,21}. Therefore, corneal volume may serve as an additional parameter in the evaluation and monitoring of keratoconus.

From a clinical perspective, the strong associations between structural parameters and HOAs suggest that combined evaluation of corneal morphology and anterior chamber characteristics may improve diagnostic accuracy and risk stratification. In addition, these parameters may be useful in predicting optical outcomes of therapeutic interventions. Previous studies have shown that corneal collagen cross-linking (CXL) induces changes in corneal volume and anterior chamber parameters that correlate with improvements in visual function.²² Similarly, surgical interventions such as intracorneal ring segment (ICRS) implantation may influence both low- and higher-order aberrations.²³ These findings support the integration of structural and optical parameters into individualized treatment planning.

This study has several limitations. First, its retrospective and single-center design may limit generalizability. Second, the use of a single imaging system (Scheimpflug–Placido, Sirius) did not allow comparison across different devices, although previous studies suggest that inter-device differences are generally clinically acceptable.²⁴ In addition, corneal biomechanical parameters and functional visual outcomes were not evaluated. Future prospective studies incorporating these parameters are needed to further elucidate the relationship between structural and optical changes in keratoconus.

Limitations

This study has several limitations. First, its retrospective single-center design limits generalizability and causal inference. Second, keratoconus severity was not stratified using established staging systems such as the Amsler–Krumeich classification, and functional visual outcomes such as visual acuity were not evaluated. In addition, measurements were obtained using a single Scheimpflug–Placido imaging device (Sirius), preventing cross-device comparison. Corneal higher-order aberrations were calculated using the device’s Zernike polynomial analysis module within a standardized pupil-centered analysis zone. Finally, epithelial thickness mapping and corneal biomechanical parameters were not included. Future prospective multicenter studies incorporating multimodal imaging and functional assessments are needed to further clarify the structural and optical characteristics of keratoconus.

Conclusion

In conclusion, keratoconus is associated with pronounced alterations in both corneal structure and anterior segment geometry, characterized by progressive corneal thinning, increased curvature, and enlargement of anterior chamber parameters. These structural changes are strongly linked to significant elevations in higher-order aberrations, particularly coma, which emerged as the most sensitive optical marker of disease severity. The demonstrated associations between corneal morphology, anterior chamber configuration, and HOAs highlight the importance of a comprehensive, multi-parametric evaluation of the anterior segment. Integrating structural and optical parameters may enhance early diagnosis, improve disease monitoring, and support

more individualized and predictive treatment strategies in keratoconus management.

Declarations

Animal and Human Rights Statement

All procedures performed in this study were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Informed Consent

Due to the retrospective nature of the study, informed consent was waived by the Ethics Committee.

Data Availability

The datasets used and/or analyzed during the current study are not publicly available due to patient privacy considerations but are available from the corresponding author on reasonable request.

Conflict of Interest

The authors declare that there is no conflict of interest.

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Author Contributions (CRediT Taxonomy)

Conceptualization: A.Y.
Methodology: A.Y., S.A.
Software: A.Y.
Validation: S.A.
Formal analysis: A.Y., S.A.
Investigation: S.A.
Resources: A.Y.
Data curation: A.Y., S.A.
Writing – original draft: A.Y.
Writing – review & editing: A.Y.
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AI Usage Disclosure

No artificial intelligence (AI) tools were used in the design, data collection, analysis, or interpretation of the study.

Abbreviations

ACD: Anterior chamber depth
ACT: Apical corneal thickness
ACV: Anterior chamber volume
ASI: Anterior symmetry index
BCVb: Baiocchi–calossi–versaci index (back/posterior)
BCVf: Baiocchi–calossi–versaci index (front/anterior)
BCV: Baiocchi–calossi–versaci index
CC: Corneal curvature
CV: Corneal volume
CXL: Corneal collagen cross-linking
HOA: Higher-order aberrations
HOAs: Higher-order aberrations
ICRS: Intracorneal ring segment
Kmean: Mean keratometry
OCT: Optical coherence tomography
PSI: Posterior symmetry index
RMS: Root mean square
SPSS: Statistical package for the social sciences
STROBE: Strengthening the reporting of observational studies in epidemiology
TCT: Thinnest corneal thickness

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