REVIEW ARTICLE

Comprehensive Corneal Thickness Evaluation: A Narrative Review of Past, Present and Future

Avaliação da Espessura Corneana: Revisão Narrativa do Passado, Presente e Futuro

Inês Mendo [1], Tomás Loureiro [1], Nelson Sena Jr [2], Filipe Moraes [1], Inês Machado [1], Nuno Campos [1], Renato Ambrósio Jr. [2]

[1] ULS Almada-Seixal, Hospital Garcia de Orta, Almada, Portugal
[2] Federal University of the State of Rio de Janeiro, Rio de Janeiro, Brazil

Recebido/Received: 2025-06-29 | **Aceite/Accepted:** 2025-10-01 | **Published online/Publicado online:** 2026-03-17 | **Publicado/Published:** 2026-03-25

DOI: https://doi.org/10.48560/rspo.42135

ABSTRACT

Corneal thickness plays a fundamental role in assessing corneal health and diagnosing ectatic diseases. Initially, pachymetry relied on single-point measurements, particularly central corneal thickness (CCT). With the introduction of corneal tomography, it became possible to map corneal thickness at multiple locations, allowing for a more precise three-dimensional evaluation. In recent years, indices derived from spatial pachymetric profiles—such as the Corneal Thickness Spatial Profile (CTSP), Percentage Thickness Increase (PTI), and Ambrósio's Relational Thickness (ART)—have significantly improved the sensitivity and specificity of early ectasia detection. Moreover, epithelial thickness analysis has gained relevance by enabling the identification of compensatory remodeling in early stages of disease. These advanced tools have also been applied in the post-refractive surgery setting, where distinguishing between naturally thin corneas and true ectatic thinning is crucial. This review aims to provide a comprehensive overview of corneal thickness evaluation over time, describe current methodologies, and discuss their clinical application in the early diagnosis and monitoring of corneal disorders.

KEYWORDS: Corneal Pachymetry; Corneal Tomography.

RESUMO

A espessura corneana tem um papel fundamental na avaliação da saúde da córnea e no diagnóstico de doenças ectásicas. Inicialmente, a paquimetria baseava-se em medições pontuais, especialmente da espessura central. Com a introdução da tomografia corneana, tornou-se possível mapear a espessura em diferentes pontos da córnea, permitindo uma avaliação tridimensional mais precisa. Nos últimos anos, foram desenvolvidos índices derivados da análise do perfil espacial da espessura corneana, como o CTSP, PTI e ART, que melhoram significativamente a sensibilidade e especificidade para deteção precoce de ectasias. Além disso, a análise da espessura epitelial ganhou importância, permitindo identificar alterações compensatórias em fases iniciais da doença. Estas ferramentas avançadas também têm sido aplicadas na avaliação pós-cirurgia refrativa, onde a distinção entre córneas finas e córneas com afinamento secundário a ectasia é essencial. Esta revisão tem como objetivo apresentar uma visão abrangente sobre a avaliação da espessura corneana ao longo do tempo, descrever as modalidades atuais e discutir a sua aplicação clínica no diagnóstico precoce e no acompanhamento de doenças corneanas.

PALAVRAS-CHAVE: Paquimetria Corneana; Tomografia Corneana.

INTRODUCTION

Corneal thickness is an essential hallmark of corneal health. The expanding knowledge about corneal thickness and its spatial profile enormously deepened in many areas in ophthalmology. In cornea and refractive surgery, the comprehensive tomographic analysis of pachymetry data enabled the distinction between thin and thinned corneas and thick and thickened corneas. Hence, pachymetric data can provide information regarding corneal thinning (ectatic) diseases and endothelium healthiness.[1]

Keratoconus and ectatic corneal diseases are among the most benefited from these recent scientific advances. The spatial pachymetric profile analysis became the basis for most diagnostic parameters. This knowledge allowed for early-stage diagnosis, which in turn changed the paradigm of the disease. Furthermore, and even though refractive surgery has become relatively safe and predictable with low rates of postoperative ectasia, spatial pachymetric profile analysis has also allowed for a more accurate determination of ectasia development after refractive surgery and, additionally, for the prediction of ectasia susceptibility before surgery.

This article reviews the advances and clinical applications of comprehensive tomographic corneal thickness analysis in current ophthalmological practice. Furthermore, we aim to identify gaps and suggest future research that could optimize the diagnosis and early management of primary ectatic diseases and post-refractive surgery ectasia.

PACHYMETRY AND PACHYMETRIC MAPS

Pachymetry derives from the Greek words *pachos*, meaning 'thick', and *metry*, meaning measure. The first optical pachymeter was introduced in 1955 by David Maurice.[2] This measurement was examiner-dependent, leading to lower reproducibility. Subsequently, the ultrasonic technique was introduced by Frederic Kremer in 1980, demonstrating greater replicability than optical pachymetry and being accepted as the gold-standard method for measuring central corneal thickness (CCT).[3] Ultrasound (US) pachymetry is a single-point measurement, which usually refers to the measurements at the geometric center of the cornea or over the pupil center. Typically, CCT follows a 'Gaussian' distribution in a normal population with a mean CCT of 556 μm and a standard deviation of 34 μm, ranging from 454 to 669 μm.[4]

The cornea does not have a uniform thickness. It is thinner in the center and thickens towards the periphery. Moreover, neither the central geometric point nor the point over the center of the pupil represents the true corneal thinnest point.[5] Although measuring other points of the cornea with the US by moving the probe is possible, it may be severely influenced by the patient's cooperation and the examiner's experience. Therefore, a pachymetric map is crucial to determine the thinnest point, its thickness and localization, to study differences between meridians, and differences between both eyes, all of which have proven important information for clinical decision-making. Hence, the advent of pachymetric maps has allowed for a more complete analysis of corneal thickness.[6]

CORNEAL TOMOGRAPHY

Tomography derives from the Greek words tomos, meaning "slice," and graphia, meaning "describing". Corneal tomography was introduced in the late 1990s and represented the three-dimensional reconstruction of the cornea. It can evaluate the anterior and posterior corneal surfaces, thereby generating reliable pachymetric maps.

Different technologies are commercially available. Horizontal slit scanning tomography was first introduced with the Orbscan (Bausch & Lomb, Rochester, NY). Later, rotational scanning was accessible with the Pentacam (Oculus, Wetzlar, Germany), Galilei (Ziemer Port, Switzerland), Sirius (CSO, Italy) and the Preciso (iVIS Technologies. Taranto, Italy).

Corneal tomography provides corneal thickness determination at different locations and has been initially proposed to help identify ectasia at earlier stages. The thinnest point, which was not adequately measured by US pachymetry, proved to have higher accuracy than CCT for keratoconus diagnosis (AUC: 0.945 *vs* 0.919; p=0001). Its location and thickness could raise suspicion of ectasia: the thickness of <470 μm and Y coordinate >-500 μm. Moreover, the difference between both eyes' thinnest points > 20 to 30 μm was also considered suspicious. The difference between superior and inferior points in a 5 mm circle (equidistant from the center) > 30 μm and the difference between corneal apex thickness and thinnest point > 10 μm were also considered abnormal.[7]

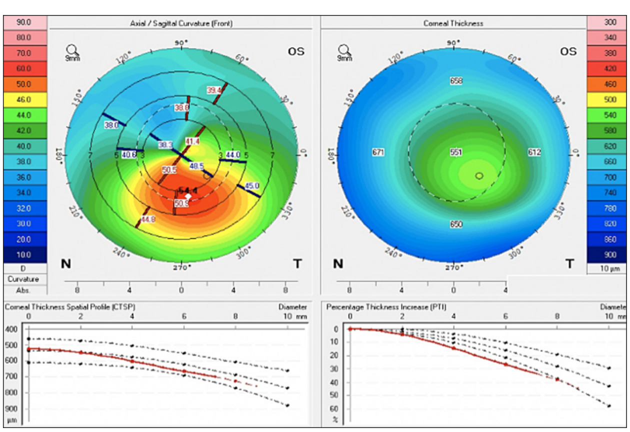
Despite representing valuable information and changing the way ectasia was identified, corneal tomography was still made up of single measurements and did not provide spatial thickness profiles. Corneal thickness spatial variation knowledge includes more points, allowing for understanding thickness progression. Mandell and Polse were pioneers and studied the horizontal profile of corneal thickness using a modified optical pachymeter.[8] In their study, the difference between central and peripheral measurements was found to be significantly greater in keratoconus and a difference greater than 0.085 mm was actually considered pathognomonic of keratoconus. Likewise, Avitable defined keratoconus index (KI) as the ratio between the mean peripheral corneal thickness and the thinnest point measured by ultrasound biomicroscopy.[9,10] The KI was very sensitive to differentiate normal and keratoconic corneas and its value was correlated with disease severity. Although KI calculation has become faster by a semi-automated method described by Castiglione, this technique has not been clinically popularized because it is still time-consuming, its measurements are very subjective and lack practicality.[11]

The concept of spatial variation of corneal thickness raised interest, prompting subsequent research to apply this knowledge to clinical practice.[12]

CORNEAL THICKNESS PROFILE

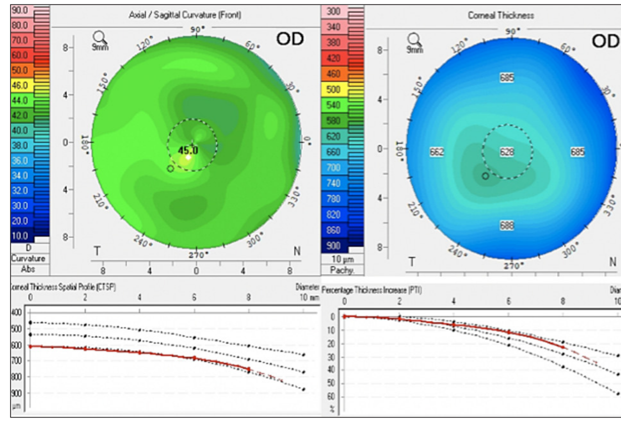
The concept of corneal thickness profile (CTP) attracted considerable interest in the field. Ambrosio and his coworkers from the Rio de Janeiro Corneal Tomography and Biomechanics Study Group (Rio-CTBSG) proposed a system to evaluate spatial variation of corneal thickness: from the thinnest point (TP), the average thickness of twenty-two imaginary circles at 0.1mm steps is calculated and presented in a graph (corneal thickness spatial profile – CTSP). From that representation, the percentage thickness increase (PTI) is calculated for each position using the formula: (CT@x - TP) / TP, where x represents the average thickness on the imaginary circles. The CTSP and PTI graphs also contain reference data with 95% confidence interval from a normal population.[1] The CTSP displays the thinnest point as the starting point, while the PTI refers to a percentage increase in thickness considering the TP. The PTI starts from zero so both normal thin and normal thick corneas may have a similar PTI, while the CTSP curve's starting point will be in accordance with the TP value.[1]

Healthy corneas present similar spatial thickness progression patterns.[12] A normal profile corresponds to a curved line plotted in red, following (but not necessarily within) the standard course of the normative black dotted curves; it does not leave the course before the 6 mm; and has an average of less than 1.2.[12,13] Even considering different overall thicknesses, analysis of variation enabled the distinction between normal thin and normal thick corneas from ectasia and edema, respectively. In clinical practice, the corneal thickness profile evaluation can help diagnose an ectasia in a cornea of normal thickness (Case 1) or exclude an ectasia in a thin cornea with normal progression indices.



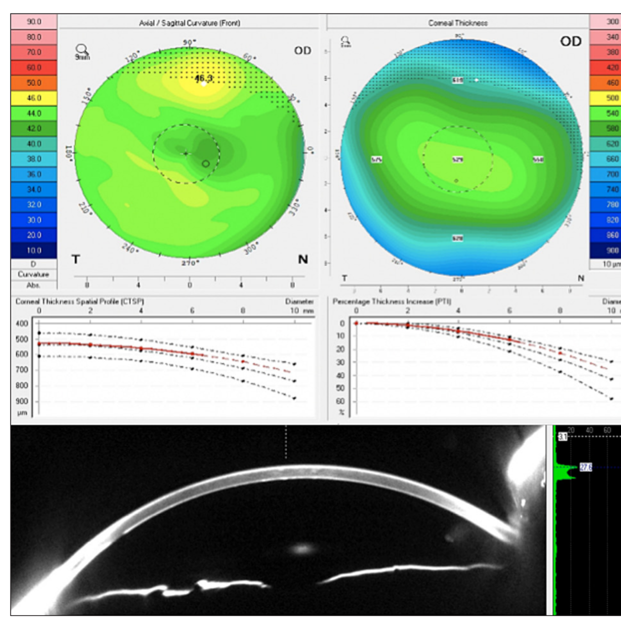
Case 1. 18-year-old female diagnosed with keratoconus grade 3. Central corneal thickness of 551 μm with a pronounced thickening from the thinnest point towards the periphery. Average PPI of 1.92, ART-Max of 163 μm, BAD-D of 7.93 and TBI of 1.00.

In addition to ectasia detection, analysis of these maps can also suggest endothelial disorders, even in patients with thin corneas whose diagnosis can be particularly challenging (Cases 2 and 3). In fuchs endothelial corneal dystrophy, it is imperative to look for signs of subclinical edema



Case 2. 66-year-old female diagnosed with Fuchs endothelial corneal dystrophy. Central corneal thickness of 628 μm, not respecting the spatial progression (plateau line). Average PPI of 0.83, ART-Max of 397 μm, BAD-D of 0.67 and TBI of 0.20.

in Scheimpflug images (loss of parallel isopachs, which are observed in pachymetric maps, displacement of the thinnest point of the cornea from its normal position in inferotemporal quadrant, and depression of the posterior corneal surface towards the anterior chamber).[14] Furthermore, the corneal densitometry can strengthen the diagnosis by showing a second hump sign at the level of the Descemet's membrane ("camel sign"), which correlates with the presence and severity of corneal guttata (Case 3).[15]



Case 3. 74-year-old male diagnosed with Fuchs endothelial corneal dystrophy in a slightly thin and thinned cornea with subclinical edema. Central corneal thickness of 529 μm not respecting the spatial progression (plateau line). Average PPI of 0.88, ART-Max of 336 μm, BAD-D of 1.43, TBI of 0.45. Densitometry analysis in Scheimpflug image reveals the "camel sign", suggesting corneal guttata.

The clinical hypothesis to evaluate corneal thickness profile considering annular rings centered at the thinnest point was developed in 1999 by Renato Ambrósio Jr, during his residency at Instituto de Oftalmologia Tadeu Cvintal (São Paulo, Brazil). Allan Luz developed the first study in 2004 using Orbscan data to evaluate corneal thickness spatial profiles manually. In Luz's first study, data from 100 normal and 25 mild to moderate keratoconus patients were evaluated, and he concluded that keratoconus corneas have a more abrupt increase in thickness from the thinnest point towards the periphery.[13] Later, Ambrósio applied this methodology to automatically generate CTSP and PTI graphs using the Pentacam. The same findings were observed when comparing 364 normal eyes and 46 eyes with mild to moderate keratoconus. Keratoconus corneas had a higher increase at each diameter centered on the TP ($p<0.0001$) compared to normal corneas.[12] This software was included in Pentacam in 2005 (Oculus, Wetzlar, Germany), and it also calculates an average progression index from the progression indices of different meridians. A higher progression index can be identified in keratoconus (1.81 ± 1.16 mm *vs* 0.91 ± 0.23 mm; $p<0.05$).[16]

Later, Ambrósio described relational thickness, which represents the ratio between single-point metrics (thinnest point) and PTI values. These parameters' ability to differentiate eyes with keratoconus from normal eyes was tested. Ambrósio's Relational Thickness (ART) is given by the formula TP/PPI. ART-Max (TP/PPI Max) and ART-Ave (TP/PPI Ave) were the best parameters with areas under the ROC curve (AUC) of 0.987 and 0.983, respectively. The best cut-offs to detect ectasia were 339 μm and 424 μm for ART-Max and ART-Ave, respectively.[16]

INTEGRATION OF PACHYMETRIC DATA IN ENHANCED ALGORITHMS

Tomographic-derived pachymetric parameters were an important breakthrough in ectasia diagnosis, representing a more accurate means of detecting ectatic disease than single-point measurements. This accuracy significantly grew when Michael W. Belin created the Belin-Ambrosio Enhanced Ectasia Display (BAD), which incorporated data from both anterior and posterior surfaces of the cornea. BAD is a comprehensive display that combines data from elevation and different tomographic criteria, which are presented as the standard deviation from the normality (d values): anterior and posterior elevation at the TP (8 mm best-fit sphere, BFS), TP thickness and location, PPI, and ART-Max. The final BAD-D variable is calculated based on regression analysis to maximize accuracy for detecting ectatic disease. A BAD-D higher than 2.1 has a sensitivity of 99.59%, and a specificity of 100% for keratoconus diagnosis, whereas a BAD-D higher than 1.22 provides a sensitivity of 93.62% and a specificity of 94.56% for detecting mild or subclinical disease.[17]

The Pentacam Random Forest Index (PRFI), a model based on artificial intelligence, improved the detection of corneal ectasia susceptibility using tomographic data. PRFI has a sensitivity of 100% to detect clinical ectasia (cut-off 0.52) and an AUC of 0.992 (94.2% sensitivity, 98.8% specificity, cut-off 0.216) to identify ectasias and very asymmetric ectasias with normal topography.[18]

Jack Holladay[19] proposed the Relative Thickness Map available on the Pentacam and the Visante time-domain OCT (Zeiss). This map comprises the percentage of thinning or thickening of the examined cornea in each position, considering the TP data and normal population profiles. In general, cases with lower than -5% of relative thinning are suspicious of ectasia, and thickening greater than +8% are suspicious of edema.

The advances in pachymetric evaluation improved the ability to diagnose keratoconus, namely early-stage diagnosis and allowed for the identification of susceptible corneas. Although it is not the aim of this paper, combining tomographic data with biomechanics has been shown to be the best approach to detecting ectasia and defining susceptibility. The Corneal Biomechanical Index (CBI) was combined with the corneal thickness spatial profile to generate the Tomographic and Biomechanical Index (TBI), which demonstrated even higher accuracy in detecting subclinical keratoconus.[20,21]

SEGMENTAL OR LAYERED TOMOGRAPHY

The concept of segmented or layered evaluation of corneal thickness was first introduced by Reinstein *et al* using very high frequency (VHF) digital ultrasound, which measures total corneal and epithelial thicknesses.[22] The area of epithelial thickness analyses increased from 3 mm to 10 mm, and VHF digital ultrasound became the gold standard for epithelial thickness measurement due to its high precision, replicability, and absence of tear film influence.[23]

VHF digital ultrasound clarified the role of corneal epithelium remodeling in cases of stromal abnormalities. Corneal epithelial thickness is not homogeneously distributed and tends to alter its profile to compensate for curvature and stromal irregularities to re-establish a stable and smooth ocular surface.[24–26] Reinstein[27–32] described these compensatory changes, and epithelial thickness analysis became of high interest in many ophthalmological diseases, such as keratoconus, and surgical fields, especially regarding refractive surgery.

Anterior segment optical coherence tomography (AS-OCT) provides high-resolution images of the corneal epithelium with no need for contact or anesthesia. With a reproducibility of 0.93 and a repeatability of 0.8, AS-OCT has been widely used to study epithelial thickness in recent years.[27] Fourier-domain (FD) OCTs replaced Time-domain (TD) due to their higher resolution and shorter acquisition time. RTVue (Optovue, Inc., Fremont, California, USA) and Avanti (Optovue) are FD-OCTs, and the latter has the additional advantage of augmenting cornea mapping area from 6 to 9 mm.[33]

Analysing epithelial changes is of great clinical importance as they could be the first morphological changes detected in the early stages of KC. In these cases, the minimum epithelial thickness could be found in the inferior areas instead of the superior observed in normal eyes.[35] Higher differences between the minimum and maximum epithelial thickness (min-max) could be registered.[27] Furthermore, in a characteristic "doughnut pattern", the epithelium thins at the cone's apex and thickens in the surrounding area. Using epithelial thickness maps, 50% of topographically normal fellow eyes of KC eyes have been found to have KC.[34]

Silverman *et al*[26] and Li *et al*[27] developed highly accurate computerized algorithms to differentiate normal and keratoconic corneas based only on epithelial thickness data. Moreover, Vega Estrada *et al*[36] showed a correlation between ET measurements and the degree of visual impairment in keratoconus. From here, epithelial thickness evaluation was necessary in KC diagnosis and integrated into the multimodal diagnostic approach.

Regarding refractive surgery, Reinstein described the behaviour of corneal epithelium following refractive surgery: epithelium thickens in areas where tissue has been removed or where the curvature has been flattened, and thins over elevated regions or where the curvature steepened.[30-32] Recently, Yang *et al*[37] reinforced the positive correlation between corneal epithelial remodeling after femtosecond laser-assisted in situ keratomileusis (FS-LASIK) and transepithelial refractive keratectomy (Trans-PRK). Even though significant curvature flattening is seen after both procedures, the corneal epithelium remodeling and subsequent thickening correlates with the specific procedure, appearing in different regions in the corresponding areas of PRK and FS-LASIK.

There is still much to know regarding epithelial mapping after refractive surgery. Understanding expected epithelial behavior could be a critical factor in the early detection of ectasia susceptibility to prevent iatrogenic ectatic disease.

WHERE TO GO FROM HERE

Tomography represented a massive step for a more comprehensive evaluation of corneal thickness. It was possible to jump into corneal spatial thickness profile evaluation from single-point measurements, which enabled the distinction between thin and thinned corneas and between thick and thickened corneas.

Thinning is the hallmark of ectasia. As such, many thin corneas have been wrongly considered ectasias before introducing spatial thickness evaluation. Nowadays, pachymetric progression indices are more relevant than single measurements and are the basis for most currently used algorithms for keratoconus diagnosis. These advances made early recognition of keratoconus and early intervention possible, significantly softening the negative impact in these patients' visual outcome.

Furthermore, the most recent algorithms have gained accuracy in recognizing corneas susceptible to developing ectasia, increasing the safety and predictability of laser vision correction (LVC) surgeries. LVC surgeries are among the most performed surgical procedures worldwide. Nevertheless, potential complications may be carefully considered, especially iatrogenic ectasia. Post-refractive surgery ectasia is a serious, sight-threatening complication that can follow several procedures, such as laser in situ keratomileusis, photorefractive keratectomy, small-incision lenticule extraction, radial keratotomy and/or arcuate keratotomy. It occurs due to corneal tissue biomechanical failure, and preoperative predisposition plays a crucial role in its development. Despite the low incidence of ectasia after LVC, some cases are still identifiable, either because they were performed before these tools became available or due to incorrect preoperative evaluation.

Iatrogenic corneal ectasia usually presents with diminished visual acuity after LVC surgery. However, clinical distinction between disease regression and over or under-correction is often difficult. Although corneas appear thin following LVC, it is still unclear whether this reflects true thinning or ectatic behaviour, as current algorithms were calibrated for untreated corneas.

The Corvis Biomechanical Index – Laser Vision Correction (CBI-LVC) is a recently published index that combines dynamic corneal response (DCR) parameters provided by a high-speed dynamic Scheimpflug camera. It was designed to allow for early identification of ectasia after refractive surgery and proved to be highly sensitive and specific to distinguish stable from ectatic post-LVC eyes.[37] However, it includes only biomechanical data. The integration of corneal spatial profiles of eyes after LVC surgery could lead to the development of more accurate algorithms. Additionally, data regarding stromal thickness, provided by OCT as the difference between full-thickness and epithelial thickness, could also provide helpful information regarding stromal changes induced by LVC.

Pachymetric analyses have led to an unquestionable paradigm shift regarding keratoconus management. Algorithms have gained such accuracy in detecting ectasia that the focus has rapidly shifted to susceptibility detection rather than disease diagnosis. Although iatrogenic ectasia is an increasingly rare complication, managing these cases remains a challenge. Hence, future comprehensive analyses and subsequent generated algorithms may focus on identifying corneal and epithelium thickness variations after refractive surgery that could more accurately differentiate normal corneal response from early-stage ectasia or susceptible corneas for ectasia progression.

CONTRIBUTORSHIP STATEMENT / DECLARAÇÃO DE CONTRIBUIÇÃO

IM, TL; Responsible for gathering data, presenting results, and writing the manuscript.

TL, FM, NSJ, RAJ: Responsible for performing complementary exams and helping in laboratory tasks.

TL, NSJ, IM, NC, RAJ: Supervised the project and contributed with their expertise to its conclusion.

All authors read and approved the final manuscript.

IM, TL: Responsáveis pela recolha de dados, apresentação dos resultados e redação do manuscrito.

TL, FM, NSJ, RAJ: Responsáveis pela realização de exames complementares e apoio em tarefas laboratoriais.

TL, NSJ, IM, NC, RAJ: Supervisionaram o projeto e contribuíram com a sua experiência para a sua conclusão.

Todos os autores leram e aprovaram a versão final do manuscrito.

RESPONSABILIDADES ÉTICAS

Conflitos de Interesse: Os autores declaram a inexistência de conflitos de interesse.

Apoio Financeiro: Este trabalho não recebeu qualquer subsídio, bolsa ou financiamento.

Proveniência e Revisão por Pares: Não solicitado; revisão externa por pares.

ETHICAL DISCLOSURES

Conflicts of Interest: The authors have no conflicts of interest to declare.

Financial Support: This work has not received any contribution grant or scholarship.

Provenance and Peer Review: Not commissioned; externally peer-reviewed.

REFERENCES

1. Renato A. Percentage Thickness Increase and Absolute Difference from Thinnest to Describe Thickness Profile. J Refract Surg. 2021; 26: 84–6. doi: 10.3928/1081597X-20100121-01.
2. Maurice DM, Giardini AA. A Simple Optical Apparatus for Measuring the Corneal Thickness, and the Average Thickness of the Human Cornea. Br J Ophthalmol. 1951; 35: 169–77.
3. González-Pérez J, González-Méijome JM, Rodríguez Ares MT, Parafita MA. Central corneal thickness measured with three optical devices and ultrasound pachometry. Eye Contact Lens. 2011;37:66–70.
4. Ambrósio R, Klyce SD, Wilson SE. Corneal topographic and pachymetric screening of keratorefractive patients. J Refract Surg. 2003; 19: 24–9.
5. Jonsson M, Behndig A. Pachymetric evaluation prior to laser in situ keratomileusis. J Cataract Refract Surg. 2005;31:701-6. doi: 10.1016/j.jcrs.2005.02.028.
6. Ambrósio R Jr, Belin MW. Imaging of the cornea: topography vs tomography. J Refract Surg. 2010;26:847-9. doi: 10.3928/1081597X-20101006-01.
7. Prakash G, Agarwal A, Mazhari AI, Kumar G, Desai P, Kumar DA, et al. A new, pachymetry-based approach for diagnostic cutoffs for normal, suspect and keratoconic cornea. Eye. 2012;26:650-7. doi: 10.1038/eye.2011.365.
8. Mandell RB, Polse KA. Keratoconus: Spatial Variation of Corneal Thickness as a Diagnostic Test. Arch Ophthalmol. 1969; 82: 182–8.
9. Avitabile T, Marano F, Uva MG, Reibaldi A. Evaluation of central and peripheral corneal thickness with ultrasound biomicroscopy in normal and keratoconic eyes. Cornea. 1997;16:639-44.
10. Avitabile T, Franco L, Ortisi E, Castiglione F, Pulvirenti M, et al. Keratoconus staging: a computer-assisted ultrabiomicroscopic method compared with videokeratographic analysis. Cornea. 2004;23:655-60. doi: 10.1097/01.ico.0000127486.78424.6e.
11. Castiglione F. Estimating the keratoconus index from ultrasound images of the human cornea. IEEE Trans Med Imaging. 2000; 19: 1268–72.
12. Alonso RS, Luz A, Coca Velarde LG. Corneal-thickness spatial profile and corneal-volume distribution: tomographic indices to detect keratoconus. J Cataract Refract Surg. 2006; 32: 1851–9.
13. Luz A, Ursulio M, Castañeda D, Ambrósio Jr R. Progressão da espessura corneana do ponto mais fino em direção ao limbo: estudo de uma população normal e de portadores de ceratocone para criação de valores de referência. Arq Bras Oftalmol. 2006; 69: 579–83.
14. Sun SY, Wacker K, Baratz KH, Patel SV. Determining Subclinical Edema in Fuchs Endothelial Corneal Dystrophy: Revised Classification using Scheimpflug Tomography for Preoperative Assessment. Ophthalmology. 2019;126:195-204. doi: 10.1016/j.ophtha.2018.07.005.
15. Ambrósio R, Faria Correia F, Belin MW. Analyzing Tomographic Thickness for Detecting Corneal Ectatic Diseases. Keratoconus. 2017:77–85.
16. Ambrósio R Jr, Caiado AL, Guerra FP, Louzada R, Sinha RA, Luz A, et al. Novel pachymetric parameters based on corneal tomography for diagnosing keratoconus. J Refract Surg. 2011;27:753-8. doi: 10.3928/1081597X-20110721-01.
17. Lopes BT, Ramos IC, Salomão MQ, Guerra FP, Schallhorn SC, Schallhorn JM, et al. Enhanced Tomographic Assessment to Detect Corneal Ectasia Based on Artificial Intelligence. Am J Ophthalmol. 2018;195:223-32. doi: 10.1016/j.ajo.2018.08.005.
18. Holladay J. Keratoconus detection using corneal topography. J Refract Surg. 2009;25:S958-62. doi: 10.3928/1081597X-20090915-11.
19. Vinciguerra R, Ambrósio R Jr, Elsheikh A, Roberts CJ, Lopes B, Morenghi E, et al. Detection of Keratoconus With a New Biomechanical Index. J Refract Surg. 2016;32:803-10. doi: 10.3928/1081597X-20160629-01.
20. Ambrósio R Jr, Lopes BT, Faria-Correia F, Salomão MQ, Bühren J, Roberts CJ, et al. Integration of Scheimpflug-Based Corneal Tomography and Biomechanical Assessments for Enhancing Ectasia Detection. J Refract Surg. 2017;33:434-43. doi: 10.3928/1081597X-20170426-02.
21. Li HF, Petroll WM, Møller-Pedersen T, Maurer JK, Cavanagh HD, Jester JV. Epithelial and corneal thickness measurements by in vivo confocal microscopy through focusing (CMTF). Curr Eye Res. 1997;16:214-21. doi: 10.1076/ceyr.16.3.214.15412..
22. Reinstein DZ, Archer TJ, Gobbe M, Silverman RH, Coleman DJ. Epithelial thickness in the normal cornea: three-dimensional display with Artemis very high-frequency digital ultrasound. J Refract Surg. 2008;24:571-81. doi: 10.3928/1081597X-20080601-05.
23. Reinstein DZ, Silverman RH, Sutton HF, Coleman DJ. Very high-frequency ultrasound corneal analysis identifies anatomic correlates of optical complications of lamellar refractive surgery: anatomic diagnosis in lamellar surgery. Ophthalmology. 1999;106:474-82. doi: 10.1016/S0161-6420(99)90105-7.
24. Huang D, Tang M, Shekhar R. Mathematical model of corneal surface smoothing after laser refractive surgery. Am J Ophthalmol. 2003;135:267-78. doi: 10.1016/s0002-9394(02)01942-6.
25. Silverman RH, Urs R, Roychoudhury A, Archer TJ, Gobbe M, Reinstein DZ. Epithelial remodeling as basis for machine-based identification of keratoconus. Invest Ophthalmol Vis Sci. 2014;55:1580-7. doi: 10.1167/iovs.13-12578.

26. Li Y, Tan O, Brass R, Weiss JL, Huang D. Corneal epithelial thickness mapping by Fourier-domain optical coherence tomography in normal and keratoconic eyes. Ophthalmology. 2012;119:2425-33. doi: 10.1016/j.ophtha.2012.06.023.
27. Rocha KM, Perez-Straziota CE, Stulting RD, Randleman JB. SD-OCT analysis of regional epithelial thickness profiles in keratoconus, postoperative corneal ectasia, and normal eyes. J Refract Surg. 2013;29:173-9. doi: 10.3928/1081597X-20130129-08. Erratum in: J Refract Surg. 2013;29:234.
28. Reinstein DZ, Srivannaboon S, Gobbe M, Archer TJ, Silverman RH, Sutton H, et al. Epithelial thickness profile changes induced by myopic LASIK as measured by Artemis very high-frequency digital ultrasound. J Refract Surg. 2009;25:444-50. doi: 10.3928/1081597X-20090422-07. .
29. Reinstein DZ, Archer TJ, Gobbe M. Change in epithelial thickness profile 24 hours and longitudinally for 1 year after myopic LASIK: Three-dimensional display with artemis very high-frequency digital ultrasound. J Refract Surg. 2012;28:195-201. doi: 10.3928/1081597X-20120127-02.
30. Reinstein DZ, Archer TJ, Gobbe M, Silverman RH, Coleman DJ. Epithelial thickness after hyperopic LASIK: three-dimensional display with Artemis very high-frequency digital ultrasound. J Refract Surg. 2010;26:555-64. doi: 10.3928/1081597X-20091105-02.
31. Reinstein DZ, Archer T. Combined Artemis very high-frequency digital ultrasound-assisted transepithelial phototherapeutic keratectomy and wavefront-guided treatment following multiple corneal refractive procedures. J Cataract Refract Surg. 2006;32:1870-6. doi:10.1016/j.jcrs.2006.07.016.
32. Swartz T, Marten L, Wang M. Measuring the cornea: the latest developments in corneal topography. Curr Opin Ophthalmol. 2007;18:325-33. doi: 10.1097/ICU.0b013e3281ca7121.
33. Reinstein DZ, Archer TJ, Urs R, Gobbe M, RoyChoudhury A, Silverman RH. Detection of Keratoconus in Clinically and Algorithmically Topographically Normal Fellow Eyes Using Epithelial Thickness Analysis. J Refract Surg. 2015;31:736-44. doi: 10.3928/1081597X-20151021-02.
34. Temstet C, Sandali O, Bouheraoua N, Hamiche T, Galan A, El Sanharawi M, et al. Corneal epithelial thickness mapping using Fourier-domain optical coherence tomography for detection of form fruste keratoconus. J Cataract Refract Surg. 2015;41:812-20. doi: 10.1016/j.jcrs.2014.06.043.
35. Vega-Estrada A, Mimouni M, Espla E, Alió Del Barrio J, Alio JL. Corneal Epithelial Thickness Intrasubject Repeatability and its Relation With Visual Limitation in Keratoconus. Am J Ophthalmol. 2019;200:255-62. doi: 10.1016/j.ajo.2019.01.015.
36. Yang F, Yang Z, Zhao S, Huang Y. To Investigate the Changes in Corneal Curvature and Its Correlation with Corneal Epithelial Remodeling After Trans-PRK and FS-LASIK. Curr Eye Res. 2024;49:1061-7. doi: 10.1080/02713683.2024.2361728.
37. Vinciguerra R, Ambrósio R Jr, Elsheikh A, Hafezi F, Yong Kang DS, Kermani O, et al. Detection of postlaser vision correction ectasia with a new combined biomechanical index. J Cataract Refract Surg. 2021;47:1314-8. doi: 10.1097/j.jcrs.0000000000000629.

Corresponding Author/
Autor Correspondente:

Inês Mendo
Centro de Responsabilidade Integrada de Oftalmologia, Hospital Garcia de Orta, E.P.E
Av. Torrado da Silva,
2805-267 Almada
E-mail: ines.smendo@gmail.com

ORCID: 0009-0007-6514-8267