Artificial Intelligence Integrates Tomography and Biomechanical Assessments for Earlier Ectasia Detection

- Renato Ambrósio Jr, MD, PhD

One of the fastest growing areas of technology is artificial intelligence (AI) and this is now being coupled with the ever-growing volume of digital health data, enabling the medical field to harness the power of computational algorithms to enhance clinical decision-making and patient care. Machine learning is a branch of AI that utilizes computer power to learn and improve from experience. While traditional computing paradigms require explicit programming to execute specific tasks, machine learning algorithms are able to autonomously extract patterns and trends from large and complex datasets, iteratively enhancing their performance through continuous refinement.[1,2] In the ophthalmological field, the development of novel diagnostic algorithms for identifying corneal ectasia represents one of the most promising applications of this novel technology.[3]

The past few decades have witnessed an extraordinary diffusion of refractive surgery on a global scale thanks to the advancements in surgical techniques such as femtosecond laser in situ keratomileusis (Femto-LASIK) and laser-assisted lenticule extraction procedures. This has driven the necessity to develop accurate and reliable techniques to diagnose mild subclinical forms of ectasia that are at risk for iatrogenic progression after laser vision correction procedures. Moreover, the availability of novel treatments capable of slowing or halting the disease progression such as collagen cross-linking has increased the clinical relevance of identifying ectatic corneal diseases at an early stage.[2]

EARLIER IDENTIFICATION

While advanced keratoconus can often be recognized at the slit-lamp from signs such as Vogt striae and Fleischer ring, these clinical findings are usually absent in milder forms. Consequently, more advanced corneal imaging techniques are required to diagnose the condition before the occurrence of significant visual loss.

Placido-disc topography involves the projection of a series of concentric rings onto the corneal surface and the analysis of the reflected image. This allows to characterize the anterior corneal surface and detect mild-to-moderate forms of ectasia. On the other hand, Scheimpflug corneal tomography utilizes a rotating camera to capture multiple cross-sectional images of the cornea, allowing for a comprehensive assessment of both the anterior and posterior corneal surfaces. Since posterior elevation is often the first sign of keratoconus, Scheimpflug tomographic analysis is considered more sensitive than Placido-disk topography in diagnosing the condition.[4,5] The OCULUS Pentacam® (Figure 1, left panel) is a Scheimpflug tomographer which is provided with the Belin/Ambrósio Enhanced Ectasia Display (BAD-D), a comprehensive screening index combining elevation-based and pachymetric corneal evaluation. The BAD-D represents one of the Scheimpflug-based indices with the highest predictive accuracy for detecting ectasia.[6]

Nonetheless, relying solely on corneal tomography for reaching the diagnosis may prove inadequate in very mild or subclinical cases in which the corneal shape is not yet altered.[7] In clinical research, eyes with a normal anterior topography from patients with clinical ectasia in the fellow eye are commonly used as models of subclinical ectasia. While the sensitivity of tomographic indices is reduced in these cases, proceeding with laser refractive surgery in subclinical or forme fruste keratoconus can still pose the risk of inducing iatrogenic ectasia.

To address these challenges and improve diagnostic sensitivity, new technologies including epithelial mapping and measurement of corneal biomechanics have been recently developed.

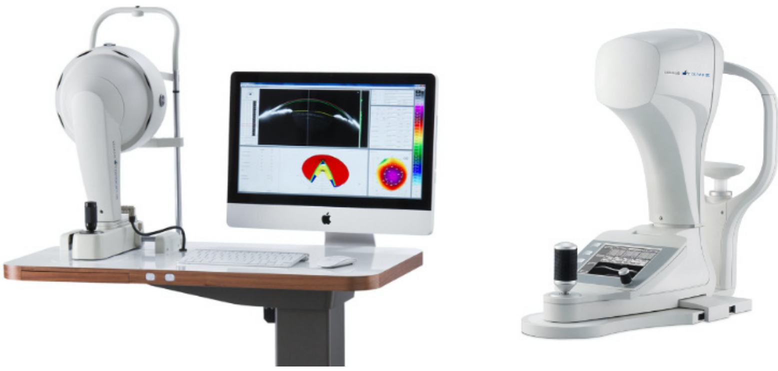


Figure 1. OCULUS Petnacam® (left) is a Scheimpflug corneal tomographer allowing for a comprehensive assessment of both the anterior and posterior corneal surfaces. Corvis® ST (right) is a non-contact tonometer employing an air pulse to evaluate corneal biomechanics.

ASSESSING CORNEAL BIOMECHANICS WITH CORVIS® ST

Corneal biomechanics involves the study of the mechanical properties of the cornea and its response to external forces and stress. Measuring biomechanical properties has emerged as a new promising technology for identifying subclinical ectatic corneal diseases.[8] Over the past few years, there has been a notable surge in the level of interest in corneal biomechanics within the ophthalmological community. From a review of the scientific literature on corneal biomechanics indexed on PubMed, out of a total of 2,812 articles published since the 1950s, a substantial 70.2% (1,974 articles) were published within the last decade, with 33.5% (943 articles) appearing in the last five years.

Corvis® ST (Figure 1, right panel) is a novel instrument for assessing corneal biomechanics that combines a pneumo-tonometer and an ultra-high speed Scheimpflug camera recording the tissue's response to the air pulse (Figure 2). As shown by several previous studies, biomechanical parameters recorded with Corvis® ST are significantly different in eyes with keratoconus and healthy control eyes.[9–11]

Although the accuracy for detecting mild forms of ectasia was relatively low with first-generation parameters, novel indices such as the Corvis Biomechanical Index (CBI) are able to correctly classify eyes with clinical ectasia in 98.8% of cases, with 98.4% specificity and 100% sensitivity.[12]

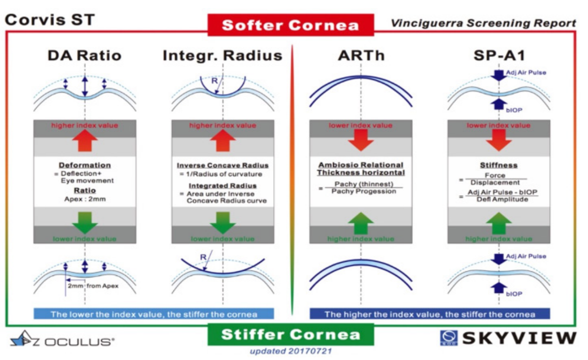


Figure 2. Schematic representation of a combination of dynamic corneal response parameters measured by Corvis® ST. DA Ratio is the maximum value of the ratio between the deformation amplitude at the apex and 2 mm from the center; Integr. Radius is the radius of curvature during the concave phase of the deformation; ARTh is Ambrósio's relational thickness through the horizontal profile; SP-A1 the stiffness parameter at inward applanation A1.

POWERFUL COMBINATION: TOMOGRAPHY AND BIOMECHANICS

The Tomographic Biomechanical Index (TBI) is a novel parameter that combines the corneal biomechanical analysis from Corvis® ST with the tomographical analysis from Pentacam®. In a recent study including eyes with normal anterior corneal topography and very asymmetric ectasia in the fellow eye, this new index has demonstrated its capacity to accurately identify subclinical or forme fruste keratoconus.[13] These excellent results led to the inclusion of the TBI in the last commercial OCULUS software (Figure 3).

In Figure 3, we present a representative case of iatrogenic ectasia following a small incision lenticule extraction procedure in a patient who had normal topography before surgery and a BAD-D score within the normal range. Although the TBI was not yet available at the time of surgery, its retrospective calculation using preoperative data revealed a high risk of ectasia.

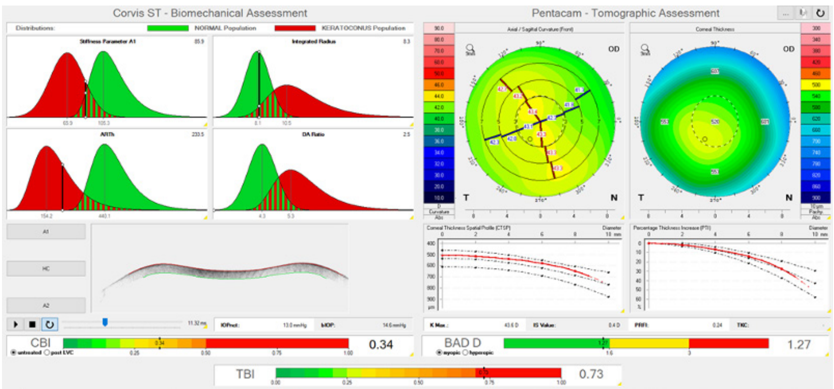


Figure 3. Preoperative integrated tomographic and biomechanical analysis in a patient who developed ectasia after small incision lenticule extraction. Although the Belin/Ambrósio Enhanced Ectasia Display (BAD D) from Pentacam® was within the norm (1.27), the Tomographic Biomechanical Index (TBI) was abnormal (0.73).

In a recent cross-sectional, case-control, multicenter retrospective study from Ambrósio et al., AI technology was applied to a large dataset including 3,886 eyes from 3,412 patients in order to optimize the TBI.[14] A random forest algorithm, which is a supervised learning technique generating multiple decision trees based on different subsets of the provided dataset, was employed for the optimization of the index with the novel dataset.

The area under the curve (AUC) of receiver operating characteristic curves for detecting subclinical ectasia was significantly higher in the optimized TBI compared to its previous version (0.945 versus 0.899; $P < 0.001$). The relevance of this optimization is shown in the representative case depicted in Figure 4. The patient, who developed ectasia after PRK, had a frankly abnormal optimized index before surgery (TBI = 0.99). Conversely, the previous version of the index was only suspicious for ectasia (TBI = 0.63).

In their paper, Ambrósio et al. concluded that: "AI optimization to integrate Scheimpflug-based corneal tomography and biomechanical assessments augments accuracy for ectasia detection." These technological advancements have the potential to enhance clinical decision-making in the preoperative diagnostic work-up of patients undergoing laser vision correction. Looking ahead, AI holds the promise of advancing the diagnostic accuracy even further by integrating multimodal data from other sources including ocular wavefront analysis and epithelial thickness mapping.

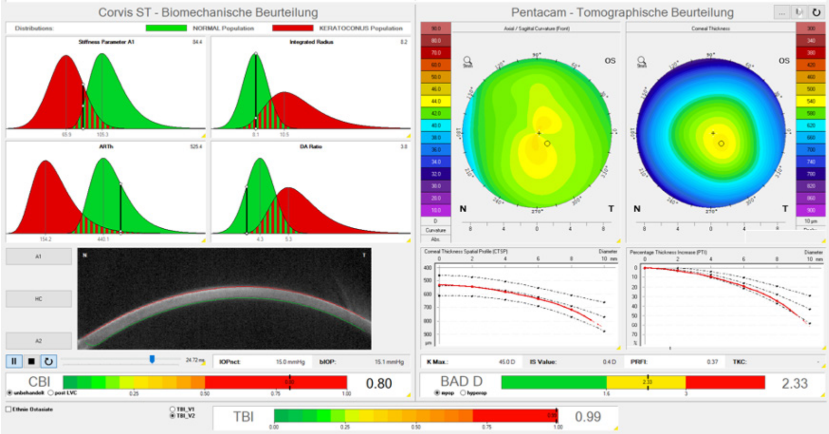


Figure 4. Preoperative integrated tomographic and biomechanical analysis in a patient who developed ectasia after photorefractive keratectomy. The analysis with the first version of the Tomographic Biomechanical Index (TBI) was 0.63, while the optimized version was 0.99. In either result, suspicious for ectasia, or ectasia susceptibility is detected as the TBI value is higher than the cutoff values from original publications.[13,14]

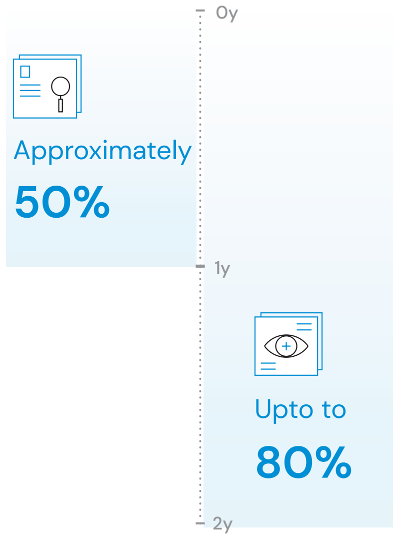
REFERENCES

1. Ting DSW, Pasquale LR, Peng L, Campbell JP, Lee AY, Raman R, Tan GSW, Schmetterer L, Keane PA, Wong TY. Artificial intelligence and deep learning in ophthalmology. Br J Ophthalmol. 2019 Feb;103(2):167-175.
2. Lopes BT, Eliasy A, Ambrosio R. Artificial intelligence in corneal diagnosis: where are we? Curr Ophthalmol Rep 2019;7(3):204–211.
3. Ambrosio Jr R. Multimodal imaging for refractive surgery:Quo vadis? Indian J Ophthalmol . 2020;68(12):2647–2649.
4. Ambrosio R, Jr., Valbon BF, Faria-Correia F, Ramos I, Luz A. Scheimpflug imaging for laser refractive surgery. Curr Opin Ophthalmol 2013;24:310-20.
5. Saad A, Gatinel D. Topographic and tomographic properties of forme fruste keratoconus corneas. Invest Ophthalmol Vis Sci 2010;51:5546-55.
6. Kataria P, Padmanabhan P, Gopalakrishnan A, Padmanaban V, Mahadik S, Ambrósio R Jr. Accuracy of Scheimpflug-derived corneal biomechanical and tomographic indices for detecting subclinical and mild keratectasia in a South Asian population. J Cataract Refract Surg. 2019 Mar;45(3):328-336.
7. Ruiseñor Vázquez PR, Galletti JD, Minguez N, Delrivo M, Fuentes Bonthoux F, Pförtner T, Galletti JG. Pentacam® Scheimpflug tomography findings in topographically normal patients and subclinical keratoconus cases. Am J Ophthalmol. 2014 Jul;158(1):32-40.e2.
8. Ambrosio Jr R, Randleman JB. Screening for ectasia risk:what are we screening for and how should we screen for it? J Refract Surg . 2013;29(4):230–232.
9. Ali NQ, Patel DV, McGhee CN. Biomechanical responses of healthy and keratoconic corneas measured using a noncontact Scheimpflug tonometer. Invest Ophthalmol Vis Sci. 2014;55(6):3651–9.
10. Ambrósio R Jr, Ramos I, Luz A, et al. Dynamic ultra high speed Scheimpflug imaging for assessing corneal biomechanical properties. Rev Bras Oftalmol 2013; 72:99–102.
11. Ye C, Yu M, Lai G, Jhanji V. Variability of Corneal Deformation Response in Normal and Keratoconic Eyes. Optom Vis Sci. 2015 Jul;92(7):e149-53.
12. Vinciguerra R, Ambrósio R Jr, Elsheikh A, Roberts CJ, Lopes B, Morenghi E, Azzolini C, Vinciguerra P. Detection of Keratoconus with a New Biomechanical Index. J Refract Surg. 2016 Dec 1;32(12):803-810.
13. Ambrósio R Jr, Lopes BT, Faria-Correia F, Salomão MQ, Bühren J, Roberts CJ, Elsheikh A, Vinciguerra R, Vinciguerra P. Integration of Scheimpflug-Based Corneal Tomography and Biomechanical Assessments for Enhancing Ectasia Detection. J Refract Surg. 2017 Jul 1;33(7):434-443.
14. Ambrósio R Jr, Machado AP, Leão E, et al. Optimized Artificial Intelligence for Enhanced Ectasia Detection Using Scheimpflug-Based Corneal Tomography and Biomechanical Data. Am J Ophthalmol. 2023 Jul;251:126-142.

OCULUS Corvis® ST Corneal Visualization with Scheimpflug Technology

SCREENING FOR CORNEAL ECTASIA

- Corneal ectasia is a rare but sight threatening, generally irreversible complication after various keratorefractive surgical procedures[1–2]
- Approximately 50% of cases occur within the first year[3]
- Up to 80% of the cases can show up within the first two years of surgery[3]
- LASIK may hasten ectasia symptoms in predisposed patients[4]
- Some ectatic patients with normal topography are missed when using the classic methods of screening



COMBINED USE OF BIOMECHANICAL AND TOMOGRAPHICAL DATA

- Enables the eye care practitioner to improve identification of patients at risk of developing ectasia after refractive surgery
- Facilitates early detection of keratoconus through corneal biomechanics
- High-speed Scheimpflug camera captures over 4,300 images per second [create infographic] permitting highly precise measurements
- Tomographic Biomechanical Index (TBIv1) is based on an artificial intelligence algorithm and combines biomechanical data from the Corvis® ST with tomographic data from Pentacam®.
- Index accuracy has been demonstrated in several peer-reviewed studies[5–8]

SCREENING FOR CORNEAL ECTASIA

- Machine-learning artificial intelligence can process large datasets to improve overall diagnostic efficiency

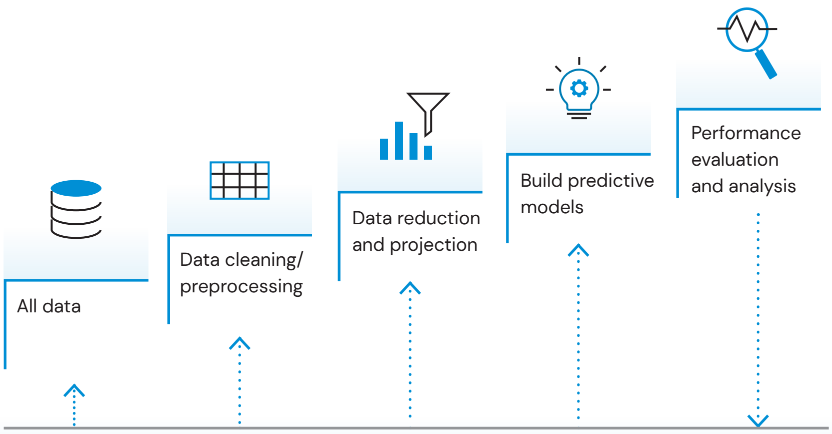


Figure 1. Basic flow of steps for the data mining and the creation of the artificial intelligence.

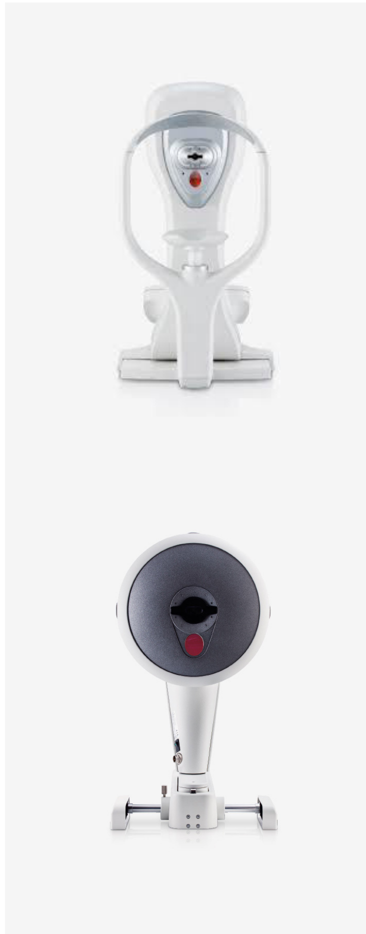
- Twenty-five international Investigators of a multicenter study[9] tested the current TBiv1 (tomographic biomechanical index) to develop an optimized AI algorithm (TBiv2)
- A total of 3,886 unoperated eyes from 3, 412 patients underwent Pentacam® and Corvis® ST (OCULUS Optikgeräte GmbH) examination
- TBIv2 algorithm was trained on:

>1680 normal patients
1181 bilateral clinical keratoconus
& >500 forme fruste keratoconus patients

- Clinical study demonstrated improved accuracy of ectasia detection in patients with bilateral keratoconus, normal topography with very asymmetric ectasia and unilateral ectasia with optimized algorithm

3,886

3,412



RISK-ASSESSMENT IN DAILY CLINICAL PRACTICE

- Preoperative integrated tomographic and biomechanical analysis with optimized AI improves accuracy for ectasia detection
- Incorporate this AI-optimized diagnostic method into your clinical practice and ensure subclinical forms of ectasia are identified
- Provides overall assessment of ectasia risk at-a-glance with mapping
- With the combined measurements of the Pentacam® and Corvis® ST, the Tomographic Biomechanical Index is calculated automatically for the clinician
- Timely diagnosis may result in better decision-making for laser vision correction patients and earlier treatment to slow disease progression[10-11]

REFERENCES

1. Giri P, Azar DT. Risk profiles of ectasia after keratorefractive surgery. Curr Opin Ophthalmol. 2017 Jul;28(4):337-342.
2. AAO PPP Corneal External Disease Committee, Hoskin Center for Quality Eye Care: Corneal Ectasia Preferred Practice Pattern American Academy of Ophthalmology 2018. Accessed on 6/18/23 https://www.aao.org/education/preferred-practice-pattern/corneal-ectasia-ppp-2018.
3. Randleman JB, Woodward M, Lynn MJ, Stulting RD. Risk assessment for ectasia after corneal refractive surgery. Ophthalmology. 2008; 115:37–50.
4. Lipner M Does post-LASIK ectasia really exist? Refractive Surgery. ACRS EyeWorld; 20 2007.
5. Ferreira-Mendes J, Lopes BT, Faria-Correia F, Salomão MQ, Rodrigues-Barros S, Ambrósio R Jr. Enhanced Ectasia Detection Using Corneal Tomography and Biomechanics. Am J Ophthalmol. 2019 Jan;197:7-16.
6. Ambrosio Jr R, Lopes BT, Faria-Correia F, et al. Integration of Scheimpflug-based corneal tomography and biomechanical assessments for enhancing ectasia detection. J Refract Surg. 2017;33(7):434–443.
7. Sedaghat MR, Momeni-Moghaddam H, Ambrósio Jr R, et al. Diagnostic ability of corneal shape and biomechanical parameters for detecting frank keratoconus. Cornea. 2018;37(8):1025–1034.
8. Steinberg et al. Tomographic and Biomechanical Scheimpflug Imaging for Keratoconus Characterization: A Validation of Current Indices. J Refract Surg. 2018;34(12):840–847.
9. Ambrósio R Jr et al. Optimized Artificial Intelligence for Enhanced Ectasia Detection Using Scheimpflug-Based Corneal Tomography and Biomechanical Data. Am J Ophthalmol. 2023 Jul;251:126-142.
10. Khamar P, Rao K, Wadia K, Dalal R, Grover T, Versaci F, Gupta K. Advanced epithelial mapping for refractive surgery. Indian J Ophthalmol. 2020 Dec;68(12):2819-2830.
11. Wolle MA, Randleman JB, Woodward MA. Complications of Refractive Surgery: Ectasia After Refractive Surgery. Int Ophthalmol Clin. 2016 Spring;56(2):127-39.

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