A New Stiffness Parameter in Air Puff Induced Corneal Deformation Analysis

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Purpose

To investigate a new stiffness parameter in corneal deformation analysis and compare responses in normal (NL) and keratoconic (KC) subjects, matched for intraocular pressure (IOP).

Methods

A new stiffness parameter (SP) is defined as the resultant pressure at inward applanation, divided by corneal deflection amplitude at highest concavity (HCDeflectAmp). The spatial and temporal profiles of the Corvis ST air puff (Oculus, Wetzlar, Germany) were characterized using hot wire anemometry from 0 to 16mm from the nozzle. Measured velocity was correlated in time with the pressure profile exported by the Corvis ST, measured within the nozzle. The z position of the cornea at the time of inward applanation was used to calculate an adjusted air pressure value (adjAP1) at the time and position of first applanation. An algorithm to correct IOP estimation based on finite element modeling, termed IOP_{FEM}, was used for the equation: SP = (adjAP1 - IOP_{FEM})/ HCDeflectAmp. Linear regression analyses between dynamic corneal response parameters (DCR's) and SP were performed on a retrospective dataset of 180 KC eyes and 482 NL eyes. DCR's from a subset of 158 of 158 subjects in each group were matched for IOP_{FEM} and compared using t-tests. Significance threshold was $p < 0.05$.

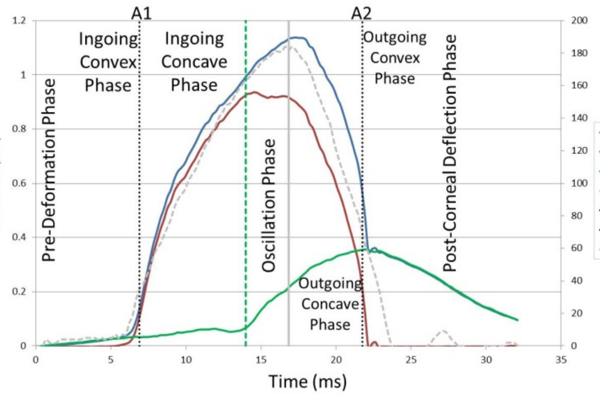
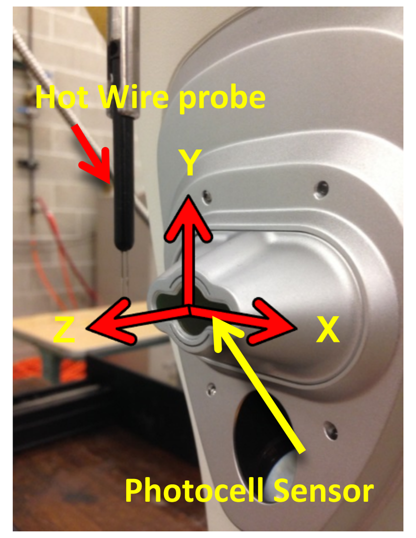


Figure 4: Phases of Deformation



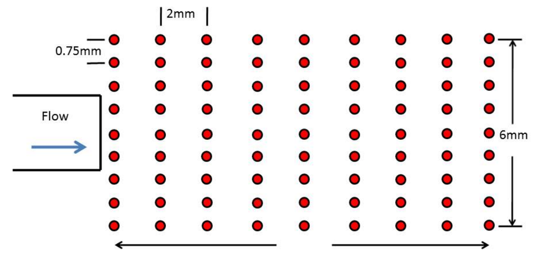


Figure 1: Above: Experimental set up for hot wire anemometry; and Below: Locations for measurement of air puff velocity relative to the nozzle

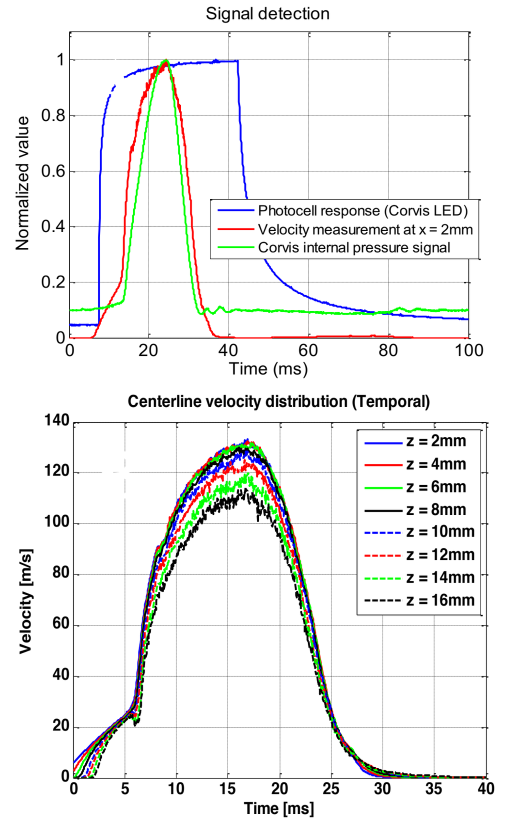


Figure 2: Top: Measured velocity (red) and Corvis-exported pressure signal (green), both time-synchronized by the photo cell signal (blue) Bottom: Centerline Velocity Distribution as a function of distance from the nozzle.

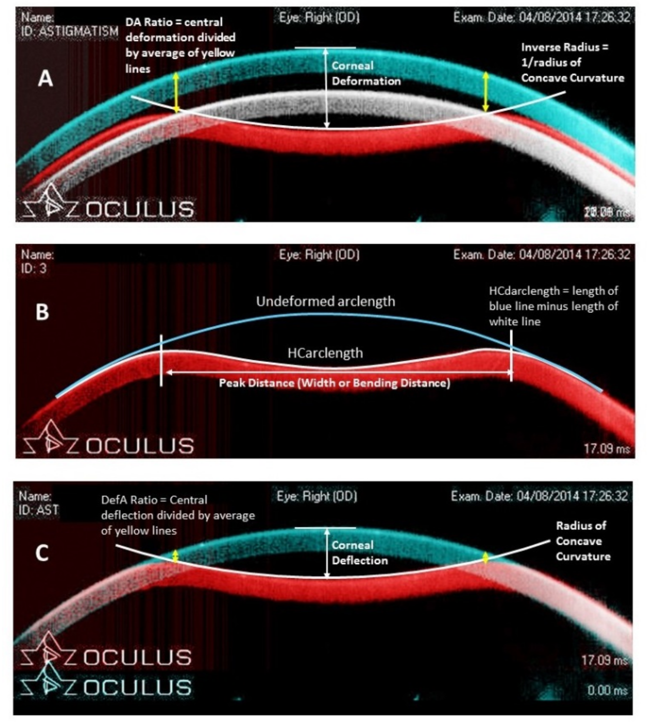


Figure 3: Superimposed frames extracted from a single exam, showing A: Cornea in the Predeformation phase (pseudocolored blue), at maximal corneal deflection (pseudocolored red), and at maximal whole eye movement (pseudocolored white); B: Cornea at maximum deflection (Highest Concavity) with illustration of displacement from predeformation anterior surface arc (blue line); and C: Correction for whole eye motion by aligning all corneal positions to that at predeformation.

Results

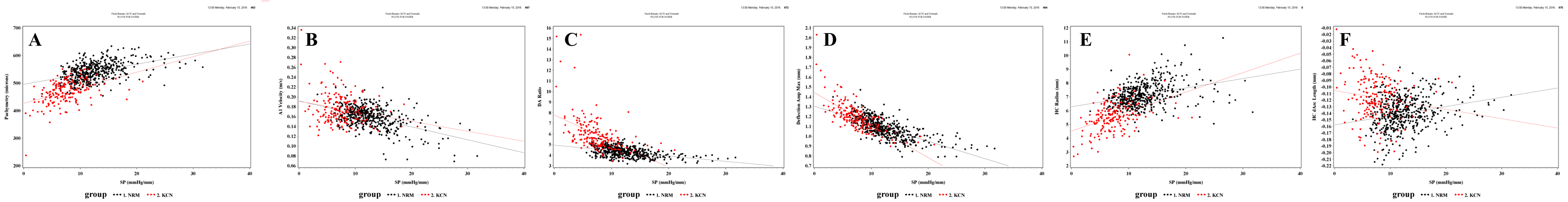


Figure 5: Regressions of the stiffness parameter against pachymetry and selected DCR's in both normal and keratoconic corneas. Regressiong statistics are given in Table 2, but all show a significant relationship. A: Pachymetry showing that thicker corneas tend to be stiffer; B: A1 Velocity showing that stiffer corneas have lower velocities due to greater resistance to deformation; C: DA Ratio, showing that stiffer corneas have less difference in deformation between the center and periphery; D: Deflection Amp Max = HC DeflAmp, showing that stiffer corneas show less deflection; E: HC Radius, showing that stiffer corneas are flatter at highest concavity (HC); F: HCdarclength, showing opposite behavior between normal and keratoconic corneas. As the cornea passes into a state of concavity, the collagen fibers crimp, and the arclength shortens, similar to what occurs in the posterior stroma with an edematous cornea. [1] The shortest arclength occurs at maximum deformation. [2] In normal eyes, stiffer corneas have greater resistance to deformation and thus lower deformation/deflection amplitudes and less change in arclength with less collagen crimping. However, keratoconic corneas that are stiffer have *greater* shortening of their arclength. It is possible that the disruption of the collagen organization that is known to occur in keratoconus [3] leads to this behavior.

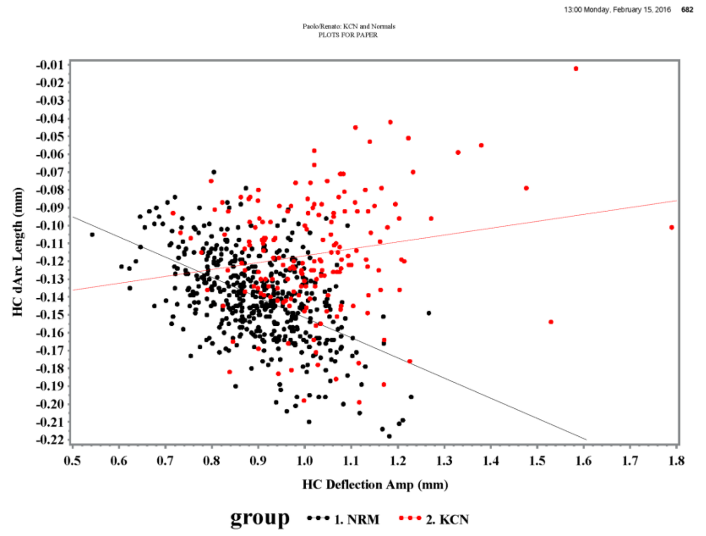


Figure 6: Regression analysis of HC Deflection Amp vs HC darclength, showing that in normal corneas, the greater the depth of deformation, the greater the change in arclength (shorter arclength at maximum deflection). However, in keratoconic corneas, the greater depth of deformation was associated the least change in arclength, possibly due to disruption of collagen in keratoconus. (NL: R^2 = .2627, p< .0001; KC: R^2 = .0307, p < .0185).

Table 1: Mean ± Standard Deviation in IOP_{FEM}-Matched t-test Comparison

N=158 in NL and KC	Normal	Keratoconus	P value
age	40 ± 16	35 ± 12	p =.0028
Pachymetry (µm)	542 ± 34	471 ± 36	< .0001
A1 Length (mm)	1.82 ± .08	1.72 ± .16	< .0001
A1 Vel (mm/ms)	.16 ± .02	.17 ± .03	< .0001
A1 Time (ms)	7.19 ± .28	7.00 ± .28	< .0001
A1 DeflAmp (mm)	.09 ± .01	.10 ± .02	< .0001
DA Ratio (unitless)	4.37 ± .42	5.81 ± .1.38	< .0001
DefA Ratio (unitless)	5.06 ± .65	7.16 ± 4.82	< .0001
DA (mm)	1.09 ± .10	1.18 ± .12	< .0001
HCDeflAmp (mm)	.91 ± .11	1.01 ± .13	< .0001
HCDeflArea (mm^2)	3.39 ± .55	3.54 ± ..53	0.013
HCdarclength (mm)	-.14 ± .02	-.12 ± .03	< .0001
Peak Distance (mm)	5.08 ± .26	5.05 ± .24	0.226
HC Radius (mm)	7.08 ± .79	5.62 ± 1.00	< .0001
InvRadMax (1/mm)	.168 ± .02	.22 ± .04	< .0001
WEM Max (mm)	.29 ± .07	.27 ± .06	0.0065
A2 Length (mm)	1.73 ± .31	1.53 ± .41	< .0001
A2 Vel (mm/ms)	-.40 ± .08	-.47 ± .11	< .0001
A2 Time (ms)	21.78 ± .37	21.96 ± .39	< .0001
SP (mmHg/mm)	11.9 ± 3.5	7.7 ± 3.1	<.0001

Note: In DefA Ratio, one KC eye was excluded as an outlier.

Table 2: Regression Analysis Statistics between Stiffness Parameter and Dynamic Corneal Response Parameters

	Normal (N = 482)	Keratoconus (N = 180)	Slope KC,NL
Pachymetry (µm)	R^2 = .2107; p < .0001	R^2 = .1926; p < .0001	+, +
A1 Length (mm)	R^2 = .0234; p = .001	R^2 = .0600; p = .001	+, +
A1 Vel (mm/ms)	R^2 = .2107; p < .0001	R^2 = .0446; p = .005	-, -
A1 Time (ms)	R^2 = .5699; p < .0001	R^2 = .4916; p < .0001	+, +
A1 DeflAmp (mm)	R^2 = .2265; p < .0001	p = .87	+, 0
DA Ratio (unitless)	R^2 = .2106; p < .0001	R^2 = .2395; p < .0001	-, -
DefA Ratio (unitless)	R^2 = ..0676; p < .0001	R^2 = .0460; p < ..0040	-, -
DA (mm)	R^2 = .4929; p < .0001	R^2 = .5189; p < .0001	-, -
HCDeflAmp (mm)	R^2 = .5818; p < .0001	R^2 = .5607; p < .0001	-, -
HCDeflArea (mm^2)	R^2 = .5303; p < .0001	R^2 = .4645; p < .0001	-, -
HCdarclength (mm)	R^2 = .0569; p < .0001	R^2 = .0237; p = .041	+, -
Peak Distance (mm)	R^2 = .5968; p < .0001	R^2 = .3605; p < .0001	-, -
HC Radius (mm)	R^2 = .0976; p < .0001	R^2 = .2006; p < .0001	+, +
InvRadMax (1/mm)	R^2 = .0846; p < .0001	R^2 = .2247; p < .0001	+, +
WEM Max (mm)	R^2 = .0221; p = .001	p = .47	+, 0
A2 Length (mm)	R^2 = .0906; p < .0001	R^2 = .0665; p = .001	+, +
A2 Vel (mm/ms)	R^2 = .4661; p < .0001	R^2 = .3027; p < .0001	+, +
A2 Time (ms)	R^2 = .2581; p < .0001	R^2 = .2448; p < .0001	+, +

Note: In DefA Ratio, one KC eye was excluded as an outlier.

Discussion

All DCR's evaluated showed a significant difference between NL and KC, except peak distance, as shown in Table 1. The KC group had lower SP values, thinner pachymetry, shorter applanation lengths, greater absolute values of applanation velocities, earlier first applanation times and later second applanation times, greater HC deformation and HC deflection amplitudes, and lower HC radius of concave curvature (greater concave curvature). All DCR's evaluated showed a significant relationship with SP in both groups, as shown in Table 2 and Figure 5. Stiffer eyes were associated with greater pachymetry, longer applanation lengths, lower absolute value of applanation velocities, later first applanation times, earlier second applanation times, lower HC deformation and HC deflection amplitudes, shorter peak distances, greater HC radius of concave curvatures (flatter), and higher values of IOP_{FEM}.

Conclusions

- Keratoconic eyes demonstrated less resistance to deformation than normal eyes with similar IOP.
- All of the deformation parameters investigated showed a significant relationship with the new stiffness parameter.
- This may be useful in future biomechanical studies comparing populations

References

1. Gallagher B, Maurice D. Striations of light scattering in the corneal stroma. Journal of ultrastructure research 1977; 61:100-14.
2. Roberts CJ, Mahmoud AM, Liu J, Sharalaya Z, Mauger TF, Lembach RG, Hendershot AJ, Kuennen R, Klyce SD. Conservation of Arclength in Keratoconic and Normal Corneas with Air Puff Induced Deformation. Invest Ophth Vis Sci. 2012;53: ARVO E-Abstract 6893.
3. Meek KM, Tuft SJ, Huang Y, Gill PS, Hayes S, Newton RH, Bron AJ. Changes in collagen orientation and distribution in keratoconus corneas. Invest Ophthalmol Vis Sci 2005; 46:1948–56.

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