What's New in Biomechanics of Keratoconus

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17th International Conference of the Research Institute of Ophthalmology
Anterior Segment Eye Diseases: Current Status & Future Directions
Royal Maxim Palace Kempinski, Cairo Egypt
January 30, 2025

THE OHIO STATE UNIVERSITY Biomedical Engineering

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Disclosures

- Consultant to Ziemer Ophthalmic Systems AG
- Consultant to Oculus Optikgeräte GmbH
- ANTERION loaned by Heidelberg Engineering GMbH

Funding: NIH R01 EY027399

Biomechanical Alteration PRECEDES Tomographic Changes:

- Curvature, thickness and elevation changes are SECONDARY symptoms of pre-clinical keratoconus

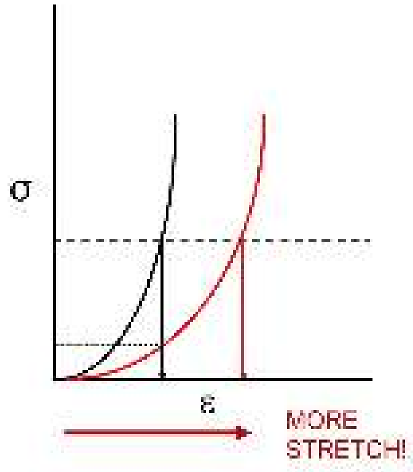
- PRIMARY corneal alteration is

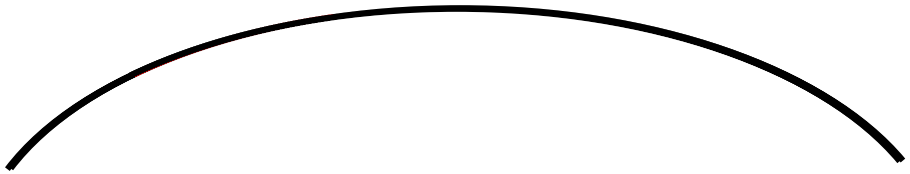
FOCAL BIOMECHANICAL WEAKENING

First proposed in 2007:

Roberts CJ. “Biomechanics of INTACS in Keratoconus.” Chapter 10 in: Ertan A and Colin J (eds). *Intracorneal Ring Segments and Alternative Treatments for Corneal Ectatic Diseases*. Ankara Turkey: Kudret Eye Hospital; 2007:157-166.

Proposal for Biomechanical Progression in Keratoconus

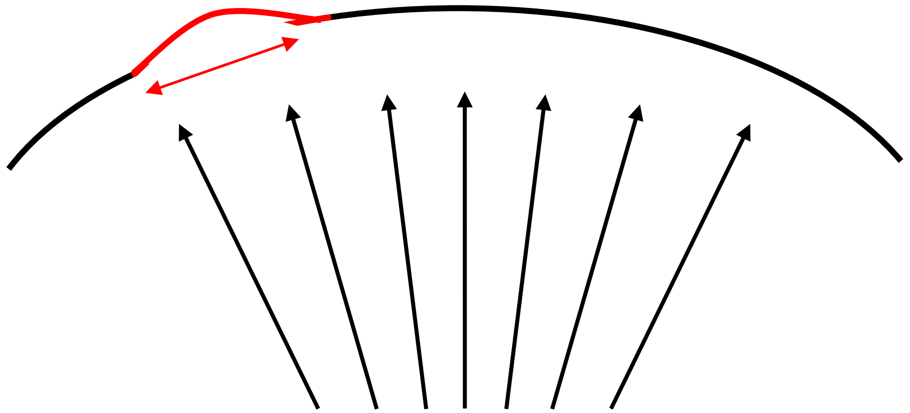


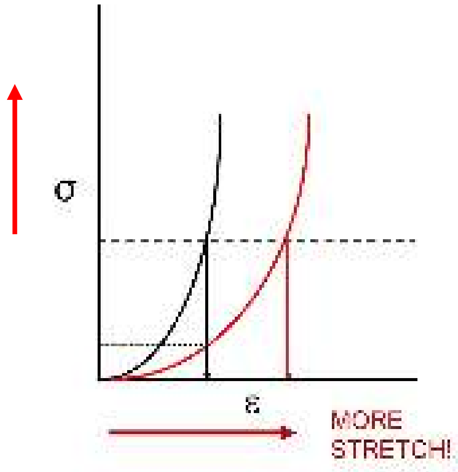


Focal Reduction in Modulus of Elasticity

(Focal Weakness = Less Resistance to Deformation)

Proposal for Biomechanical Progression in Keratoconus



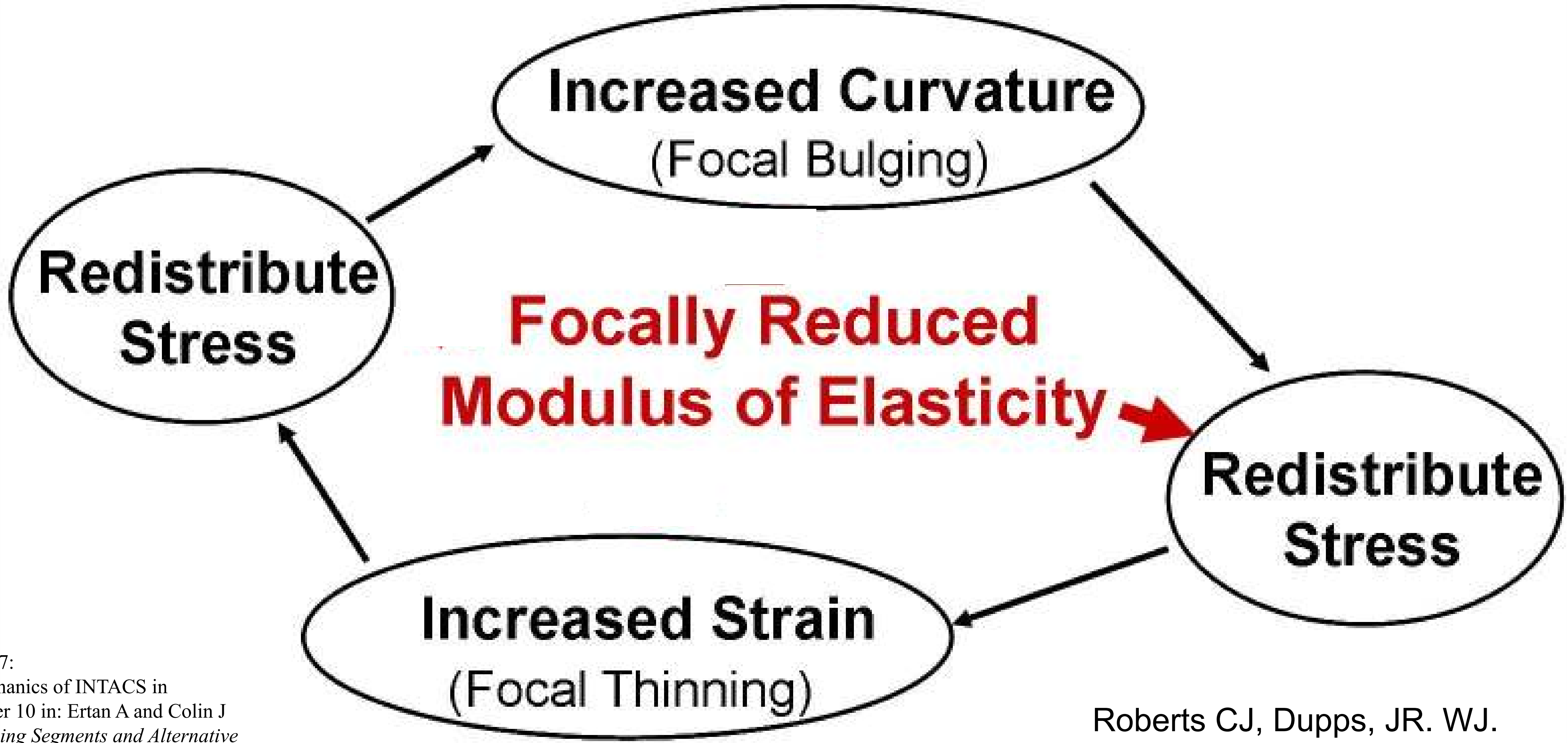


Focal Reduction in Modulus of Elasticity

Greater deformation (stretching) in weak region

THINNING!

Biomechanical Cycle of Decompensation in Ectasia



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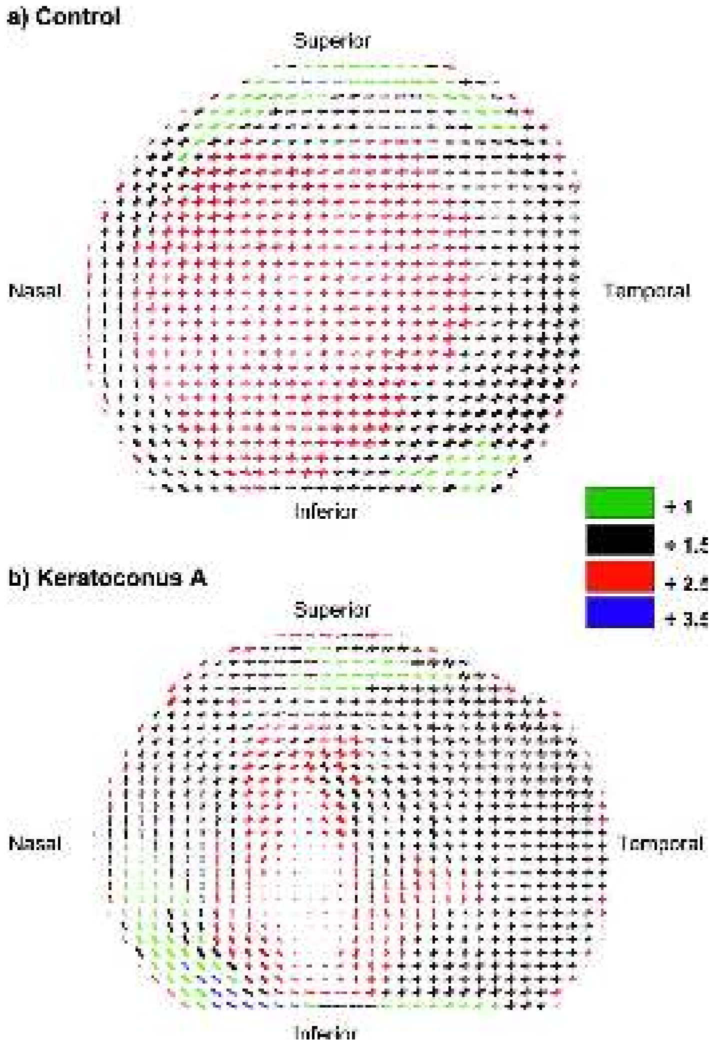
Roberts CJ, Dupps, JR. WJ.
J Cataract Refract Surg 2014

Collagen Orientation in Keratoconus

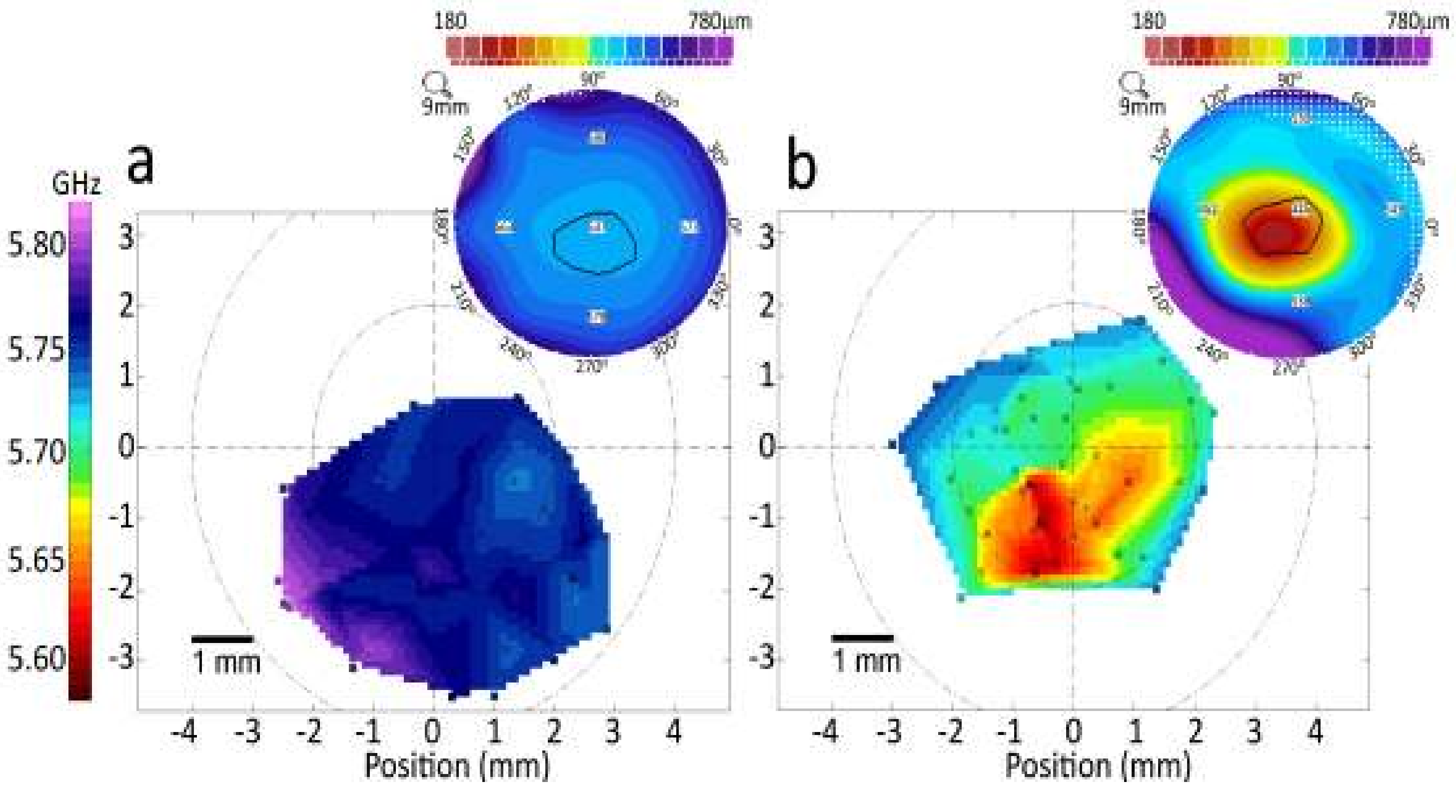


Normal preferred orientation of lamellar orientation

Lamellar structure is disrupted in keratoconus in the area of pathology

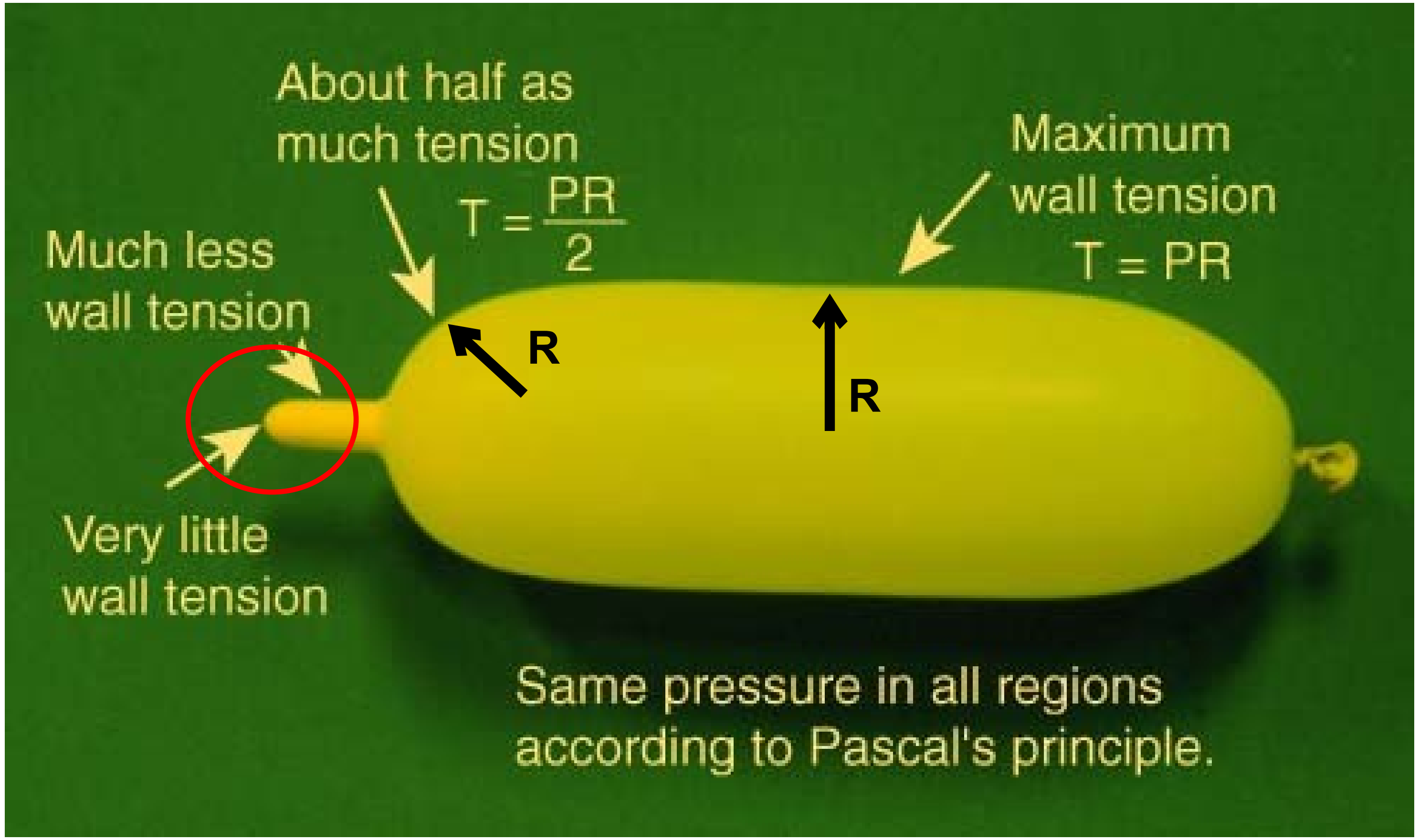
- Meek KM, et al. Changes in Collagen Orientation and Distribution in Keratoconus Corneas, IOVS 2005; 46:1948-1956.

In Vivo Normal (a) and Keratoconic Subject (b)



- Brillouin Microscopy maps from group of Giuliano Scarcelli, Harvard

LaPlace's Law and Wall Tension



http://hyperphysics.phy-astr.gsu.edu/hbase/ptens.html

Stress Distribution

- Hoop stress (circumferential stress) for a Spherical Shell:

  $\sigma = P \bullet r / 2t$

  P = internal pressure

  r = radius of curvature

  t = thickness

- Higher stress:
  - Thinner (smaller t in denominator)
  - Flatter (greater r in numerator)

Corneal Contribution to Stress (CCS)

- Removes the influence of IOP which always determines maximum stress

- CCS = R/2t

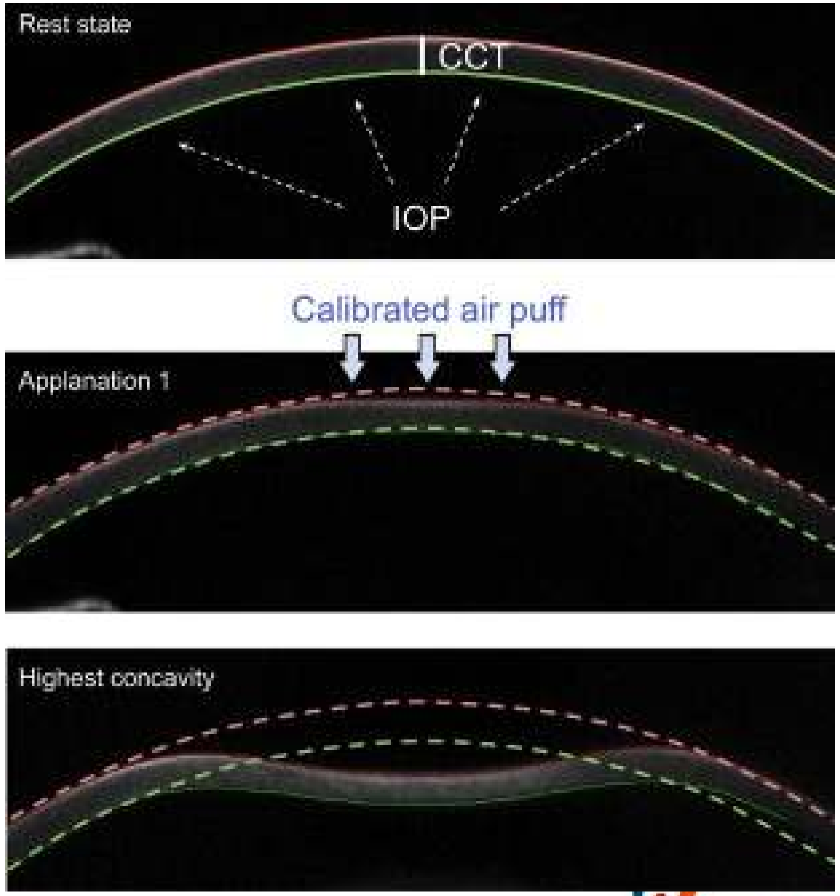
  R = radius of curvature

  t = thickness

- Higher stress:
  - Thinner (smaller t in denominator)
  - Flatter (greater r in numerator)

Prospective Observational Study

- 67 eyes of 41 subjects diagnosed with keratoconus
- Corvis ST Biomechanical Parameters
  - ↑ with ↑ stiffness: SP-A1, SP-HC, SSI
  - ↓ with ↑ stiffness: DA Ratio, IIR
- Pentacam Tomography
  - Zonal Kmax (Zkmax) and Kmax Distance
    Axial Map
  - Cspot and Radial Distance (Crad)
    Tangential Map



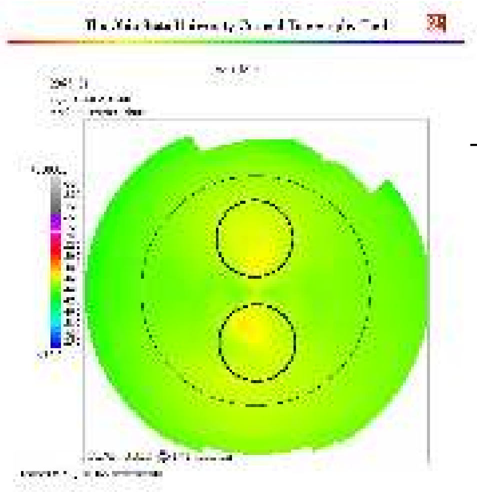
Funding: NIH R01 EY027399

Deformation Amplitude Ratio 2mm (DA Ratio); Integrated Inverse Ratio (IIR)

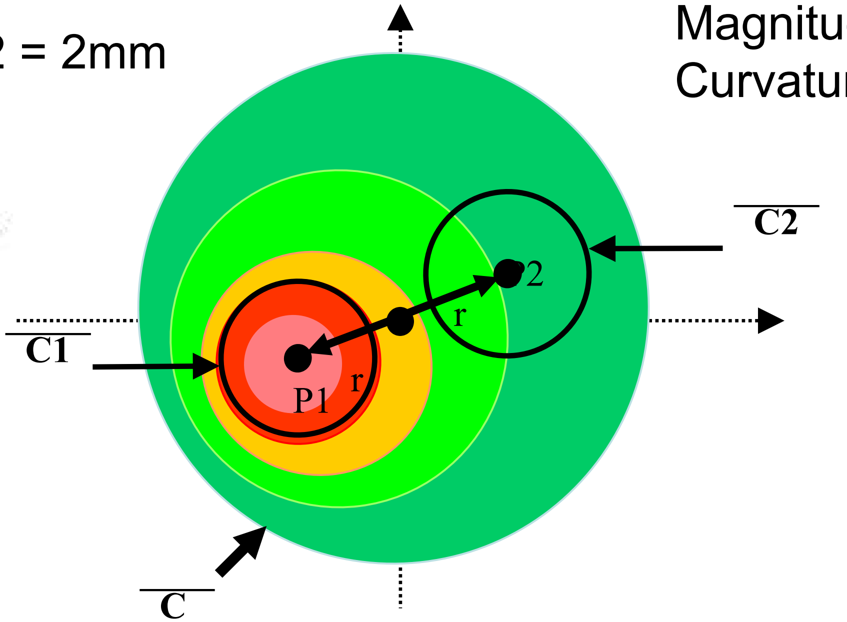
CLMI:
<u>C</u>one <u>L</u>ocation and <u>M</u>agnitude <u>I</u>ndex

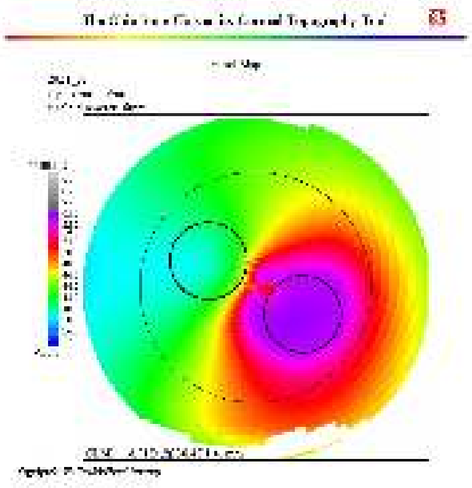
Diameter of C1, C2 = 2mm

Magnitude of Average Curvature in C1 = Cspot



Normal





Kertaconus

CLMI = (C1 – C2)

- Mahmoud, et al. *Cornea*, 2008; 27(4):480-487.
- Mahmoud, et al. *Am J Ophthalmol*. 2013;156 (6):1102-11.

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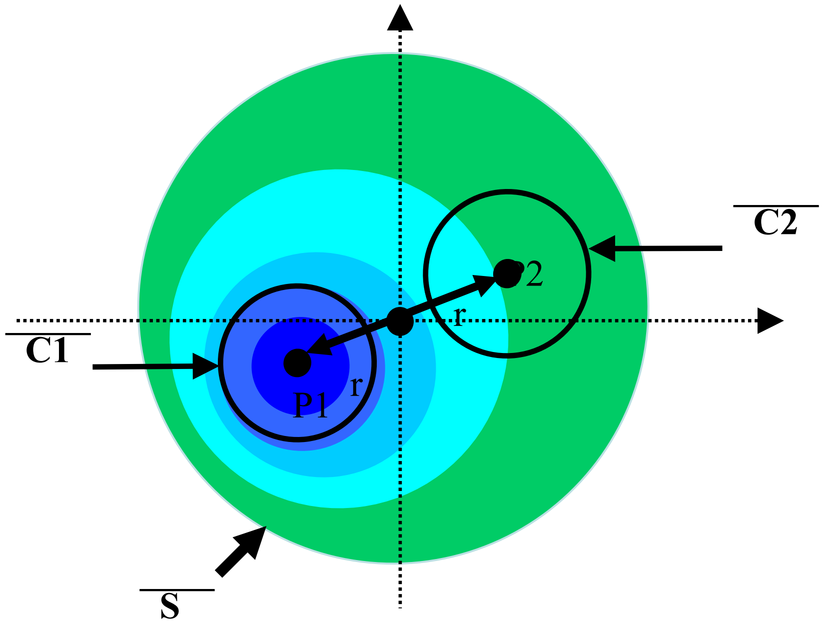
Pachymetric Response:

Minimum Vlaue

MINIMUM



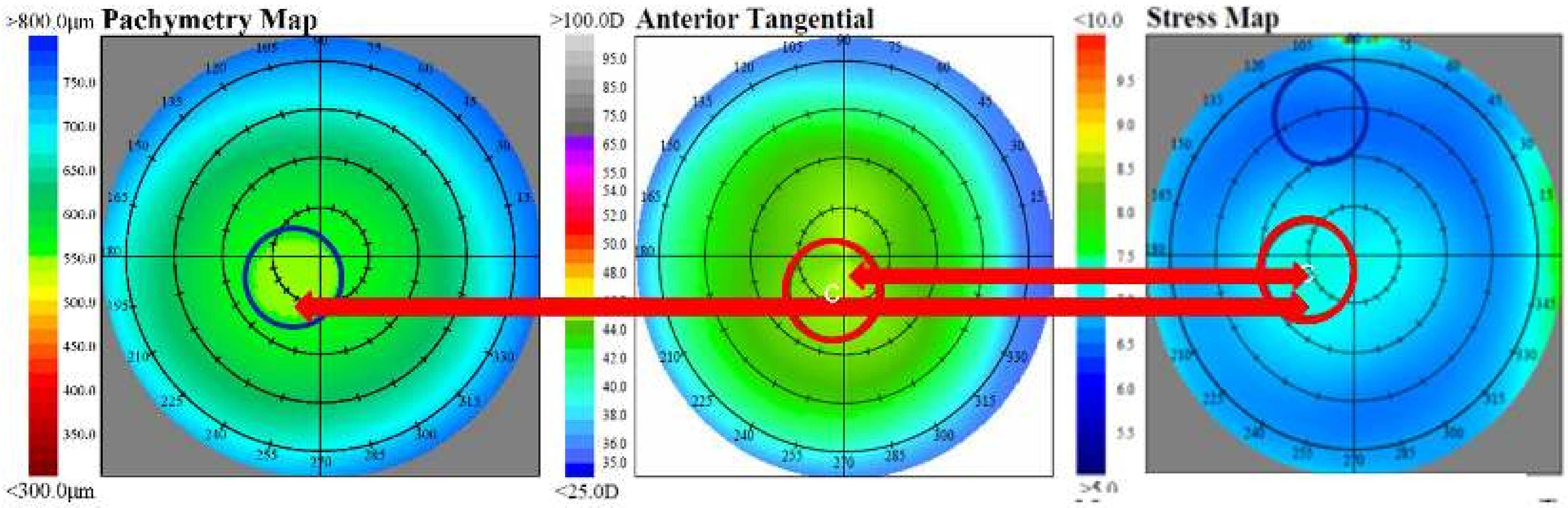
Developed for:

Post-Myopic Refractive Surgery Functional Optical Zone*

Pachymetry Map for Thin Spot, since this also is a minimum

*Qazi MA, Roberts CJ, Mahmoud AM, Pepose JS: "Topographic and biomechanical differences between hyperopic and myopic laser in situ keratomileusis." *J Cataract Refract Surg*. 2005; 31(1): 48-60.

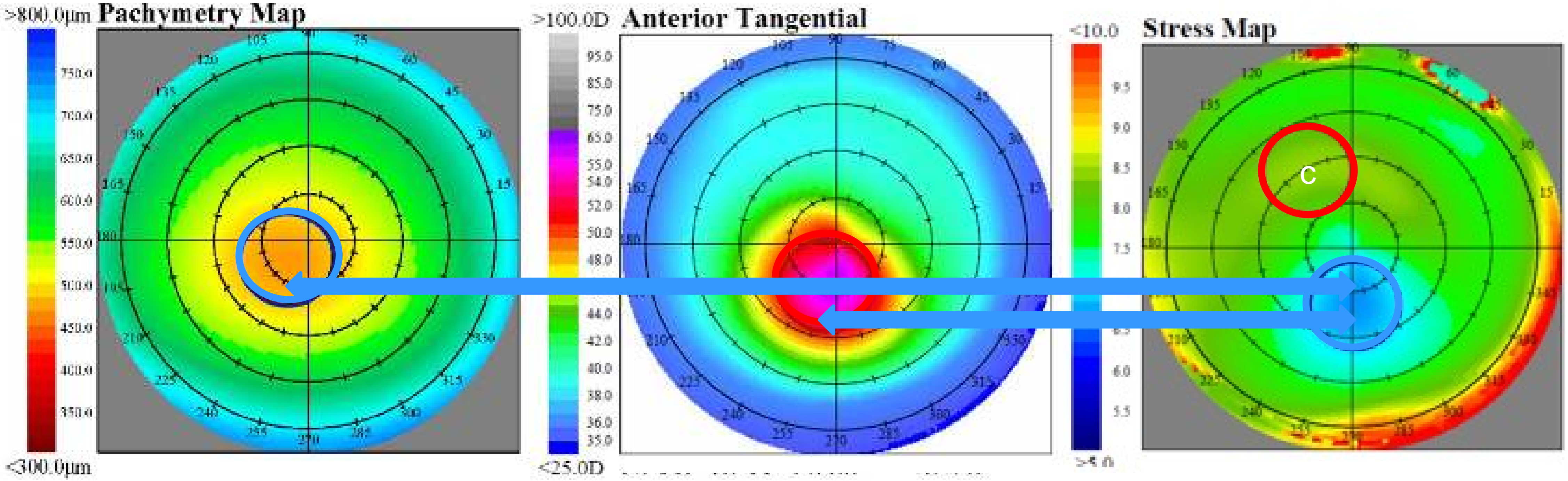
Average Maps of 147 NRL Eyes



CCS = R/2t (↑R, ↓t = Max); Dominated by **Thickness**

Blue Circles = Minimum Values; **Red Circles** = Maximum Values

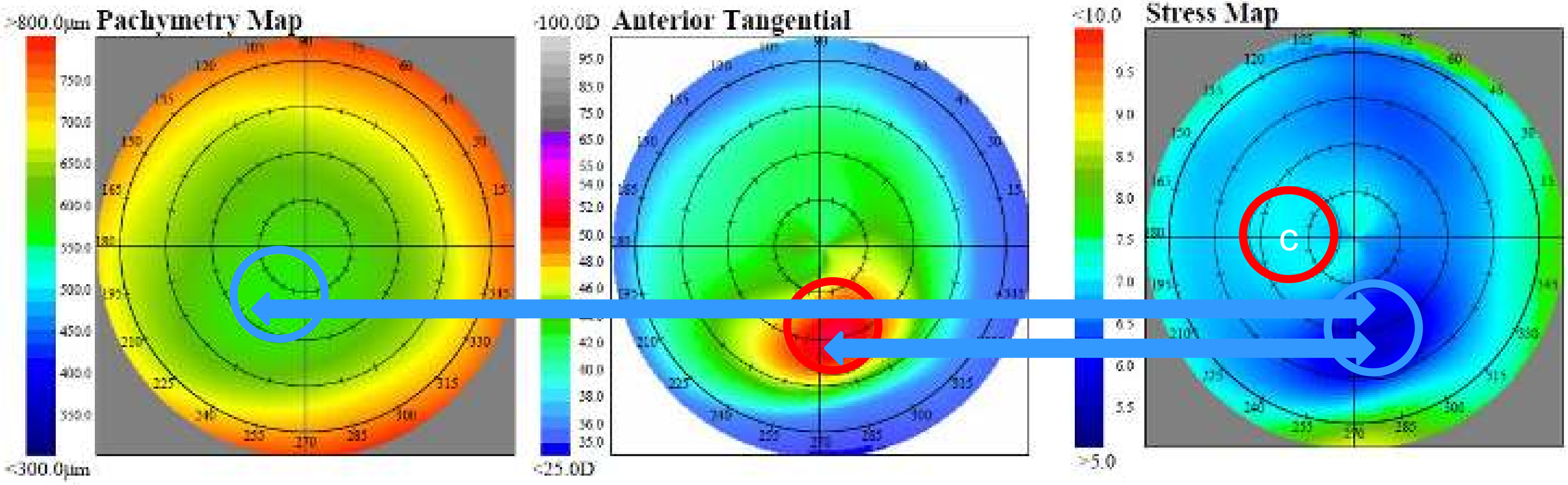
Average of 57 KCN Eyes with Central Cones



CCS = R/2t (↓R, ↑t = Min); Dominated by <u>Curvature</u>!

Blue Circles = Minimum Values; **Red Circles** = Maximum Values

Average of 4 KCN Eyes with Inferior-Nasal Cones



<u>ANALOGOUS STRESS PATTERN TO CENTRAL CONES!</u>

CCS = R/2t (↓R, ↑t = Min); Dominated by <u>Curvature</u>!

Blue Circles = Minimum Values; **Red Circles** = Maximum Values

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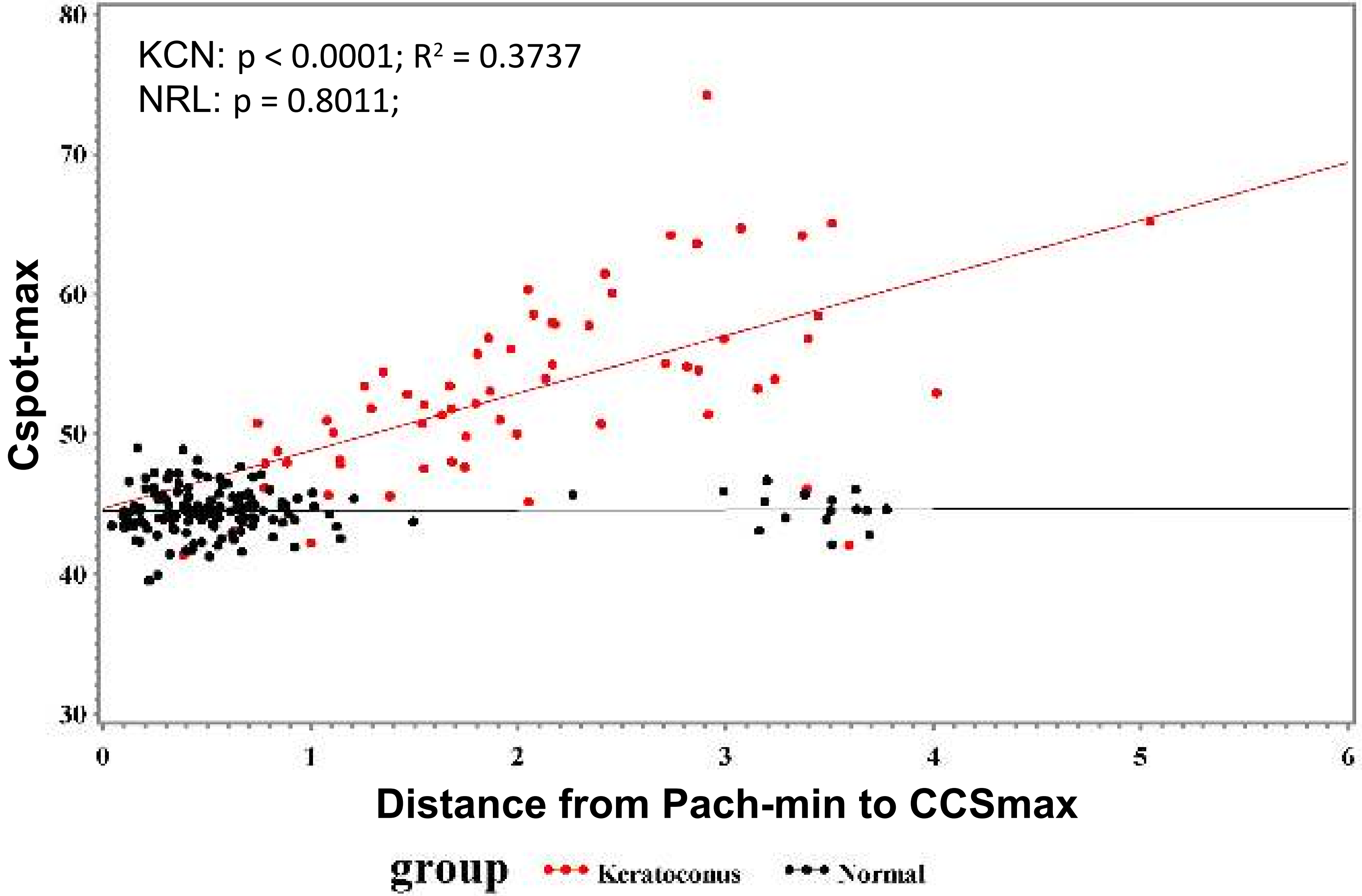
Cynthia J. Roberts, Ph.D.



As KCN progresses, Maximum Stress moves farther and farther away from Minimum Pachymetry

l Engineering

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AMERICAN ACADEMY OF OPHTHALMOLOGY®

Corneal Stress Distribution Evolves from Thickness-Driven in Normal Corneas to Curvature-Driven with Progression in Keratoconus

Cynthia J. Roberts, PhD,[1,2] *Kayla M. Knoll, MS,*[1,3] *Ashraf M. Mahmoud, BS,*[1,2] *Andrew J. Hendershot, MD,*[1] *Phillip T. Yuhas, OD, PhD*[3]

Purpose: To introduce the novel parameter of Corneal Contribution to Stress (CCS) and compare stress distribution patterns between keratoconus (KCN) and normal corneas.

Design: Prospective, observational, cross-sectional study.

Participants: The study included 66 eyes of 40 subjects diagnosed with KCN and 155 left eyes from 155 normal control (NRL) subjects.

Methods: Tomography was obtained to calculate the newly proposed CCS, defined according to the hoop stress formula without intraocular pressure, R/2t, where R is radius of curvature and t is thickness. CCS maps were calculated from pachymetry and tangential curvature maps. Custom software identified the 2-mm diameter zones of greatest curvature (Cspot-max), thinnest pachymetry (Pach-min), greatest stress (CCSmax), and lowest stress (CCSmin). Stress difference (CCSdiff) was calculated as CCSmax − CCSmin. Distances between Cspot-max vs. Pach-min, vs. CCSmax, and vs. CCSmin, as well as between Pach-min vs. CCSmax and vs. CCSmin, were calculated. *t* tests were performed between cohorts, and paired *t* tests were performed within cohorts. Univariate linear regression analyses were performed between parameters and distances. The significance threshold was $P < 0.05$.

Main Outcome Measures: Corneal stress parameters, corneal features of maximum curvature, minimum thickness, and distances between corneal stress parameters and corneal features.

Results: CCSmax was significantly closer to Pach-min (0.79 ± 0.92) and Cspot-max (2.04 ± 0.85) than CCSmin (3.17 ± 0.38, 2.73 ± 1.53, respectively) in NRL, $P < 0.0001$, whereas CCSmin was significantly closer to Cspot-max (1.35 ± 1.43) than CCSmax (2.52 ± 0.72) in KCN, $P < 0.0001$. Cspot-max (severity) was significantly related to CCSdiff in KCN ($P < 0.0001$; $R^2 = 0.5882$) with a weak relationship in NRL ($P < 0.0080$, $R^2 = 0.0451$). Cspot-max was significantly related to the distance from Pach-min to CCSmax ($P < 0.0001$; $R^2 = 0.3737$) without significance in NRL ($P = 0.8011$).

Conclusions: Corneal stress is driven by thickness in NRL, with greatest stress at thinnest pachymetry and greatest curvature. However, maximum stress moves away from thinnest pachymetry with progression in KCN, and *minimum* stress is associated with maximum curvature. Severity in KCN is significantly related to greater difference between maximum and minimum stress, consistent with the biomechanical cycle of decompensation.

Central Cone: Center of Circular Zone is Inside of 3mm Diameter Cornea Center

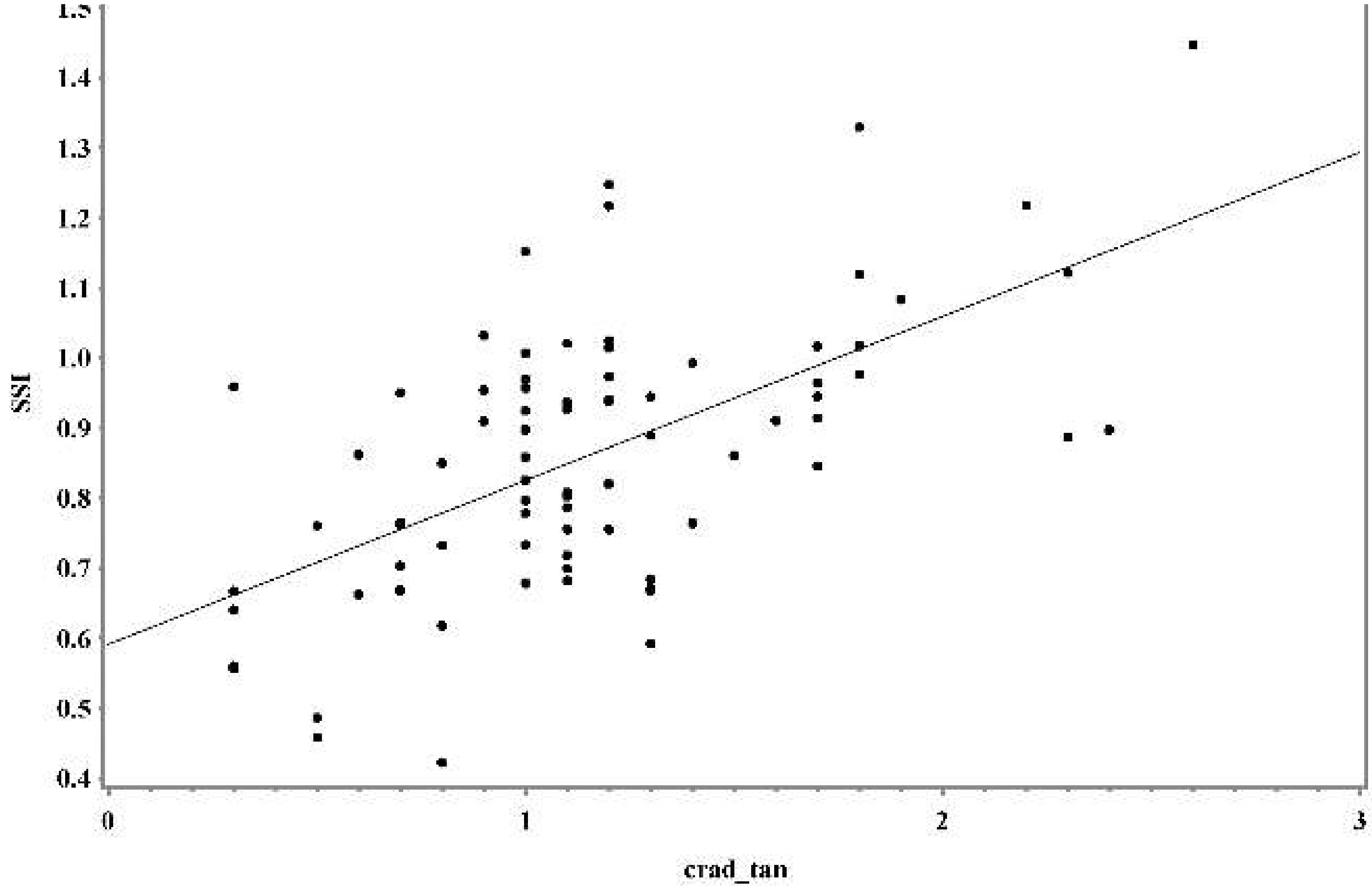
	Axial	Tangential
Central Cone	28 (42%)	58 (87%)
Eccentric Cone	39 (58%)	9 (13%)

Eccentric Cone: Center of Circular Zone is Outside of 3mm Diameter Cornea Center

Stress Strain Index

SSI vs Crad

- P < .0001
- $R^2 = 0.3636$



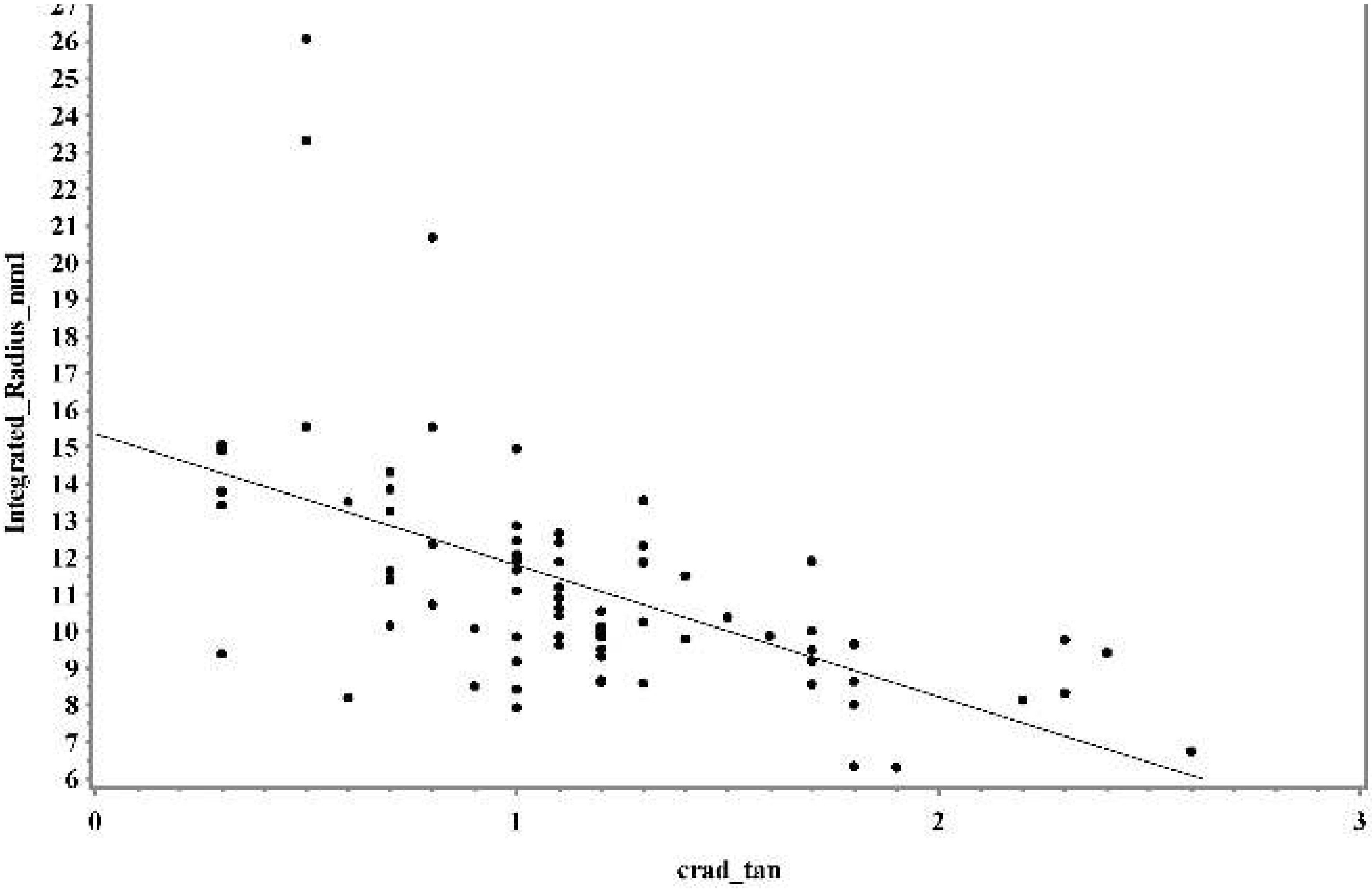
Stiffness of Biomechanical Response INCREASES

As Distance of Cone from Corneal Center on Tangential Map INCREASES

Integrated Inverse Radius

IIR vs Crad

- P < .0001
- $R^2 = 0.3005$

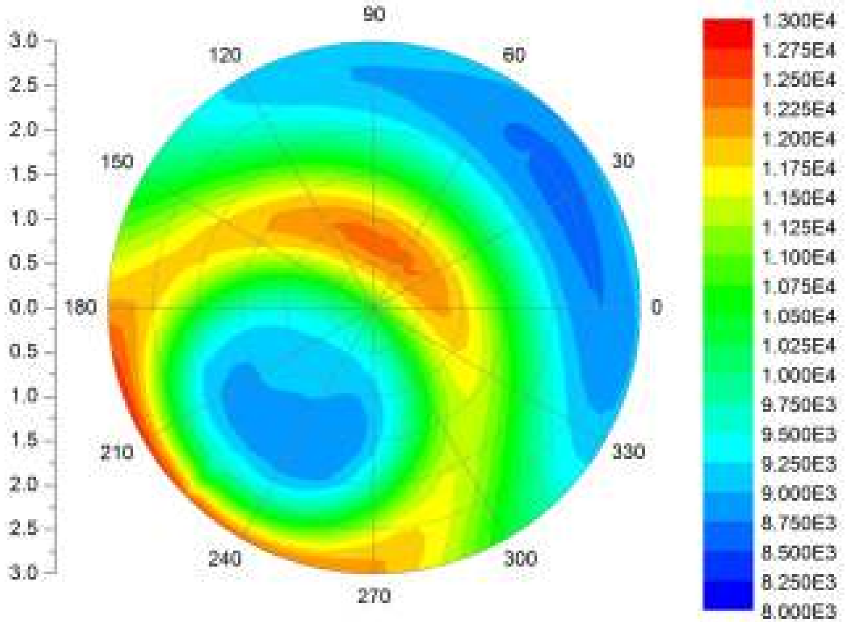


Stiffness of Biomechanical Response INCREASES

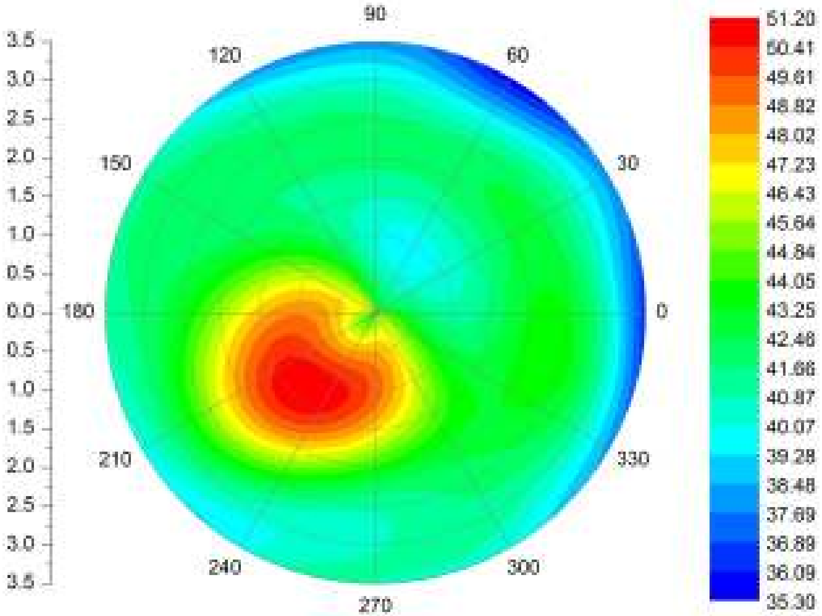
As Distance of Cone from Corneal Center on Tangential Map INCREASES

Stress Distribution

von Mises Stress



Curvature



NOTE THE **LOWEST** STRESS IS AT THE **STEEPEST** POINT

DRIVEN by **CURVATURE**, **NOT THICKNESS**

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TAKE-HOME MESSAGE in Keraoconus

In Keratoconus, the thinnest spot is NOT the highest stress, which is opposite of normal corneas.

Continual change in stress distribution causes the evolution from thickness-driven to curvature-driven response

Roberts CJ, et al. Ophthalmol Sci. 2023;4(2):100373. PMID: 37868791

The location of Cone impacts the measured air-puff induced Biomechanical Response

The further the Cone from the Center, the Stiffer the Response

Bruner, Mahmoud, Roberts. Eccentric Pathology in Keratoconus Exhibits Stiffer Biomechanical Response Than Central Pathology. Ophthalmol Sci. In Press

Thank You!