Keratoconus / Ectasia Detection with the Oculus Pentacam: Belin / Ambrósio Enhanced Ectasia Display

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Belin / Ambrósio Enhanced Ectasia Display

While the basis for the development of ectasia may ultimately be a structural, genetic, or biochemical abnormality of the cornea, measurable structural components, such as elevation and pachymetry should be thoroughly evaluated.[1] The measurements must be reviewed in a comprehensive manner, rather than assessing isolated values. While measurements such as aberrometry and curvature can be used in evaluating a patient for ectatic disease, they are derivatives of elevation.[2] With subclinical disease, curvature alone may not provide enough information to detect early corneal abnormality.

The goal of the *Belin / Ambrósio Enhanced Ectasia Display* is to combine elevation based and pachymetric corneal evaluation in an all inclusive display. This gives the clinician a global view of the structure of the cornea and allows the physician to quickly and effectively screen patients for ectatic disease. The elevation maps and pachymetric data are placed side by side in a comprehensive display. By evaluating these measurements from different perspectives, the ability to identify abnormalities is increased. The elevation and pachymetric components of the display are designed to be complimentary.

The combination of the pachymetric graphs and indices and the enhanced elevation maps provided by the *Belin / Ambrósio Enhanced Ectasia Display* have increased sensitivity and specificity in the screening of patients for ectasia. Keratoconus, is by definition, a bilateral (often highly asymmetric) corneal disease characterized by progressive thinning and protrusion which leads to an increase in curvature, irregular astigmatism and progressive myopia. In about 5% of the cases, there is significant asymmetry in that the less involved eye initially presents with a normal curvature map. Longitudinal studies have found that about 50% of such cases progress to clinical keratoconus. The study of eyes with highly asymmetric keratoconus has confirmed the superior sensitivity **(Figure 1)** of the

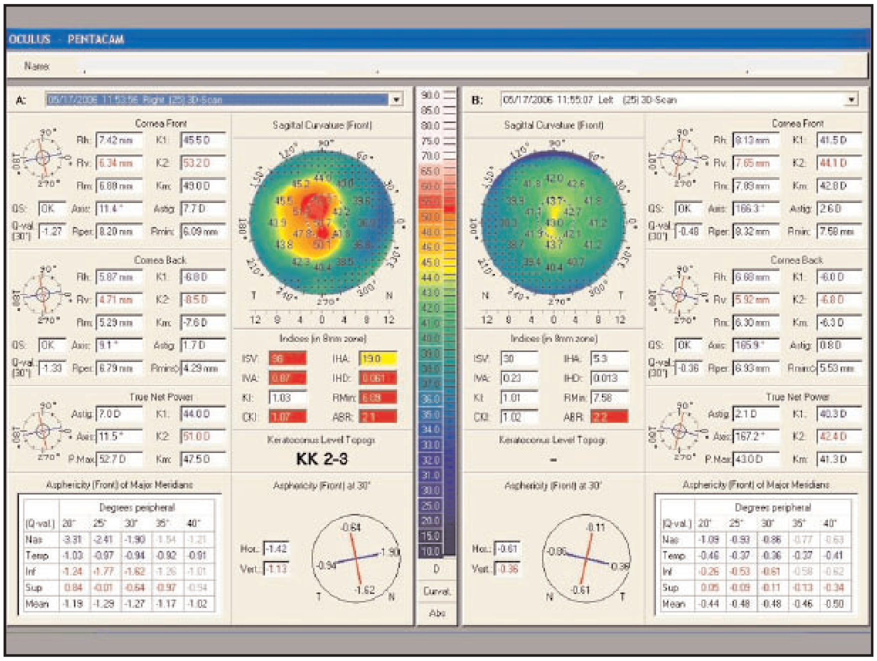

Figure 1A and 1B: Asymmetric keratoconus. Curvature display along with Belin /Ambrósio Enhanced Ectasia Display reveals that despite normal curvature in the left eye (1A), abnormalities suggestive of ectatic disease can be easily detected when using the enhanced display (1B).

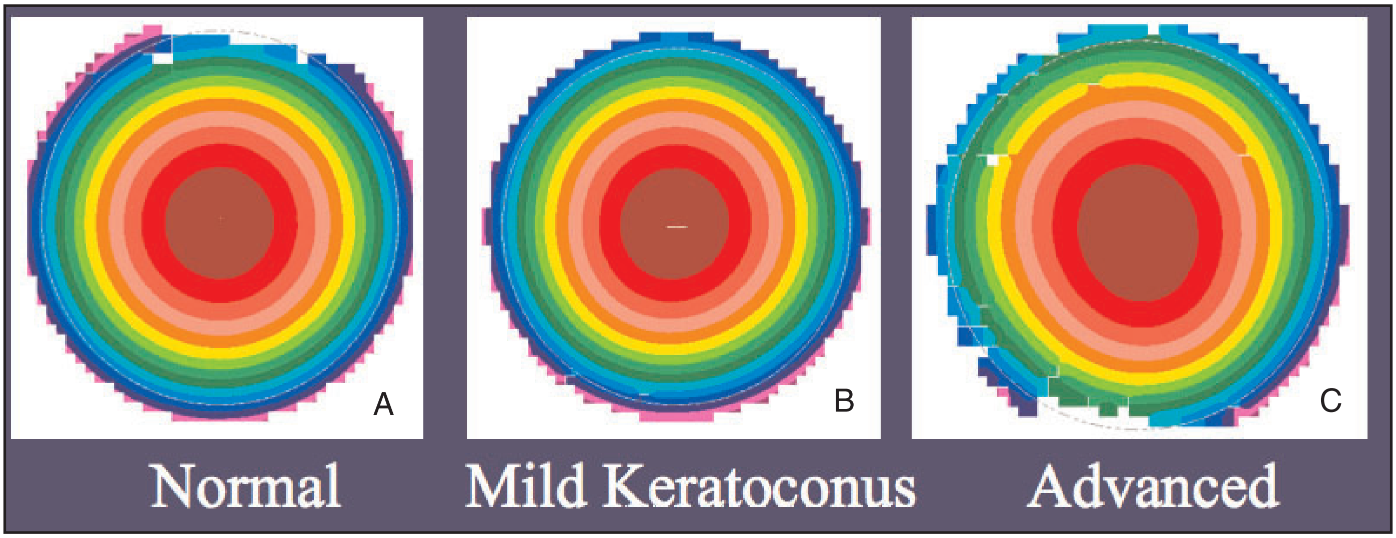

Figure 2: Raw elevation maps generated using data from a normal cornea (a) a mild cone (b) and an advanced cone (c). A side by side comparison of the raw elevation maps from three different corneas shows that adequate qualitative comparison is not possible without comparing the data to an appropriate reference surface.

display.[3-6] The new elevation based approach has increased sensitivity to 75% in eyes from patients previously diagnosed with unilateral keratoconus (Salomão and Ambrósio, unpublished data 2007). Superior specificity is demonstrated in studying eyes with inferior steepening on corneal anterior curvature with no keratoconus.

Elevation Based Topography

The basics and advantages of elevation based topography were discussed by Belin and Khachikian in an earlier issue of HIGHLIGHTS OF OPHTHALMOLOGY.[7] Elevation based Scheimpflug imaging has advantages over Placido based systems in that it allows for the measurement of both the anterior and posterior corneal surfaces and the computation of a complete pachymetric map.[8] This paper will concentrate on the use of a new Keratoconus / Ectasia Detection Display *(Belin / Ambrósio Enhanced Ectasia Display)* available on the Oculus Pentacam *(OCULUS Optikgerate GmbH, Wetzlar, Germany).*

Elevation maps are typically viewed by comparing the data to some standard reference surface (shape). The reason for viewing elevation data in this format is that the actual raw elevation data lacks enough surface variability for an easy qualitative inspection that would allow the clinician to separate normal from abnormal corneas. In other words, raw elevation data from normal eyes looks surprisingly similar to the raw elevation data in abnormal eyes (e.g. Keratoconus) **(Figure 2)**. By subtracting a known shape, however, the differences or variance become highlighted or exaggerated **(Figure 3)**. This method of depicting elevation data and the subtracted reference shapes commonly used (best-fit-sphere (BFS), best-fit-ellipse, and the best-fit-toric ellipsoid) were first introduced by Belin MW in 1990 on the PAR CTS.[9] *(The term "Elevation Maps" while ingrained are technically incorrect. A better term would be an "Elevation Subtraction Map" since we do not look at the actual elevation data, but only the data after subtracting out some reference shape.)*

For refractive surgery screening and for most clinical situations using a best-fit-sphere gives the most useful qualitative map (i.e. easiest to read and understand). Fitting a best-fit-sphere to the central 8 – 9 mm zone appears best for clinical interpretation. Since the normal eye is an aspherical prolate surface the central 8 – 9 mm zone yields a reference surface that allows for subtle identification of both ectatic disorders and astigmatism. Larger zones would typically yield a flatter BFS and smaller zones a steeper BFS. While other shapes may have some clinical utility, shapes

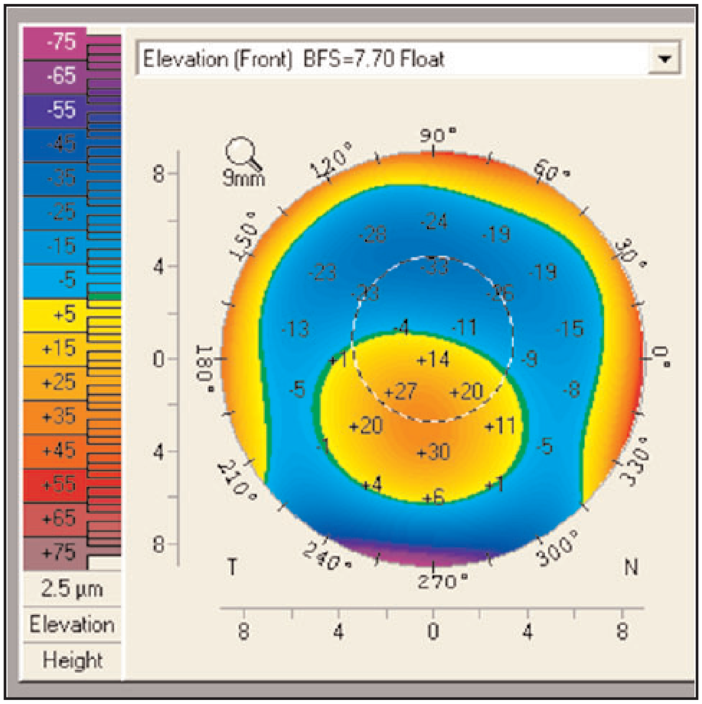

Figure 3: Anterior elevation map of a patient with keratoconus. The central island of elevation is clearly visible and it corresponds to the location of the cone. This would not be visible if one were not comparing raw data to a reference surface.

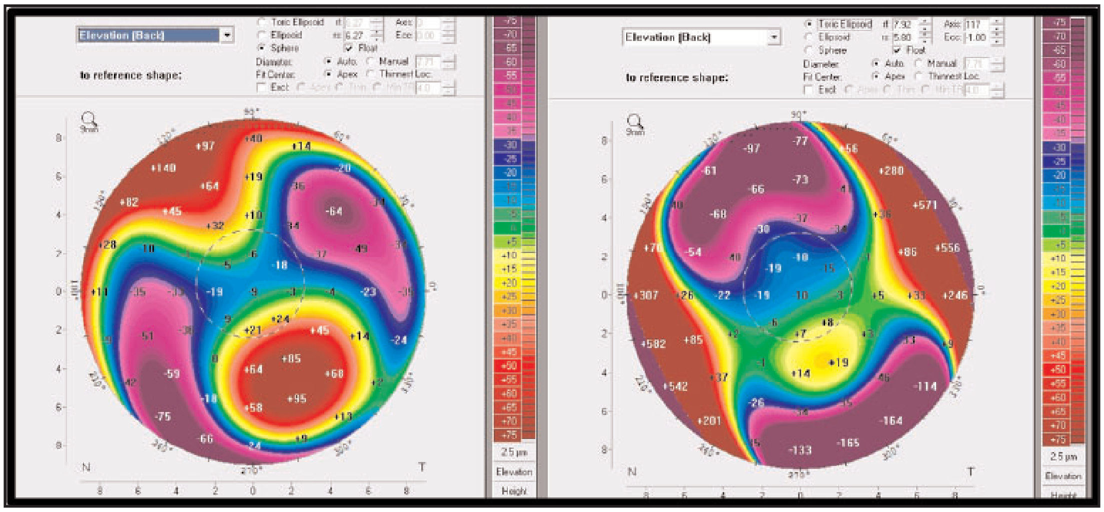

Figure 4. Side by side comparison of elevation reference surfaces. The elevation map on the left shows corneal elevation data from a patient with advanced keratoconus as compared to a BFS (4a). The cone and associated area of elevation can clearly be seen. Figure 4b shows the same elevation data using a toric ellipse as a reference surface. While the area of the cone is still visible, it is muted by the use of a suboptimal reference surface.

that more closely approximate a cone (e.g. toric ellipsoid) will actually mask the cone as the best-fit-toric ellipsoid more closely matches the cone contour **(Figure 4)**.

Enhanced Reference Surface

While the Best-Fit-Sphere (BFS) is qualitatively useful, the clinician typically assumes that the reference surface (the shape being subtracted) closely approximates a "normal" cornea. Some investigators, in the past, have attempted to compare individual corneas to some "average normal shape." The problem here is that there is such variability in corneal shape that the "normal" or "average" shape does not represent a clinically useful reference surface for individual corneal evaluation. What is typically not appreciated is that the BFS will be influenced by any abnormal portion of the cornea. In the case of keratoconus or ectasia, the cone or apical protrusion will have the effect of steepening the BFS. This will actually minimize the elevation difference between the apex of the cone and the BFS **(Figure 5)**. What the clinician would really like to see is how the corneal shape compares to the more normal portion of the individual's cornea, as this would better approximate the "normal" for this individual. This would have the effect of better defining or exaggerating the ectatic regions of the cornea.

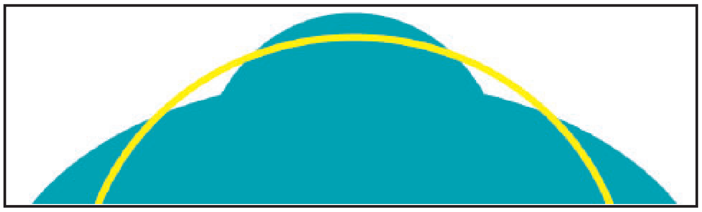

Figure 5. Schematic drawing showing how inclusion of the cone in the reference surface calculation will influence the BFS and hide the corneal abnormality.

We designed a new screening display *(Belin / Ambrosio Enhanced Ectasia Display)* that effectively does just that. Our goal was to design a reference surface that more closely approximates the individual's normal cornea and then to compare the actual corneal shape to this new reference shape. In simple terms, what we did was to define a reference surface based on the individual's own cornea after excluding the conical or ectatic region. To do this, we identified a 4 mm optical zone centered on the thinnest portion of the cornea (exclusion zone). We defined the new "enhanced BFS" by utilizing all the valid data from within the 9.0 mm central cornea with the exception of the exclusion zone **(Figure 6)**. Earlier investigations looked at centering the exclusion zone on

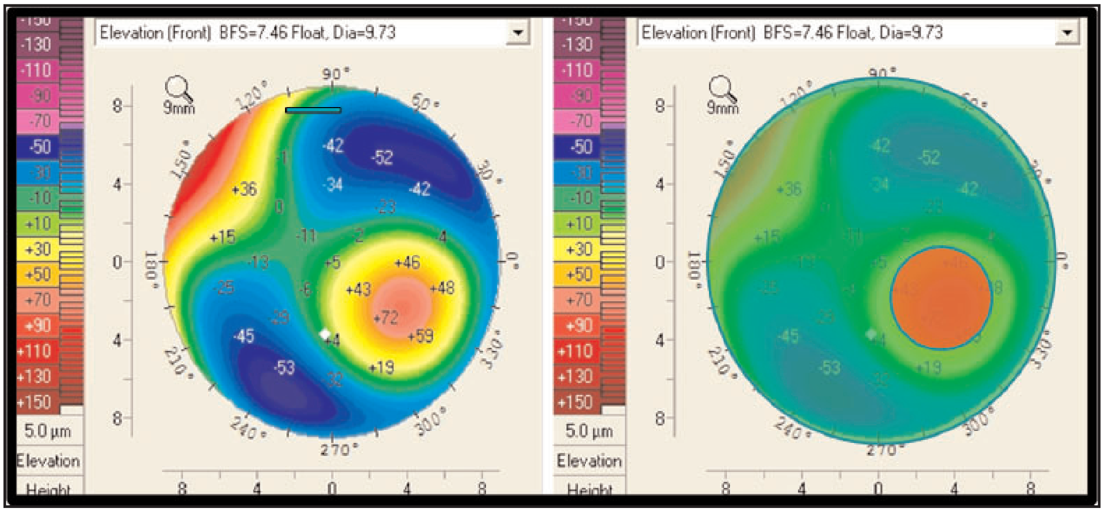

Figure 6. The image on the left shows a patient with Keratoconus and a large area of abnormal elevation. The image on the right reflects how this abnormal area of elevation (red circle) is excluded from the BFS calculation.

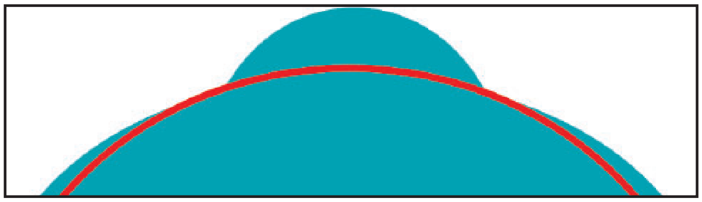

Figure 7. Schematic drawing showing how exclusion of the cone from the reference surface calculation will influence the best-fit sphere and highlight the corneal abnormality.

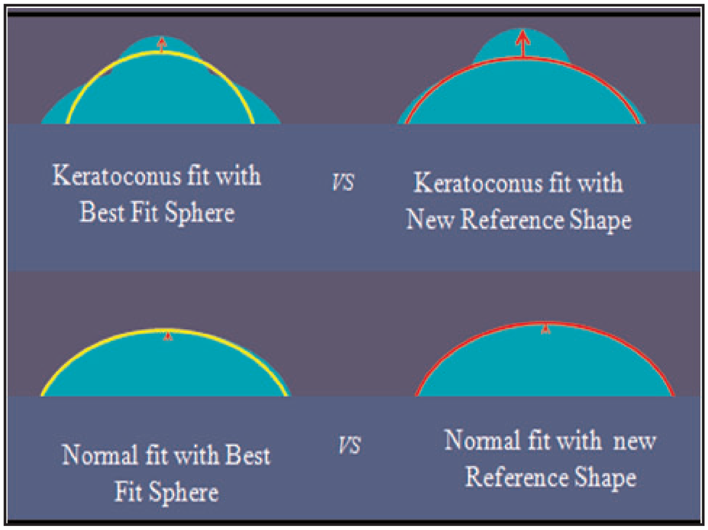

Figure 8. Schematic drawing comparing how removal of the exclusion zone will affect the BFS.

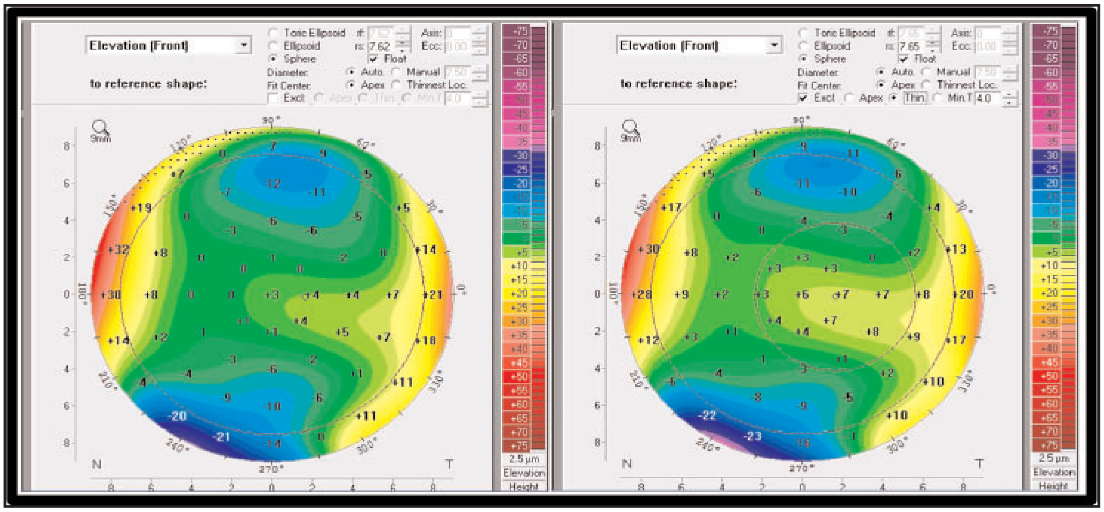

Figure 9. In the normal cornea, there is little change in relative elevation, or the appearance of the elevation map when comparing the BFS (left) to the enhanced BFS (right).

the apex and also the zone of minimal radius of tangential curvature, but the thinnest region turned out to be the most reliable. We also looked at different optical zone sizes. Larger zones increased sensitivity at the expense of specificity, while smaller zones did the opposite. A 4 mm exclusion zone appeared to balance the need for sensitivity without significant false positives. The resulting new reference surface ("Enhanced BFS") closely approximates the more normal peripheral cornea while further exaggerating the conical protrusion **(Figure 7)**. The elevation difference between using a standard BFS and the new "enhanced" BFS will be significant for a conical cornea, while the difference is minimal in a normal cornea **(Figure 8)**. Because a normal cornea is only slightly prolate, the resulting "Enhanced" BFS (after excluding the 4.0 mm zone centered on the thinnest portion of the cornea) is only minimally changed and the resulting maps (standard BFS v. enhance BFS) look very similar **(Figure 9).** With a conical cornea, removing the 4 mm zone eliminates the cone or steep portion of the cornea and results in a significantly flatter BFS based more on the normal peripheral cornea. The resulting elevation maps show a significant difference as the conical portion of the cornea is now more pronounced (i.e. easier to identify) **(Figure 10)**. The average change for both anterior and posterior corneal surfaces for normal and known keratoconic eyes were as follows:

Normal eyes showed an avg change in anterior apex and maximum elevation of 1.86±1.9µm and 1.63±1.4µm.

Keratoconus eyes showed anterior apex and maximum elevation changes of 20.4±23.1µm and 20.9±21.9µm.

(P<.0001).

Posteriorly, normal eyes showed an average change in apex and maximum elevation of 2.86±1.9µm and 2.27±1.1µm.

Keratoconus eys showed posterior apex and maximum elevation changes of 39.9±38.1µm and 45.7±35.9µm.

(P<.0001).

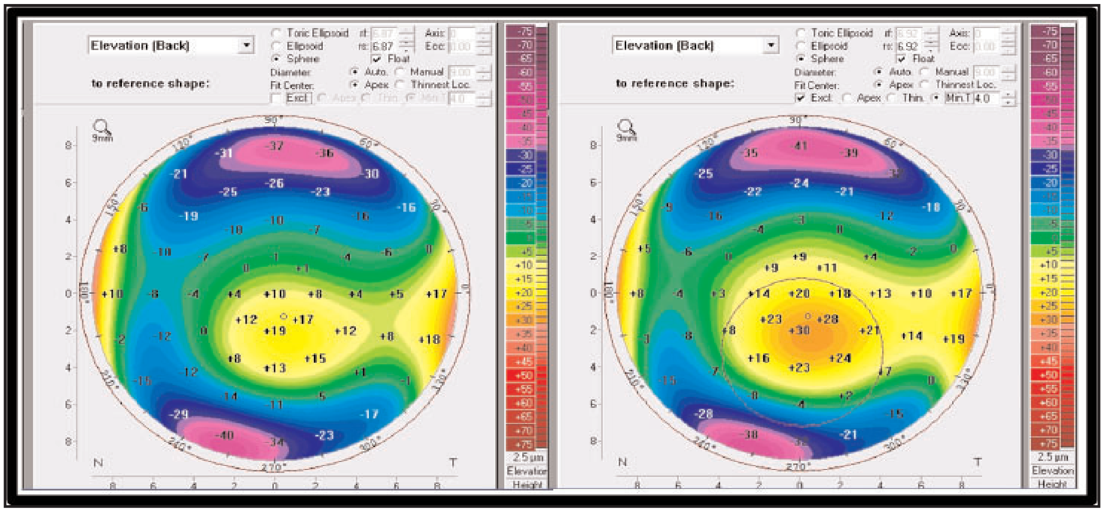

Figure 10. In the abnormal cornea, there is significant change in relative elevation, and the appearance of the elevation map when comparing the BFS (left) to the enhanced BFS (right). The area of the cone is more easily seen on the exclusion map (right).

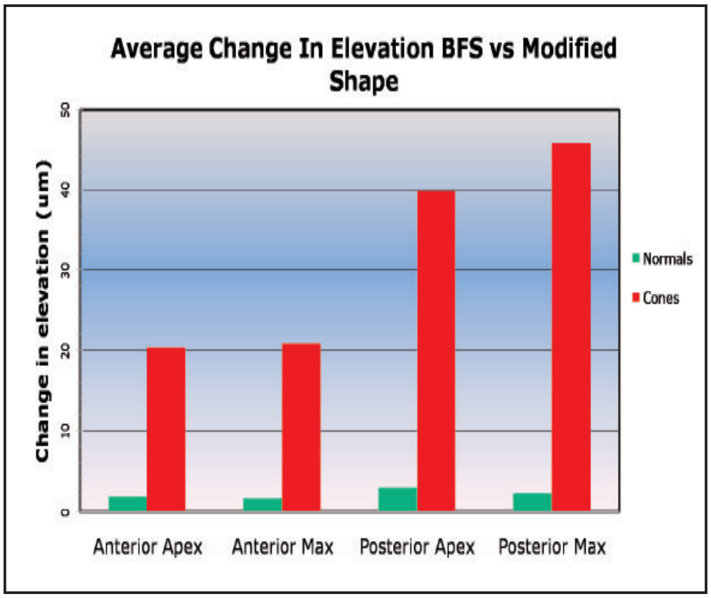

Figure 11. Bar graph showing the relative change in elevation for normal eyes (green) and keratoconics (red) when comparing elevation measured with the baseline BFS and the enhanced BFS.

This change (the elevation difference between the standard BFS and the "Enhanced" BFS) appears to have significant prognostic value as all normal eyes tested showed minimal change while eyes with keratoconus or ectasia showed a significant increase in elevation values **(Figure 11).**

Elevation Display Interpretation

Baseline Elevation Maps - We can begin by looking at the left half of the *Belin /Ambrosio ectasia display* where the elevation data is shown **(Figure 12)**. The first two elevation maps (placed side by side) display the baseline relative elevation of the cornea of off the best fit sphere. This map is displayed for the front surface (left map) and back surface (right map) of the cornea. The radius of curvature of the best fit sphere (BFS) in millimeters and the diameter of the zone used to compute the BFS is noted above each map. In this sample map **(Figure 12)** the radius of curvature of the Best Fit Sphere for the front surface of the cornea is 8.17mm and the radius of curvature of the BFS for the back surface of the cornea is 6.63. "Float" describes the positioning of the reference surface relative to the corneal surface. The last number above the elevation map is the diameter of the circle (in millimeters) centered on the corneal apex inside of which valid corneal data is taken to compute the BFS. In this sample 8.19 mm for the anterior map and 7.50 mm for the posterior. Based on experience we have found that the ideal size is > 8.0 mm for the anterior and > 7.5 mm for the posterior display. A poor pentacam image will contain less valid data and therefore the diameter of the circle from which data is taken is smaller. To the left of the elevation map is the number 9mm, this is the diameter of the cornea being displayed. To the right of the map is the eye being examined, OD or OS. Left clicking anywhere on the elevation maps brings up the elevation value at that point. Right clicking on the map brings up the same options available on all Pentacam elevation maps such as highlighting the thinnest point, the apex, and others. Looking at the color scale of the map itself, warm colors represent areas of the cornea that are above the BFS, and cool colors represent areas of the cornea below the BFS.

Exclusion Maps - Immediately below the standard anterior and posterior elevation maps are the anterior and posterior exclusion maps. These are enhanced elevation maps, which display the same elevation data as the baseline maps, but the method used to calculate the best fit sphere (the reference surface) has been modified to accentuate ectatic or conical regions. In these maps (both anterior and posterior) the best-fit sphere is calculated using all the raw elevation data located outside a 4mm circle centered on the thinnest point of the cornea. Therefore, the raw elevation data inside the 4mm circle centered on the thinnest point is excluded from the BFS calculation. This area of excluded data is called the exclusion zone and the map is an exclusion map. The location of the exclusion zone is indicated by a 4mm red circle and cannot be modified. The newly calculated BFS is known as the "Enhanced Best Fit Sphere."

This "exclusion map" may be significantly different from the baseline elevation map, or it may be very similar, depending on the relative impact the 4 mm exclusion zone made to the original (standard) BFS computation.

The exclusion map below **(Figure 12)** shows that for the front surface of the cornea the radius of curvature of the enhanced BFS is only 0.01mm different from the baseline BFS. The baseline BFS for the front of the cornea is 8.17 mm, the enhanced BFS for the exclusion map is 8.18mm. The size of the BFS changed very little, as did the elevation map, when going from the baseline to the exclusion map. For the back surface of the cornea, however, the enhanced BFS was 6.84mm whereas the radius of curvature of the BFS for the baseline elevation map was 6.63mm. The exclusion map of the back surface of the cornea using the enhanced BFS highlights an "island" of elevation in the inferotemporal cornea that was present in the standard map but not as promient. There is a significant increase in the relative elevation value when going from the baseline map to the exclusion map and this may suggest an area of abnormality.

The bottom 2 maps are difference maps showing the relative change in elevation from the baseline elevation map to the exclusion map. The bottom maps contain only 3 colors, each one corresponding to the amount of elevation change that occurs when moving between the baseline elevation map and the exclusion map. The green on the difference map represents a change in elevation (from the baseline to the exclusion map) of less than 6 microns on the front surface and 8 microns on the back surface of the cornea and are typically within the range seen in normal eyes. The red represents areas where the elevation difference between the 2 maps is ≥ 12 microns anteriorly or 20 microns posteriorly and are the mag-

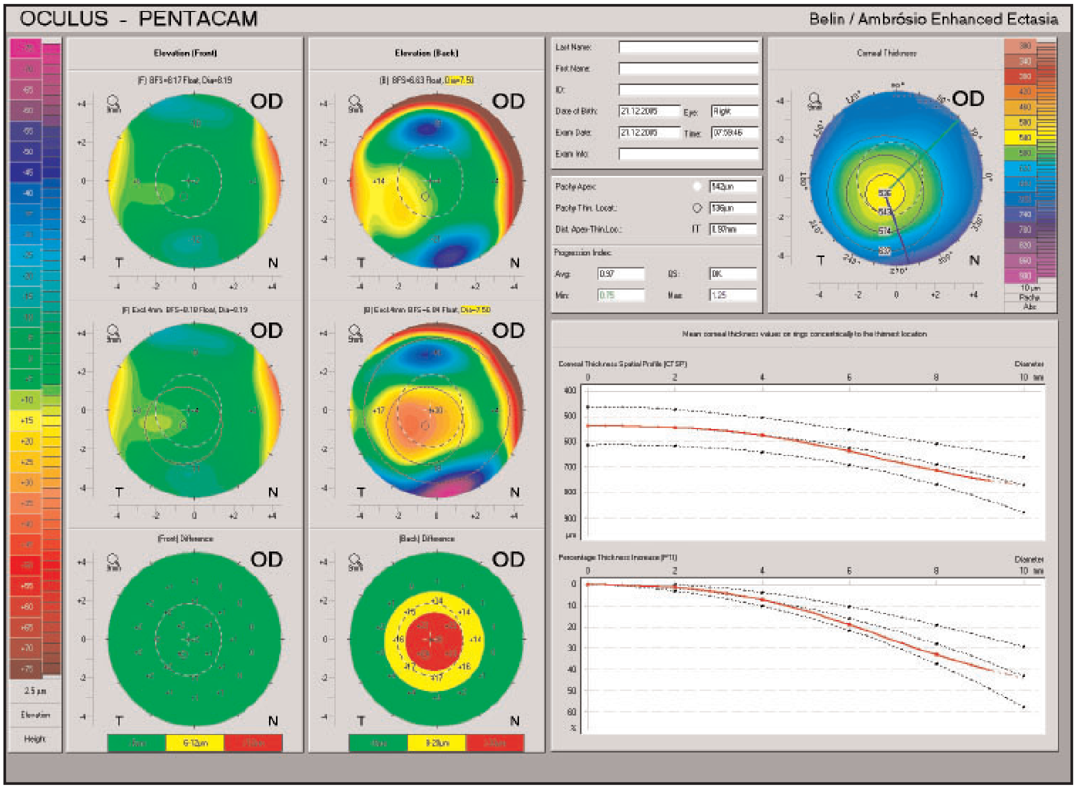

Figure 12. Belin/Ambrosio Enhanced Ectasia Display with elevation data presented on the left and pachymetric data presented on the right.

nitude typically seen in eyes with known keratoconus. The yellow areas represent a change between 6 and 12 microns for the front surface and 8 to 20 microns for the back surface. These eyes fall in the suspicious or suspect zone. As you can see from Figure 12, while the front surface does not show much change from the baseline to the exclusion elevation map (the map is all green), the posterior surface has substantial change (central area of red).

Pachymetric Evaluation

The importance of corneal thickness and pachymetric distribution evaluation were discussed in an earlier issue of HIGHLIGHTS OF OPHTHALMOLOGY by Ambrósio, Silava and Simonato.[10] Corneal thickness data has been used for the study of corneal endothelial disease and it provides important clinical considerations for ocular hypertension and glaucoma patients. It is also, however, critical for evaluating candidacy for refractive surgery patients.[11-19] The Pentacam provides a detailed corneal thickness distribution map with 3 *um* accuracy and repeatability.[20]

Display Interpretation (pachymetry)- The pachymetric portion of the display includes the pachymetry map (Corneal Thickness), the two graphs (see below) and the pachymetric indices. It identifies the corneal thickness at the apex (center of the exam), the thinnest point (TP) and the location and distance of the thinnest point relative to the apex. The direction of the TP is displayed as temporal (T), nasal (N), superior (S) and inferior (I) or intermediate (e.g. IT inferio-temporal). In only about 12% of normal corneas, the pachymetric difference between the TP and the apex is > 10µm. We also found a positive correlation ($r^2 = 0.61$) comparing the distance difference and the pachymetric difference between the apex and thinnest point (TP). In eyes with keratoconic the distance between the apex and the thinnest point is significantly higher (1.52 ± 0.58mm) than normals (0.9 ± 0.23mm) ($p<0.05$). Along with the thinnest point evaluation, the pachymetric display evaluates the thickness profile of the cornea.

The Corneal Thickness Spatial Profile (CTSP) and the Percentage Thickness Increase (PTI)

The CTSP displays the average thickness measurements along twenty-two concentric circles centered on the thinnest point with increasing diameters of 0.4mm steps **(Figure 13).**

In addition to the average values, the standard deviations of the pachymetry along each circle are calculated. The second graph (percentage of thickness increase (PTI)) is calculated using a simple formula: (CT@x - TP)/TP, where x represents the diameter of the imaginary circle centered on the TP with increased diameters as provided by the CTSP. Each graph displays the examined eye data in red and three broken dark lines, which represent the upper and lower double standard deviation (95% - confidence interval) and the average values from a normal population **(Figure 14)**.

We found that keratoconus patients have thinner corneas and a faster and more abrupt increase of the CTSP and PTI than normal corneas.[21] These findings were in agreement with previous reports in the literature pioneered by Mandell and Polse.[22] The CTSP and PTI graphs were designed to enable the rapid identification of very early forms of ectasia, increasing sensitivity and specificity for screening candidates for refractive surgery. The thickness profile also enables clinical differentiation of a normal thin cornea from an ectatic cornea, and a normal thick cornea from an edematous cornea.[4-5]

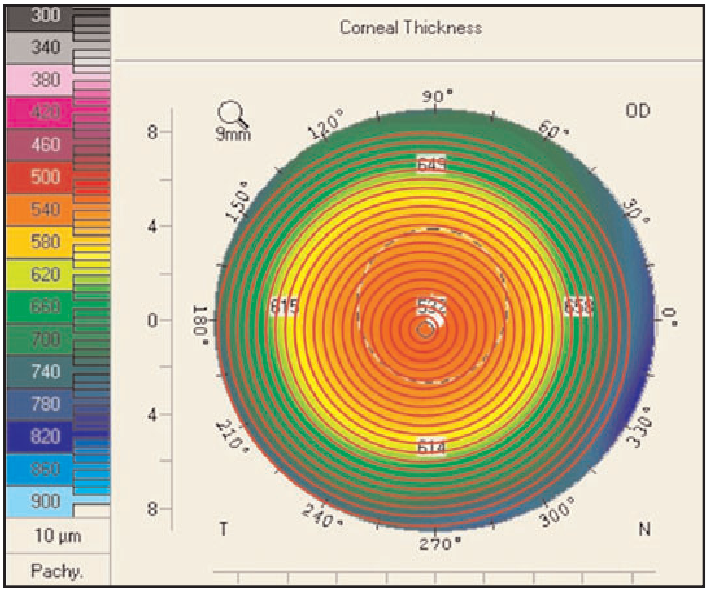

Figure 13. Top down view of the corneal thickness spatial profile showing 22 imaginary concentric circles centered on the TP. The pachymety values along these circles are averaged and graphed on the CTSP graph.

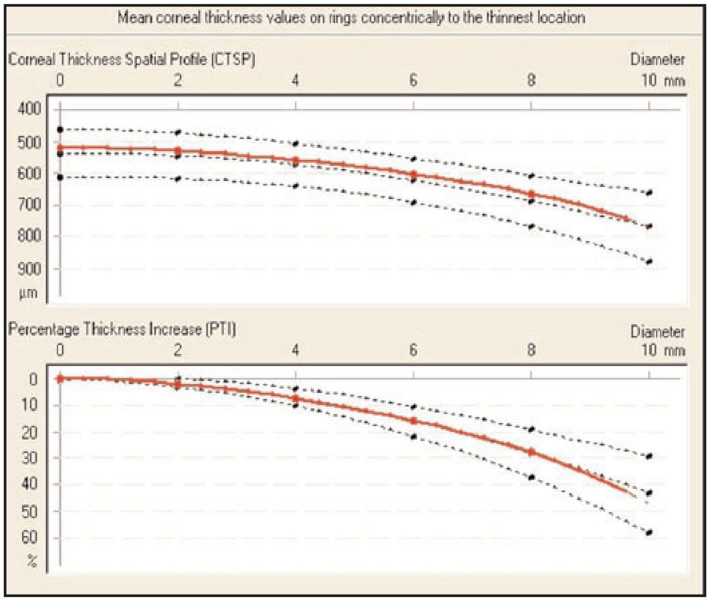

Figure 14. Corneal thickness spatial profile graph. The top graph shows the average pachymetry (along each of the 22 concentric circles) as you go from the thinnest point to the periphery. The bottom graph shows the percentage thickness increase value at those same points.

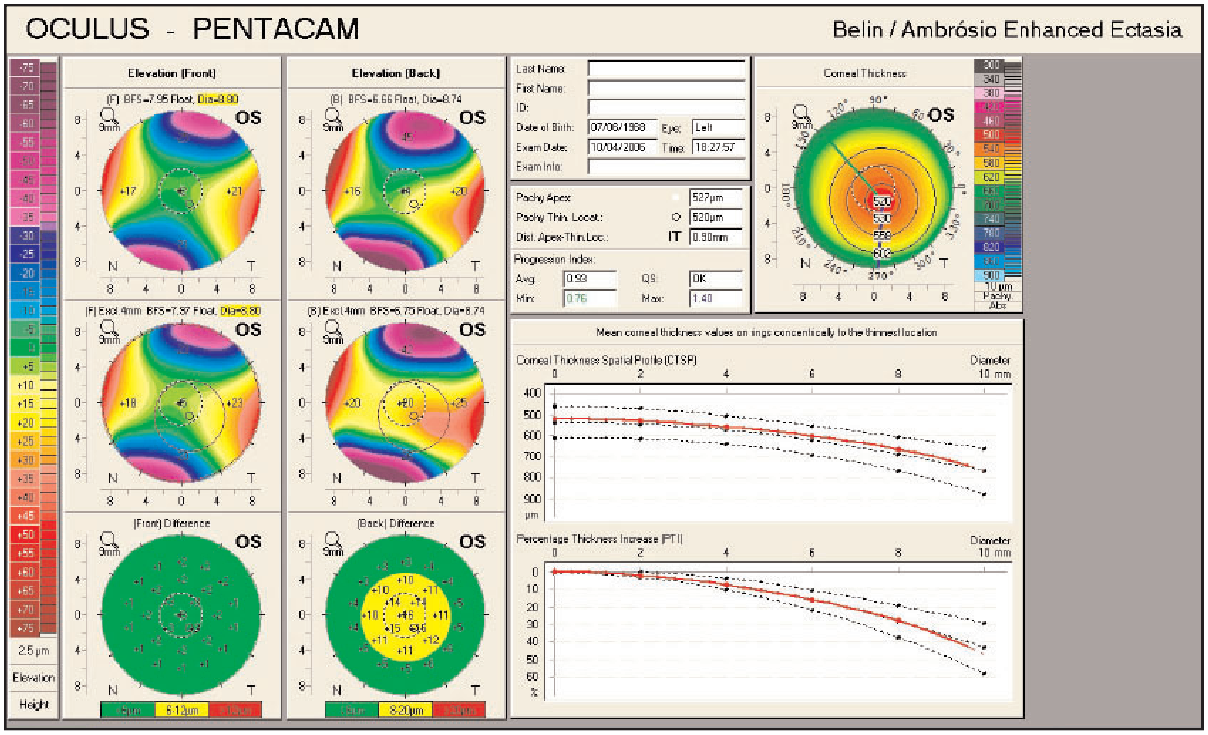

Figure 12. Belin/Ambrosio Enhanced Ectasia Display with elevation data presented on the left and pachymetric data presented on the right.

The arithmetic average of thickness on the 1mm, 2mm, 3mm, 4mm and 5mm diameter rings is represented as the average progression index. This metric has a statistically significant difference among normal (0.91 ± 0.23mm) when compared to keratoconus (1.81 ± 1.16mm) ($p<0.05$). The arithmetic averages of the values on the thinnest (maximal progression) and thickest (minimal progression) hemi-meridian are also calculated and displayed. These hemi-meridians are displayed on the thickness map. Usually the thickest hemi-meridian is nasal and superior and the thinnest is temporal and inferior **(Figure 15)**.

Normal corneas typically have an average progression index lower than 1.2 and a CTSP and PTI lines within the 95% CI limits. However there is some overlap between normal and keratoconic eyes. About 7% of normal eyes have an average progression index between 1.2 and 1.8.[4-5] Our current hypothesis is that these cases may have higher susceptibility to develop ectasia if stressed such as intensive eye rubbing and/or subjected to lamellar refractive surgery. In addition, 11% of the cases with clinical keratoconus have an average progression index lower than 1.2 and may have a CTSP and PTI within the normal limits. We also hypothesize that these cases have lower odds for ectasia progression and, in some conditions, may benefit from advanced customized surface ablation procedures. Combined studies with clinical *in vivo* biomechanical measurements and long-term longitudinal studies to evaluate ectasia progression will be needed to corroborate this hypothesis.

Conclusion

The Belin / Ambrósio Enhanced Ectasia Display is the first comprehensive refractive surgical screening tool to be fully elevation based. The goal of the software is to assist the refractive surgeon in identifying those patients who may be at risk for post-operative ectasia and/or to assist in the identification of early or subclinical keratoconus. By utilizing information from both the anterior and posterior corneal surfaces, as well as full pachymetric data it is hoped to have increased sensitivity without the false positive rates typically associated with curvature based programs.

REFERENCES

For detailed and complete References, please visit our "Journal Bibliography" Section at our webpage: www.thehighlights.com