OCULUS Special Supplement

Get a Complete View!

Biomechanical Assessment with the Corvis ST and Integration with Tomography

September 2016

Two Novel Stiffness Parameters for the Corvis ST

The New Vinciguerra Screening Report and Corvis Biomechanical Index (CBI)

Ultimate Ectasia Detection 2016: Integrating Corneal Tomography and Biomechanical Assessment

Biomechanically Corrected IOP Measurement

Published by
Jaypee Highlights Medical Publishers, Inc.
www.jphmedical.com

OCULUS®

Two Novel Stiffness Parameters for the Corvis ST

Author: Prof. Cynthia Roberts, PhD (Ohio, USA)

Corneal biomechanical characterization has generated great interest from clinicians. The Corvis ST uses a consistent air puff to deform the cornea, along with an ultra-high speed camera utilizing Scheimpflug geometry to capture images of the horizontal meridian at greater than 4,300 frames per second, resulting in 140 images during the 30ms air puff.[1] The cornea is viscoelastic in nature, which means that biomechanical characterization depends on the magnitude of the applied load and how quickly that load is delivered, as well as on the intraocular pressure (IOP).[2] With the Corvis ST, each cornea experiences the same load over the same time period, facilitating biomechanical comparisons between eyes. In addition, a biomechanically corrected IOP (bIOP) has been developed, the derivation of which will be explained in a later section. This is critically important, since both the cornea and sclera stiffen with increasing IOP, which influences the deformation response. A stiffer sclera will limit maximum corneal deformation since it generates greater resistance to displacing fluid.[3]

As the air pressure reaches the cornea, it begins to deflect in the backward direction. Whole eye motion is simultaneously initiated, also in the backward direction. Dynamic corneal response (DCR) parameters which include whole eye motion are described as "deformation" parameters, and those for which whole eye motion is removed are described as "deflection" parameters. This is illustrated in **Figure 1**, along with some of the DCR's. First applanation (A1) parameters include: A1 Time, A1 length, A1 velocity, A1 Deformation Amplitude, and A1 Deflection Amplitude. Parameters at highest concavity (HC) include: HC Time, Peak Distance, Radius of Concave Curvature, HC Deformation Amplitude (equivalent to Maximum Deformation Amplitude), and HC Deflection Amplitude. Parameters at second applanation (A2) include: A2 Time, A2 length, A2 velocity, A2 Deformation Amplitude, and A2 Deflection Amplitude. Additional parameters include Deflection Amplitude Maximum (which may not be at highest concavity); Deformation Amplitude Ratio (DA Ratio) which is the central deformation divided by an average of the deformation 2mm either side of center with maximum value just prior to A1; Deflection Amplitude Ratio (DeflAmp Ratio) which is similar to DA Ratio, but uses corneal "deflection" which is corrected for whole eye motion; and Maximum Whole Eye Motion which occurs near A2.

With the goal to develop a simple clinical parameter that correlates with stiffness, the spatial and temporal velocity profiles of the air puff have been experimentally measured using hot wire anemometry.[4] The measured velocity is converted to pressure and allows the air pressure (AP) at the time and position of first applanation to be determined for each exam. This adjusted air pressure (adjAP1) minus bIOP represents the resultant pressure (Pr), or load on the cornea at A1. By dividing Pr by corneal displacement, a clinical stiffness parameter (SP) is calculated. The stiffness parameter that is most closely related to corneal properties is determined by using displacement of the apex from the undeformed state to first applanation (SP-A1). This value has already proven to be clinically useful in screening for keratoconus with the highest sensitivity and specificity of any single parameter value, which will be discussed later in this article. In addition, SP-A1 has shown a significant difference after laser vision correction in multiple datasets (unpublished data), and shows promise as being a strong indicator of corneal biomechanical properties. The stiffness parameter that is also influenced by scleral properties is determined by using displacement from first applanation to highest concavity (SP-HC). These new stiffness parameters, along with the DCR parameters can be used to biomechanically characterize eyes with specific pathologies.

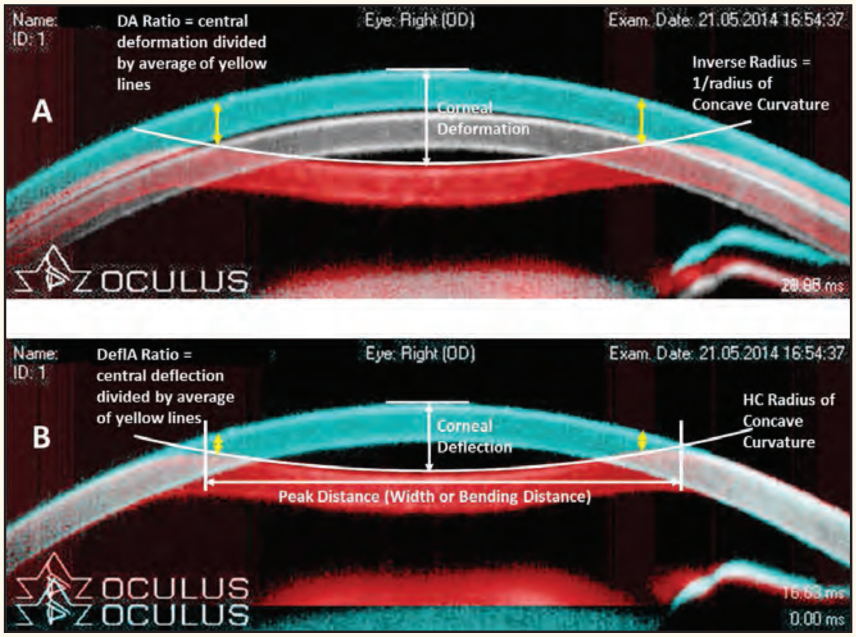

Figure 1: Superimposed frames extracted from a single exam, showing A: Cornea in the Predeformation phase (pseudocolored blue), at maximal corneal deflection (pseudocolored red), and at maximal whole eye movement (pseudocolored white); and B: Correction for whole eye motion by aligning all corneal images in the periphery to that at predeformation. Note the crystalline lens appears to have moved toward the cornea. However, this is due to optical distortion caused by viewing through a concave surface and does not represent actual movement of the lens.

The New Vinciguerra Screening Report and Corvis Biomechanical Index (CBI)

Authors: Riccardo Vinciguerra, MD; Prof. Paolo Vinciguerra, MD (Milan, Italy)

The in-vivo evaluation and interpretation of corneal biomechanics has been a topic of great interest, as the mechanical instability of the cornea is thought to be the initiating event of keratoconus, even before notable changes in corneal morphology takes place.

However, it is extremely difficult to measure the biomechanics of the cornea due to its hyperelastic and viscoelastic behavior, which makes the cornea's behavior nonlinear and dependent on the rate of loading.

Additionally, a fundamental confounding factor is IOP: according to Laplace's Law, the wall tension is a function of the internal pressure. This means that as IOP increases, the wall tension will increase and due to the nonlinear properties, and a soft cornea with higher IOP may exhibit stiffer behavior than a fundamentally stiffer cornea with a lower IOP. On the other hand, IOP measurements are influenced by corneal stiffness, which is not only dependent on the thickness, as widely accepted, but also the tissue´s material properties. For this reason, in order to be able to judge a possibly abnormal cornea, it is mandatory first to create normative values for each parameter as a function of age and IOP and second an index to separate normal from ectatic corneas.

The Vinciguerra Screening Report and Normative Values

The Vinciguerra Screening Report is a new display of the Corvis ST aimed to report, in a single interface, the comparison of normative values to imported exams as well as to include an index to separate normal from keratoconic patients.

The multicenter study that supported the creation of the normative values included 705 healthy patients enrolled in three continents to include variability from various ethnic groups.[5]

The study demonstrated that IOP and pachymetry have important influences on most corneal biomechanical metrics provided by the Corvis ST and - for this reason - the creation of normative values is of crucial importance to judge the possible abnormality of a selected exam.

Figure 2 shows a clinical example of the use of normative values of the Vinciguerra Screening Report: the interface is designed with two graphs. The left one (B) shows the diagram of the selected Dynamic Corneal Response parameter (in this case Deflection Amplitude) with the normal ranges for the patient´s bIOP in the evaluated exam. The chart on the right side displays the obtained results compared to the whole normal range of bIOP). The actual profile fits inside the mean ± 2SD range of the normative values displayed.

The display also provides the absolute values and the standard deviations from the mean of the Ambrósio's Relational Thickness to the horizontal profile, which is based on the thickness profile in the temporal-nasal direction (ARTh)[7] and a novel stiffness parameter at first applanation (SP-A1). The standard deviations are also provided for two Dynamic Corneal Response parameters (DA Ration and integrated Radius). In addition, the biomechanically corrected IOP value [6] (bIOP) for the patient is provided together with the CCT of the patient.

The display may help in the evaluation of an abnormal exam where a keratoconic patient´s exam clearly extend beyond the mean ± 2SD normative value range displayed **(Figure 3).**

Corvis Biomechanical Index (CBI)

To further increase the capability of the Corvis ST to separate normal from keratoconic patients, a novel biomechanical index (CBI) was developed **(Figure 3)**.

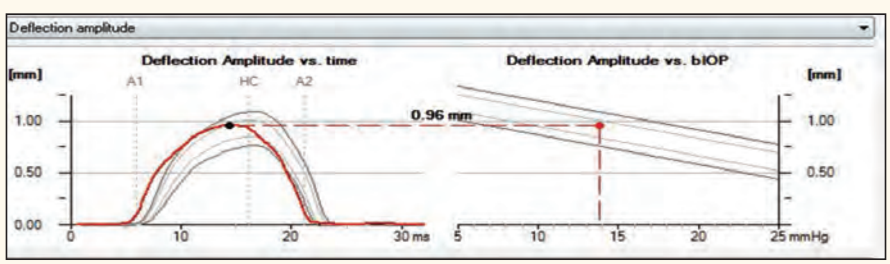

Figure 2: Normal ranges for the deflection amplitude curve for the specific bIOP of this patient and plot of maximal deflection amplitude vs bIOP with ± 2 SD range.

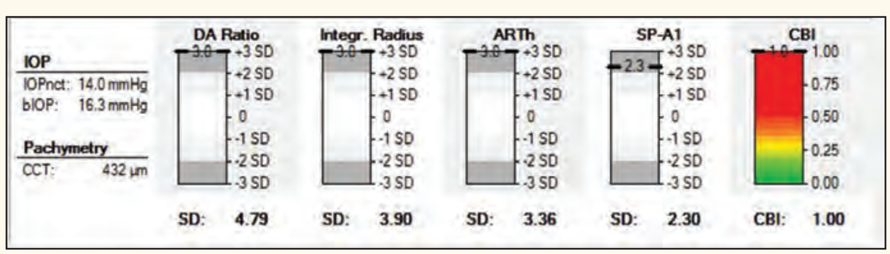

Figure 3: Standard Deviations from the mean for two Dynamic Corneal Response Parameters, the Ambrósio Rational Thickness (ARTh) and the Stiffness Parameter at first applanation (SP-A1) are plotted. In addition, the Corvis Biomechanical Index (CBI) was developed to identify patients with corneal ectasia.

The paper that demonstrated the capability of CBI to separate healthy from ectatic patients included 662 patients enrolled in two different continents.[8]

Logistic regression was employed to determine the optimal combination of best predictors from the individual indices for the creation of the CBI for the accurate separation between normal and keratoconic eyes, using one dataset for training and the other for validation to exclude over-fitting.

The results of the study showed that, with a cut off of 0.5, CBI was able to correctly classify 98.2% of the cases with 100% specificity and 94.1% sensitivity in the training dataset. In the validation dataset, the same cut-off point correctly classified 98.8% of the cases with 98.4% specificity and 100% sensitivity.[8]

To our knowledge, this was the first time that an index based on biomechanics has been able to produce such an efficient separation. Further to that study, we recently evaluated more than 100 forme fruste keratoconus (FFKC), defined as the normal fellow eyes (both topographically and tomographically) of unilateral keratoconus and many of those showed an abnormal CBI while the other exams were normal.

Figure 4 shows a clinical example. The Belin Ambrósio total D was 6.69 in the diseased eye while it was 1.18 in the FFKC eye indicating no abnormality. Furthermore topography revealed no abnormal pattern on the FFKC eye. Based on topographical keratoconus staging (KKS) OS was stage 2 whereas OD was not identified as keratoconus.

Figure 5 shows the Vinciguerra Screening report of the FFKC eye; CBI is above 0.5 (the cut off for abnormality) in both eyes.

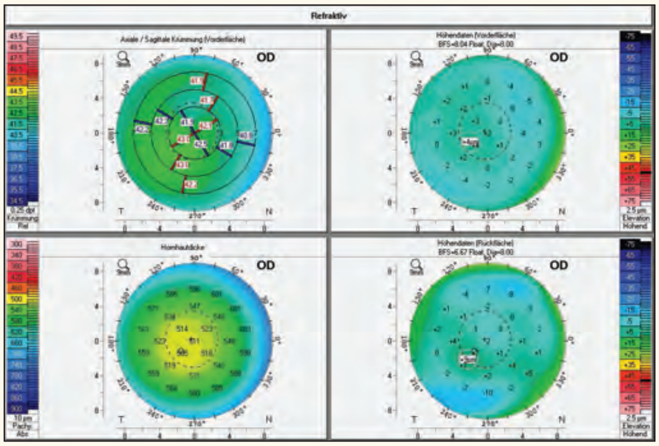

Figure 4a

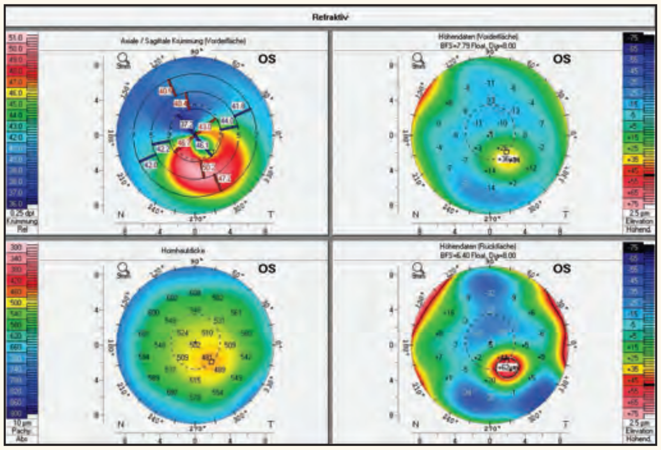

Figure 4b

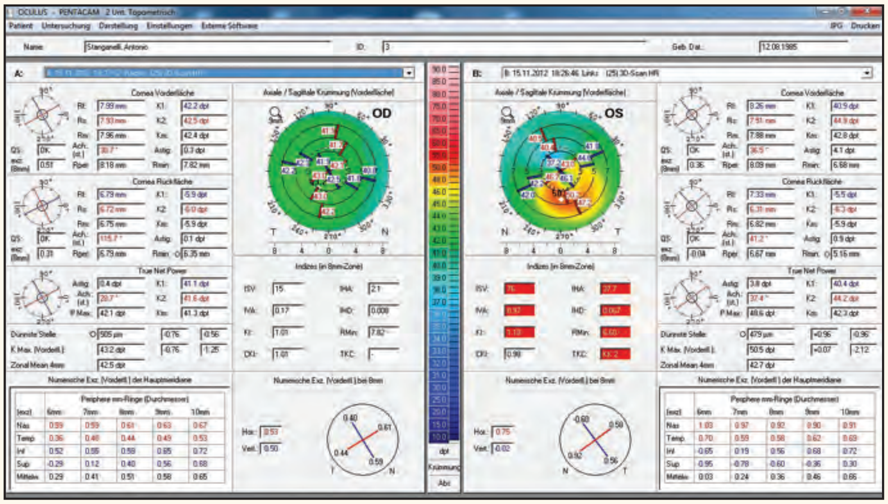

Figure 4c

Figure 4 a,b,c: 4 Maps Refractive display OD (a) and OS (b). The topographical keratoconus staging does not indicate keratoconus OD as well (c).

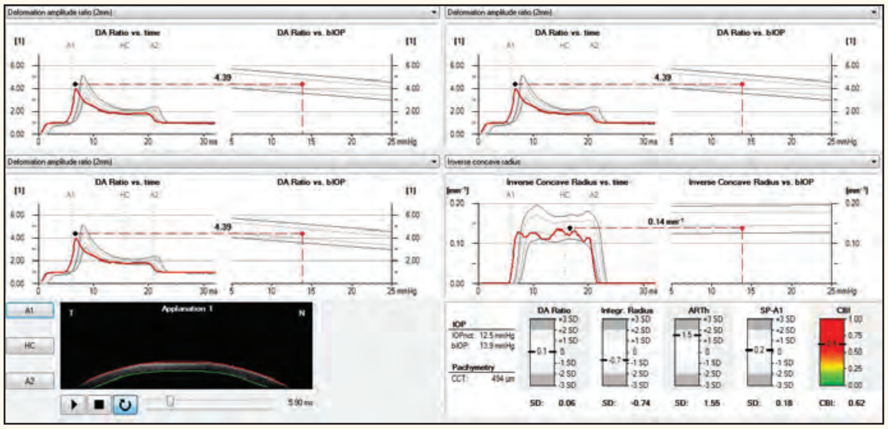

Figure 5: The Vinciguerra Screening report of the FFKC eye with CBI close to 1.

Conclusion

In conclusion, the introduction of our normative value ranges inside the Vinciguerra Normative Display provides, for the first time, the possibility to interpret corneal biomechanics in the context of normative values and suspect pathology in clinical practice. Additionally CBI for keratoconus diagnosis was shown to be highly sensitive and specific alone to separate healthy from ectatic eyes.

At last, as suggested by our recent evaluation of FFKC, CBI might be an additional help to diagnose ectasia at a stage where tomography and topography are normal.

Ultimate Ectasia Detection 2016: Integrating Corneal Tomography and Biomechanical Assessment

Authors: Prof. Renato Ambrósio Jr, MD, PhD; Bernardo T. Lopes, MD (Rio de Janeiro, Brazil)

The detection of mild or sub-clinical forms of ectatic corneal diseases (ECD) has gained its momentum because these cases are at very high risk for iatrogenic progressive ectasia (keratectasia) after corneal Laser Vision Correction (LVC) procedures[9,10] In addition to elective Refractive Surgery, augmenting sensitivity for identifying very mild ectasia cases and monitoring disease progression have become of utmost importance because of the definitive paradigm shift on the management of ECD, which was related to the introduction of novel therapeutic approaches such as collagen cross-linking.[11]

Pentacam: A Revolution on Corneal Imaging

From the characterization of the front surface by Placido-disk based corneal topography, we evolved into 3D tomographic analysis, which characterizes corneal front and back elevation along with thickness mapping.[12,13] Elevation maps represent the subtraction of the corneal surface from a geometric (i.e. sphere or toric ellipsoid) reference body that is calculated to best fit the examined corneal surface.[14] Michael Belin, MD, deserves the credit for many contributions that advanced this field, including the concept of calculating a second enhanced reference with an exclusion zone that facilitates the identification of a protrusion within the area of exclusion zone,[14-16] and defining elevation metrics for monitoring ectasia progression.[17] The concept of corneal thickness profile, introduced by Ambrósio in 2004, details how the cornea gets thicker spatially towards the periphery.[18,19] The relational thickness values represent an objective method that combines the thinnest value and the pachymetric progression indices, which also improves accuracy for detecting ectasia.[20]

The Belin/Ambrósio Enhanced Ectasia Display, available on the Oculus Pentacam, combines elevation and thickness data and includes the `d` indices. Considering the significant variability of subjective classification of color-coded maps,7 objective metrics are needed. The `d` values were developed to represent the deviation from normality towards ectasia for different parameters. The final BAD-D, currently in its third version, combines the `d` values using a logistic regression analysis to optimize ectasia detection. Different studies have found the BAD-D to be the most accurate parameter to detect ectasia.[16,21-24] For example, the analysis of a combination of the populations from two studies leading in total to one eye randomly selected from 811 normal eyes and from 422 keratoconic corneas, the area under the ROC (receiver operating characteristic) curve for BAD-D was 0.999 (95% confidence interval: 0.993 to 1.000) with 98.9% sensitivity and 99.8% specificity with a cut off value of 2.14.

The Quest for Going Beyond Tomography: Biomechanical Assessment

The eyes with normal topography from patients with clinical ectasia detected in the fellow eye, referred to as forme fruste keratoconus (FFKC) by Klyce,[25] have been widely used to demonstrate the enhanced ability of corneal tomography to detect ECD in comparison to Placido-disk based topography.[22,26-28] However, despite of criteria optimization, accuracy of BAD-D for detecting those milder or subclinical cases is much lower than when detecting frank keratoconus. For example, criteria of BAD-D higher than 1.22 provided 93.62% sensitivity in one series[22] and higher than 1.61 provided 89.2% sensitivity in another.[29] Also, a larger population with 241 FFKC eyes had 81.33% sensitivity considering criteria of 1.43.

Beyond shape analysis, biomechanical understanding is thereby supreme for augmenting the sensitivity for identifying mild ECD or its susceptibility. Reichert Ocular Response Analyzer (ORA) is a non-contact tonometer that monitors corneal deformation through an infrared apical reflex, providing data for biomechanical assessment.[30] While first generation pressure-dependent parameters had a relatively low accuracy for detecting keratoconus,[31] studies demonstrated that parameters derived from corneal deformation improved sensitivity to detect keratoconus and mild forms of ECD.[32] These data were found useful to improve diagnostic accuracy when combined with Pentacam data.[13] In fact, the validity of integrating corneal tomography and biomechanical assessment for enhancing ectasia risk detection was demonstrated on anecdotal cases, such as the findings on the fellow non operated eye from a patient that had progressive keratectasia after LASIK with no detectable preoperative risk factors.[33]

Oculus Corvis ST & ARV (Ambrósio, Roberts & Vinciguerra) Tomographic and Biomechanical Integration

The Oculus Corvis ST is also a non-contact tonometer that uses an ultra-high speed Scheimpflug camera to monitor corneal deformation in a much higher detail than ORA[34] The CBI was developed combining deformation parameters and the horizontal thickness profile,[35] being very effective to detect keratoconus (Vinciguerra et al., JRS 2016 in press). A new software developed by Oculus enables a robust integration with corneal tomography by Pentacam. The TBI (Tomography and Biomechanical Index) is calculated using a regression formula to optimize ectasia detection. In a study involving one eye randomly selected from 478 normal eyes and from 180 keratoconic corneas, the area under the ROC (receiver operating characteristic) curves for CBI, BAD-D and TBI were respectively 0.986, 0.999 and 1.0. Considering 94 FFKC cases, the TBI had 92.55% sensitivity with 98.74% specificity. The integration of Corvis ST and Pentacam does improve the detection of FFKC in cases with BAD-D lower than 1.6 **(Figure 6)**.

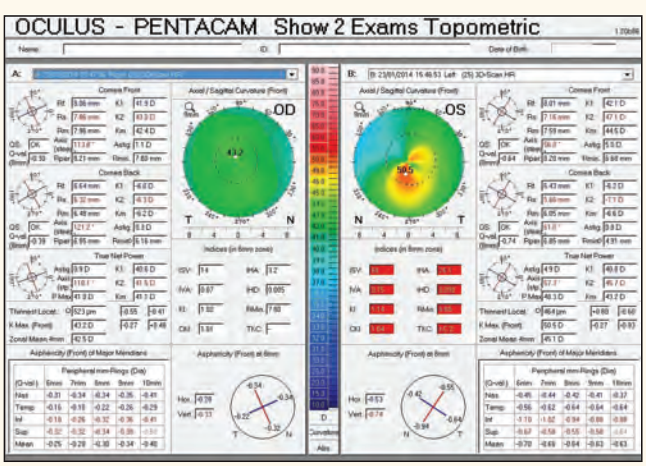

Figure 6a: Tomographical assessment of a FFKC case (OS: stage 2, OD: topographical and tomographical normal).

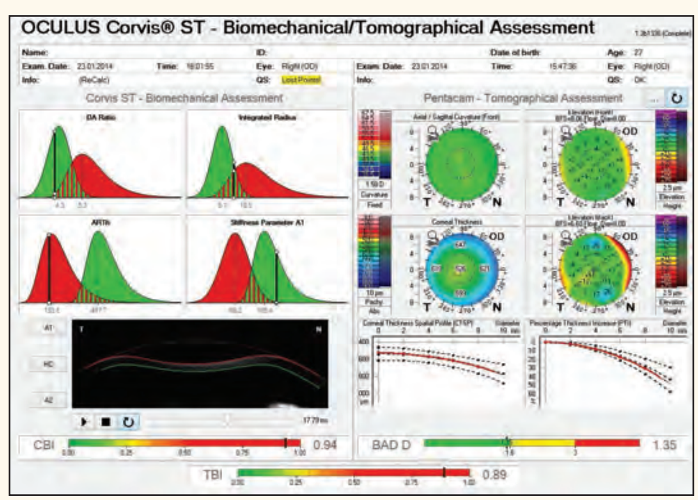

Figure 6b: The biomechanical/tomographical assessment OD with Tomographical Biomechanical Index (TBI) of 0.89 indicating an ectasia in the FFKC eye.

In addition, it has been also useful to enhance specificity, as in a case with mild asymmetric bow tie on topography from a patient that had LASIK in the fellow eye with no ectasia development **(Figure 7)**.

Future advances in corneal imaging include segmental or layered tomographic characterization with epithelial,[36,37] and Bowman's layer thickness mapping.[38] However, while genetic screening is not available, the integration of Pentacam and Corvis ST data is the ultimate approach for ectasia detection.

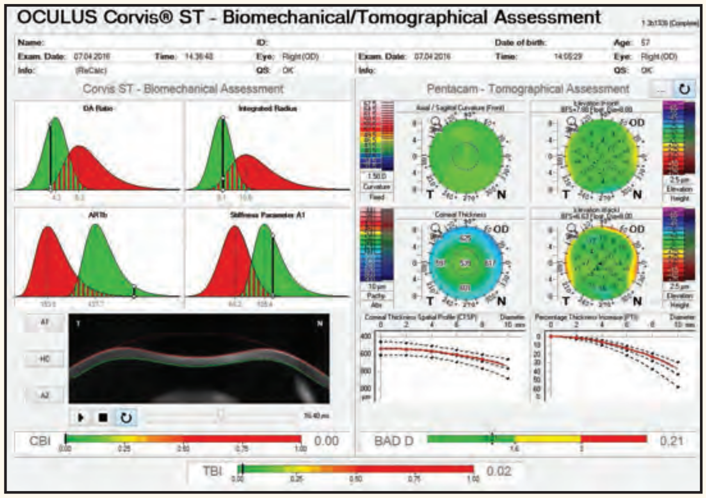

Figure 7: The biomechanical/ tomographical assessment of a stable eye with mild asymmetric bow tie.

Biomechanically Corrected IOP Measurement

Authors: Prof. Ahmed Elsheikh, PhD; Ashkan Mohammadvali; Kai-Jung Chen; (Liverpool, UK)

Intraocular pressure (IOP) measurement, through both contact and non-contact methods, is based on a basic concept; apply a mechanical force on the eye and correlate the resistance to deformation to IOP. As such, IOP measurements are affected by ocular stiffness, which in turn increases with larger corneal thickness and age, and reduces with keratoconus and refractive surgery [39]. This source of error can cause significant over-estimations or under-estimations in IOP measurement, leading to possible adverse effects on glaucoma management.

A method to enable the measurement of IOP in a way that is independent of ocular stiffness has been developed and validated extensively [40]. The method relies on accurate and representative numerical simulations of ocular globes with wide ranges of tissue thickness and material behaviour, and IOP levels, **(Figure 8).**

Through simulations of the Corvis procedure, and consideration of the Corvis deformation output, the new method enables the accurate estimation of an IOP that is less dependent on ocular properties, and thus biomechanically corrected IOP (bIOP).

bIOP has been first tested experimentally on several ex-vivo human eye globes. The eyes were subjected to known levels of IOP and to the Corvis procedure, **(Figure 9).** Both the uncorrected and corrected IOP measurements were compared with the applied IOP. In all cases, bIOP was significantly closer to true IOP than the Corvis measurement (the mean of the absolute differences between bIOP and true IOP was 0.84±0.97 mmHg compared with 3.46±1.09 mmHg for the absolute differences between uncorrected Corvis IOP and true IOP).

bIOP was then assessed clinically on a number of clinical databases involving

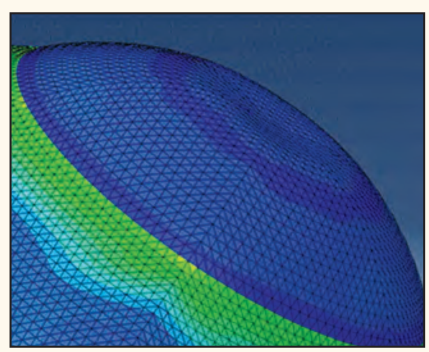

Figure 8: A numerical model of a human eye subjected to a pre-set IOP and the air pressure generated by the Corvis procedure.

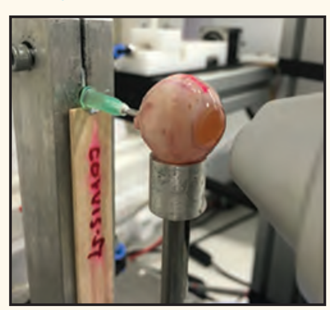

Figure 9: An ex vivo human eye subjected to known levels of IOP and to the Corvis procedure.

thousands of Corvis measurements. In all cases, bIOP significantly reduced the association between IOP measurements and both corneal thickness and age. bIOP was also assessed for patients undergoing the LASIK refractive surgeries **(Figure 10)**. The difference in bIOP taken before and after surgery was 1.0 mmHg (14.6±2.0 pre-surgery vs 13.6±2.1 post-surgery), compared with 3.4 mmHg for uncorrected Corvis readings (14.8±2.4 pre-surgery vs 11.4±1.9 post-surgery) and 3.1 mmHg for Goldmann Applanation Tonometry (GAT) readings (15.8±2.4 pre-surgery vs 12.7±2.3 post-surgery).

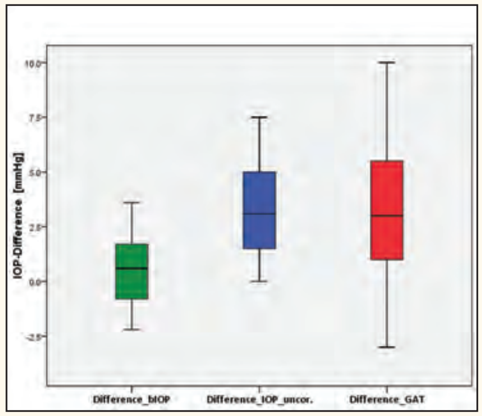

Figure 10: Differences in IOP reading before minus after LASIK for bIOP, uncorrected Corvis IOP, and GAT IOP.

References

1. Ambrósio Jr R, Ramos I, Luz A, Faria-Correia F, Steinmueller A, Krug M, Belin MW, Roberts C. Dynamic Ultra-High-Speed Scheimpflug imaging for assessing corneal biomechanical properties. Rev Bras. Oftalmol 2013, 72(2):99-102.
2. Roberts CJ. Concepts and Misconceptions in Corneal Biomechanics. J Cataract Refract Surg 2014;40:862-869.
3. Metzler K, Mahmoud AM, Liu J, Roberts CJ. Deformation Response of Paired Donor Corneas to An Air Puff: Intact Whole Globe vs Mounted Corneoscleral Rim. J Cataract Refr Surg 2014;40(6):888-96
4. Roberts CJ, Mahmoud AM, Bons J, Hossain A, Elsheikh A, Vinciguerra R, Vinciguerra P, Ambrósio R. A New Stiffness Parameter in Air Puff Induced Corneal Deformation Analysis. Invest Ophth Vis Sci. 2016;57: ARVO E-Abstract 2390.
5. Vinciguerra R, Elsheikh A, Roberts CJ, et al. Influence of Pachymetry and Intraocular Pressure on Dynamic Corneal Response parameters Provided by Corvis ST in Healthy Subjects: Normative Values and Suspect Pathology. J Refract Surg 2016;In press.
6. Joda AA, Shervin MMS, Kook D, Elsheikh A. Development and validation of a correction equation for Corvis tonometry. Computer Methods in Biomechanics and Biomedical Engineering 2015:1-11.
7. Lopes BT, Ramos IdC, Salomão MQ, Canedo ALC, Ambrósio Jr. R. Perfil paquimétrico horizontal para a detecção do ceratocone. Revista Brasileira de Oftalmologia 2015;74:382-5.
8. Vinciguerra R, Elsheikh A, Roberts CJ, et al. Detection of Keratoconus with a new Corvis ST Biomechanical Index. J Refract Surg 2016;Under review.
9. Binder PS, Lindstrom RL, Stulting RD, et al. Keratoconus and corneal ectasia after LASIK. J Refract Surg 2005;21:749-52.
10. Ambrosio R, Jr., Randleman JB. Screening for ectasia risk: what are we screening for and how should we screen for it? J Refract Surg 2013;29:230-2.
11. McGhee CN, Kim BZ, Wilson PJ. Contemporary Treatment Paradigms in Keratoconus. Cornea 2015;34 Suppl 10:S16-23.
12. Ambrosio R, Jr., Belin MW. Imaging of the cornea: topography vs tomography. J Refract Surg 2010;26:847-9.
13. Ambrosio R, Jr., Nogueira LP, Caldas DL, et al. Evaluation of corneal shape and biomechanics before LASIK. Int Ophthalmol Clin 2011;51:11-38.
14. Belin MW, Khachikian SS. An introduction to understanding elevation-based topography: how elevation data are displayed - a review. Clin Experiment Ophthalmol 2009;37:14-29.
15. Ramos IC, Correa R, Guerra FP, et al. Variability of subjective classifications of corneal topography maps from LASIK candidates. J Refract Surg 2013;29:770-5.
16. Belin MW, Ambrosio R. Scheimpflug imaging for keratoconus and ectatic disease. Indian J Ophthalmol 2013;61:401-6.
17. Duncan JK, Belin MW, Borgstrom M. Assessing progression of keratoconus: novel tomographic determinants. Eye Vis (Lond) 2016;3:6.
18. Ambrosio R, Jr., 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.
19. Luz A, Ursulio M, Castaneda D, Ambrosio R, Jr. [Corneal thickness progression from the thinnest point to the limbus: study based on a normal and a keratoconus population to create reference values]. Arq Bras Oftalmol 2006;69:579-83.
20. Ambrosio R, Jr., Caiado AL, Guerra FP, et al. Novel pachymetric parameters based on corneal tomography for diagnosing keratoconus. J Refract Surg 2011;27:753-8.
21. Orucoglu F, Toker E. Comparative analysis of anterior segment parameters in normal and keratoconus eyes generated by scheimpflug tomography. J Ophthalmol 2015;2015:925414.
22. 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.
23. Lopes BT, Ramos IC, Dawson DG, Belin MW, Ambrosio R, Jr. Detection of ectatic corneal diseases based on pentacam. Z Med Phys 2016.
24. Muftuoglu O, Ayar O, Hurmeric V, Orucoglu F, Kilic I. Comparison of multimetric D index with keratometric, pachymetric, and posterior elevation parameters in diagnosing subclinical keratoconus in fellow eyes of asymmetric keratoconus patients. Journal of cataract and refractive surgery 2015.
25. Klyce SD. Chasing the suspect: keratoconus. Br J Ophthalmol 2009;93:845-7.
26. Saad A, Gatinel D. Topographic and tomographic properties of forme fruste keratoconus corneas. Invest Ophthalmol Vis Sci 2010;51:5546-55.
27. Arbelaez MC, Versaci F, Vestri G, Barboni P, Savini G. Use of a support vector machine for keratoconus and subclinical keratoconus detection by topographic and tomographic data. Ophthalmology 2012;119:2231-8.
28. Smadja D, Touboul D, Cohen A, et al. Detection of subclinical keratoconus using an automated decision tree classification. Am J Ophthalmol 2013;156:237-46 e1.
29. Ruisenor Vazquez PR, Galletti JD, Minguez N, et al. Pentacam Scheimpflug tomography findings in topographically normal patients and subclinical keratoconus cases. American journal of ophthalmology 2014;158:32-40 e2.
30. Luce DA. Determining in vivo biomechanical properties of the cornea with an ocular response analyzer. J Cataract Refract Surg 2005;31:156-62.
31. Fontes BM, Ambrosio R, Jr., Jardim D, Velarde GC, Nose W. Corneal biomechanical metrics and anterior segment parameters in mild keratoconus. Ophthalmology 2010;117:673-9.
32. Luz A, Lopes B, Hallahan KM, et al. Discriminant Value of Custom Ocular Response Analyzer Waveform Derivatives in Forme Fruste Keratoconus. Am J Ophthalmol 2016;164:14-21.
33. Ambrosio R, Jr., Dawson DG, Salomao M, Guerra FP, Caiado AL, Belin MW. Corneal ectasia after LASIK despite low preoperative risk: tomographic and biomechanical findings in the unoperated, stable, fellow eye. J Refract Surg 2010;26:906-11.
34. Ambrósio Jr R, Ramos I, Luz A, et al. Dynamic ultra high speed Scheimpflug imaging for assessing corneal biomechanical properties. Revista Brasileira de Oftalmologia 2013;72:99-102.
35. Lopes BT, Ramos IdC, Salomão MQ, Canedo ALC, Ambrósio Jr. R. Perfil paquimétrico horizontal para a detecção do ceratocone. Revista Brasileira de Oftalmologia 2015;74:382-5.
36. 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.
37. Reinstein DZ, Gobbe M, Archer TJ, Silverman RH, Coleman DJ. Epithelial, stromal, and total corneal thickness in keratoconus: three-dimensional display with artemis very-high frequency digital ultrasound. J Refract Surg 2010;26:259-71.
38. Abou Shousha M, Perez VL, Fraga Santini Canto AP, et al. The use of Bowman's layer vertical topographic thickness map in the diagnosis of keratoconus. Ophthalmology 2014;121:988-93.
39. Elsheikh, A., Alhasso, D., Gunvant, P. & Garway-Heath, D. F. Multi-parameter correction equation for Goldmann applanation tonometry. Optometry and Vision Science 88(1) (2011).
40. Joda, A. A., Shervin, M. M., Kook, D. & Elsheikh, A. Development and validation of a correction equation for Corvis tonometry. Computer methods in biomechanics and biomedical engineering 19, 943-953 (2016).