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FEATURE ARTICLE ON LINE

Uncorrected Wavefront Error and Visual Performance During RGP Wear in Keratoconus

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ABSTRACT

Purpose. To examine the relationship between uncorrected residual wavefront error and visual performance (VP) in rigid gas permeable (RGP) contact lens-wearing keratoconic eyes.

Methods. Seven eyes from six subjects (six moderate, one severe) were studied (mean ± SD age: 42.71 ± 11.38 years). Significant corneal scarring was an exclusion criterion. Measurements were taken with RGP lenses in place. After pupil dilation, the VP measures of high contrast logMAR visual acuity (VA) and Pelli-Robson contrast sensitivity (PRCS) were measured through a 5-mm artificial pupil. Wavefront error was measured using a Shack–Hartmann wavefront sensor and calculated over 5 mm. For both VP and wavefront error, comparisons were made to previously collected normal values by calculating the interval encompassing 95% of normals, then reporting how many of the seven keratoconic eyes fell outside the normal interval. Additionally, second to sixth order aberrations were processed into four previously reported image quality metrics: root mean square of the wavefront (RMSw), root mean square of the slope (RMSs), average blur strength (Bave) and diameter containing 50% light energy (D50) and regressed against VP measures.

Results. Five of seven keratoconic eyes fell outside the normal interval (−0.23 to 0.09) for VA and two of seven fell outside the normal interval (1.59 to 2.03) for PRCS. Five of seven keratoconic eyes fell outside the normal interval (0.07 to 0.35 μm) for total higher order RMS. Linear regressions demonstrated relationships between both VA and PRCS and the image quality metrics RMSw, D50, RMSs, and Bave with R^2 values for VA = 0.30, 0.30, 0.47, 0.62, and PRCS = 0.21, 0.15, 0.45, 0.75 respectively.

Conclusions. VP in RGP-wearing keratoconic eyes is reduced and higher order wavefront aberrations are elevated compared to normals. Metrics of retinal image quality demonstrate a relationship between keratoconic VP and residual wavefront aberrations. This relationship suggests developing corrections that more completely correct aberrations may improve visual performance in keratoconus.

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Key Words: aberration, keratoconus, optical quality metrics, visual performance, Zernike polynomial

Keratoconus is classified as a corneal dystrophy, or a progressive degeneration of the physiological structures comprising the cornea.[1] Over time, this degeneration leads to a thinning and weakening of the central or para-central corneal stroma.[1] These changes result in reduced visual performance due to elevated optical aberrations and/or corneal scarring.[1–3] Unlike normal eyes whose visually significant refractive errors are typically well described through the use of low order aberration terms, the keratoconic eye contains elevated levels of higher order aberrations, of which coma and secondary astigmatism have been reported to combine for the majority of the variance.[4] These and other high order aberrations cannot be treated effectively with conventional soft contact lenses or spectacles. Currently, the visual complaints of the majority of keratoconic eyes are addressed with some form of rigid lens correction.[5] Besides allowing for the inclusion of optical power, rigid lenses improve visual performance in the keratoconic eye by providing both a new, more spherical, first refracting surface to the optical system and an index-matching tear lens, which fills between the cornea and rigid lens. Both of these latter components serve to reduce the optical aberration induced by the anterior surface of the diseased cornea. However, the indices of refraction of the lens, tears, and cornea are not perfectly matched, and may leave some anterior surface aberrations uncorrected. Further, aberration can be induced at the posterior corneal surface in keratoconus,[6] and these posterior corneal aberrations are not compensated by the contact lens. Consequently, it is hypothesized that ocular aberrations induced by keratoconus may continue to play a role in reducing visual performance in keratoconic eyes even with a rigid gas permeable (RGP) correction in place.

Visual performance has been studied in keratoconic eyes wearing optical corrections, and is reduced when compared to normal eyes.[5,7] In the keratoconus population as a whole, a portion of the reduced performance can be attributed to corneal scarring.[3,8,9] The most recent and largest prospective study of keratoconus to date, the Collaborative Longitudinal Evaluation of Keratoconus (CLEK), reported that only 23.3% of unscarred keratoconic eyes had high contrast entrance visual acuity of 0.0 logMAR or better[3] when tested with their habitual (spectacle or contact lens) corrections. These findings suggest that uncorrected ocular aberrations likely play a role in reducing habitual performance in this patient population.

The level of aberration present in an eye can be quantified using a wavefront sensor. This measurement allows for quick, noninvasive, objective assessment of optical quality of the optics of the eye.[10,11] The data reported by the wavefront sensor are typically described using the ANSI standard Zernike polynomial (ANSI Z80.28), which is an orthogonal mathematical function described over the eye's pupil. While excellent for quantifying and compartmentalizing ocular wavefront error components, the raw list of Zernike coefficients alone gives limited insight into resultant retinal image quality or visual performance. To assess the manner in which the individual aberration terms combine to impact image quality, wavefront error data can be transformed using previously reported single value metrics of optical quality.[12–21] Root mean square (RMS) of the wavefront error is the most commonly reported optical quality metric. In this report, four retinal image quality metrics are employed in an effort to examine resultant logMAR visual acuity (VA) and Pelli-Robson contrast sensitivity (PRCS) visual performance in these keratoconic eyes as a function of optical aberrations experienced during RGP wear. The purpose of this study was to quantify uncorrected aberration in keratoconic eyes during RGP contact lens wear and examine its relationship to visual performance measures.

METHODS

General Data Collection

Appropriate University Institutional Review Board (IRB) and informed consent approval were obtained before initiating data collection. Seven eyes of six subjects with clinically diagnosed keratoconus of varying severity were recruited to serve as subjects from the University Eye Institute at the University of Houston, College of Optometry (UHCO). Significant central corneal scarring that was judged a possible influence on visual performance was used as an exclusion criterion. General information including age, slit lamp findings of corneal scarring, Vogt striae, and Fleischer's ring were recorded. Before visual performance and wavefront aberration measurement, the study eye contact lens was removed, corneal topography was measured and the eye was dilated and accommodation paralyzed using 1 drop 0.5% Tropicamide ophthalmic solution. After dilation, the contact lens was reinserted and worn for all subsequent measures.

Visual Performance Testing

Six high contrast logMAR letter charts were generated with Visual Optics Laboratory Pro 6.83 (Sarver and Associates, Carbondale, IL). Letters on the charts were randomized such that every acuity chart had a unique letter combination. Visual acuity on each chart was determined using previously published procedures.[13–15] In summary of the procedure, visual acuity data were recorded through the RGP (three charts) and RGP plus spectacle overcorrection (three charts) and a 5-mm artificial pupil with head stabilized in the UHCO HeadSpot forehead and chin rest (UHCO technical services, Houston, TX). Each eye read each acuity chart until five letters were missed. The number of letters correctly identified up to the fifth miss was recorded. The average number of letters correct for the three trials was calculated and the corresponding high contrast logMAR visual acuity recorded. Comparative high contrast logMAR VA for an age-matched, dilated normal control group was obtained for 73 well-corrected eyes from the Texas Investigation of Normal and Cataract Optics (TINCO) study. PRCS data were collected on the keratoconic eyes while viewing the PRCS target from 1 m through a 5-mm artificial pupil placed in a trial frame. The PRCS data were scored in two ways. First, standard triplet scoring was computed and compared to a normal age matched dataset consisting of 26 eyes made available to the authors by Dr. Mantyjarvi, who reported normal PRCS data in 2001.[22] Second, PRCS data were scored according to the method of Elliott et al. using a protocol that provided credit for each correctly identified letter.[23] These latter data were used for regression analysis with the retinal image quality metrics. The method of Elliott et al. was chosen for metric correlation because it allowed finer resolution of the PRCS scale.

Wavefront Error

Wavefront aberration data were collected on the seven keratoconic eyes during RGP wear using a COAS HD wavefront sensor (Wavefront Sciences, Albuquerque, NM). The multifile acquire option was used to collect five consecutive Shack–Hartmann images separated by ~1 s (Only three well-centered, 5-mm wavefront measurements were obtained for eye K6; these three measures were used to calculate the average wavefront error of the eye). Subjects were instructed not to blink between measurements. A 5 mm pupil diameter was chosen so that comparison could be made to normal aberration data sets previously collected at that the same pupil size. Further, a 5-mm pupil is a pupil size that can be commonly encountered in everyday life. Analysis of raw data was performed using COAS and CLAS 2-D software (Wavefront Sciences, Albuquerque, NM) and reported as Zernike coefficients (ANSI Z80.28) at 555 nm over a 5-mm pupil for second to eighth radial order. The average coefficient values for each Zernike mode calculated from the consecutive wavefront measures on the RGP-corrected eye represented the aberrations for that eye. Normal age and pupil size-matched aberration data were obtained from the TINCO data set for the same eyes as reported above for high contrast logMAR VA. In the analysis of wavefront aberration that

TABLE 1.
Eye number, age, steep K, disease classification, and slit lamp findings for the seven keratoconic eyes enroled in the study are reported

Eye (#)	Age (yr)	Steep K (D)	Disease classification	Scarring	Vogt striae	Fleischer's ring
K1	39	45.50	Moderate	None	Subtle	None
K2	43	47.88	Moderate	None	None	None
K3	55	48.20	Moderate	None	None	None
K4	55	49.35	Moderate	Subtle, para-central	None	None
K5	50	49.54	Moderate	None	None	None
K6	27	50.93	Moderate	None	Subtle	None
K7	30	54.08	Severe	None	Subtle	Present

K3 and K4 are fellow eyes of the same subject. Incidence of scarring seen here is low by design as central corneal scarring was an exclusion criterion. All eyes except K3 wore a specialty contact lens specifically designed for use with keratoconus. K3's lens was a traditional spherical RGP lens.

follows, only aberrations through the 6th radial order from both the keratoconic eyes and normal eyes are included.

Calculation of Image Quality Metrics

Root Mean Square of the Wavefront (RMSw), Root Mean Square of the Slope (RMSs), Average Blur Strength (Bave), and Diameter containing 50% light energy (D50): For each keratoconic eye enrolled in the study, the average 2nd to 6th order Zernike coefficients (a total of 25 coefficients) were reduced to a single value by each of four optical quality metrics (Thibos release: 1v, September 13, 2006). Detailed descriptions and mathematical formulations for the metrics used here were previously published by Thibos et al. in 2004.[16] A brief summary of these definitions for the three optical quality metrics reported is drawn from Thibos et al. 2004[16] and presented here. Currently in vision science, RMSw, or root mean square wavefront error, is the most commonly reported metric of optical quality. In this formulation of RMS, the metric first calculates the wavefront error surface from the Zernike coefficients. The wavefront surface is then reduced to a single value by calculation of the standard deviation of the point by point values of wavefront error over the pupil of interest, here 5 mm. Root mean square wavefront slope is a measure of the spreading of light rays that blur the image. Bave, or average blur strength, represents the average of the localized focusing error that is responsible for image degradation. D50 is the diameter of a circular area centered on the PSF peak capturing 50% of the light energy.

Statistics

For VP and wavefront error measurements, values reported for each individual keratoconic eye are compared against an interval ($\pm$2 SD) encompassing 95% of normal measures.[24] The number of keratoconic eyes falling outside the interval on each measure is reported. Linear regression was used to explore the relationships between single-value wavefront aberration metrics and visual performance measures.

RESULTS

General Eye Information

Coded eye number, age, steep keratometry measurement (K), disease severity, and corneal anomalies recorded at the slit lamp are reported in Table 1. Severity of keratoconus was determined from steep keratometric axis power reported over central 5 mm on the Keratron corneal topographer (Optikon, Rome Italy). Here keratoconus severity is classified in a similar manner as used in the CLEK baseline study where the distinction between mild, moderate, and severe keratoconus is between steep keratometric axis powers of 45D and 52D.[5] Table 1 reports that six of the seven keratoconic eyes are classified as moderate, with the seventh eye being classified as a severe keratoconic eye. Six of the keratoconic eyes enrolled in this study wore a specialty contact lens specifically designed for use in keratoconus, and the seventh eye wore a more generic spherical RGP contact lens design. One of the seven keratoconic eyes had subtle para-central corneal scarring, and was deemed acceptable for enrolment. Table 2 contains information on the fitting characteristics of each lens studied.

Visual Performance

Table 3 reports the individual visual performance measures recorded on each keratoconic eye during RGP wear, the average keratoconic performance for the seven eyes, average normal performance for the control group, interval encompassing 95% of the normal group and the number of keratoconic eyes falling outside the normal interval. On average, high contrast VA in these RGP-corrected keratoconic eyes (0.15 $\pm$ 0.11 logMAR) is poorer than the normal age-matched control group (-0.07 ± 0.08, logMAR). Five of seven keratoconic eyes fall outside the normal interval. The best visual acuity achieved was 0.0 logMAR by eye K6 and one of the worst visual acuity reached is 0.28 logMAR by K7. K6 and K7 are of a similar age (27 and 30, respectively). Previous reports demonstrate that normal eyes of this age obtain high contrast visual acuity of -0.15.[7] Average PRCS measures for these keratoconic eyes (1.61 $\pm$ 0.14) were also poorer than that of normals (1.81 $\pm$ 0.11), with two of seven keratoconic eyes falling outside the normal interval. Table 3 also reports logMAR visual acuity measurements for the seven eyes for the RGP + spherocylindrical over-correction. This table demonstrates a spectacle-corrected gain for two eyes (K1: two lines, K3: one line) and a loss for one eye (K4: one line) with respect to RGP wear alone. The change for the remaining four eyes was $\leq$[½] line of acuity. With either mode of correction (RGP alone or RGP + spectacle over-correction), three of the seven eyes still had reduced logMAR VA as compared to normals.

TABLE 2.
Lens fit characteristics for each lens studied

				RGP parameters		
Eye	Centration	Movement	Lid Attach	BC (mm)	Power (D)	Overall diameter (mm)
K1	Good	Good	No	7.50	−3.25	9.0
K2	Good	Good	No	7.30	−9.25	9.0
K3	Good	Good	No	7.58	−4.00	9.3
K4	Slightly inferior	Acceptable	No	6.90	−8.75	9.0
K5	Good	Good	No	7.20	−2.25	8.7
K6	Good	Good	No	7.65	−6.00	9.0
K7	Good	Good	No	6.80	−7.00	8.7

Data pertaining to lens centration, lens movement and whether the lens was designed as a lid attachment fit as well as the lens parameters base curve, power, and overall diameter are reported.

TABLE 3.
Individual visual performance measures for these keratoconic eyes during RGP wear, average keratoconic performance, average normal performance, calculated interval encompassing 95% of the normals, and the number of keratoconic eyes falling outside the normal interval

Eye	RGP corrected high contrast logMAR VA	RGP + spectacle over refraction high contrast logMAR VA	PRCS
K1	0.11	−0.12	1.65
K2	0.09	0.10	1.80
K3	0.12	0.02	1.65
K4	0.30	0.41	1.35
K5	0.15	0.10	1.65
K6	0.00	−0.05	1.65
K7	0.28	0.23	1.50
Average KC	0.15 ± 0.11	0.10 ± 0.18	1.61 ± 0.14
Average normals	−0.07 ± 0.08	−0.07 ± 0.08	1.81 ± 0.11
Interval for 95% normals	−0.23–0.09	−0.23–0.09	1.59−2.03
KC eyes outside normal interval	5	4	2

For RGP wear alone, five of seven keratoconic eyes fall outside the normal interval for VA and two of seven keratoconic eyes fall outside the normal interval for PRCS. Best spectacle-corrected VA demonstrates a considerable gain for two eyes (K1: two lines, K3: one line) and a considerable loss for one eye (K4: one line) with respect to RGP wear alone. The change for the remaining four eyes was ≤[½] line of acuity. When either treatment modality is considered, three of the seven eyes (K4, K5, and K7) do not reach normal logMAR VA, further demonstrating the importance of residual uncorrected higher order aberrations. (Normal data: TINCO for high contrast VA and Mantyjarvi for PRCS).

Wavefront Aberration

Uncorrected wavefront aberration maps during RGP wear representing both lower and higher order aberrations (second to sixth orders) are plotted in Figure 1. The maps in Figure 1 display rotational asymmetry, resulting from the combination of both residual low and high order aberration terms during RGP lens wear. Table 4 reports the individual higher order aberration measures that were recorded on these keratoconic eyes during RGP wear, the average keratoconic performance for the seven eyes, average normal performance for the control group, interval encompassing 95% of the normal group and the number of keratoconic eyes falling outside the normal interval. The keratoconic eyes studied here have elevated total 3rd to 6th order aberrations (0.59 ± 0.36) when compared to normal eyes (0.21 ± 0.07) from the TINCO study, with five of seven eyes falling outside the normal interval. Keratoconus eyes also fell outside the normal interval for component aberrations coma (five eyes), secondary astigmatism (six eyes), secondary coma (seven eyes), and tertiary astigmatism (four eyes). These components of the high order aberration structure of keratoconic eyes were recently reported as significant in uncorrected keratoconic eyes.[4] In the current study, the RMS level reported for coma, secondary astigmatism, secondary coma, and tertiary astigmatism includes both components of the aberration.

Metric Output

Figures 2 (a–d) and 3 (a–d) show scatter plots for the two RGP-corrected visual performance measures with respect to the four optical quality metrics studied here. Plots are grouped according to visual performance measure to demonstrate the superiority of some metrics at explaining the same visual performance measure. Linear regression models and coefficients of determination are shown on the scatter plots. Linear regressions demonstrated relationships between both VA and PRCS and the image quality metrics RMSw, RMSs, Bave, and

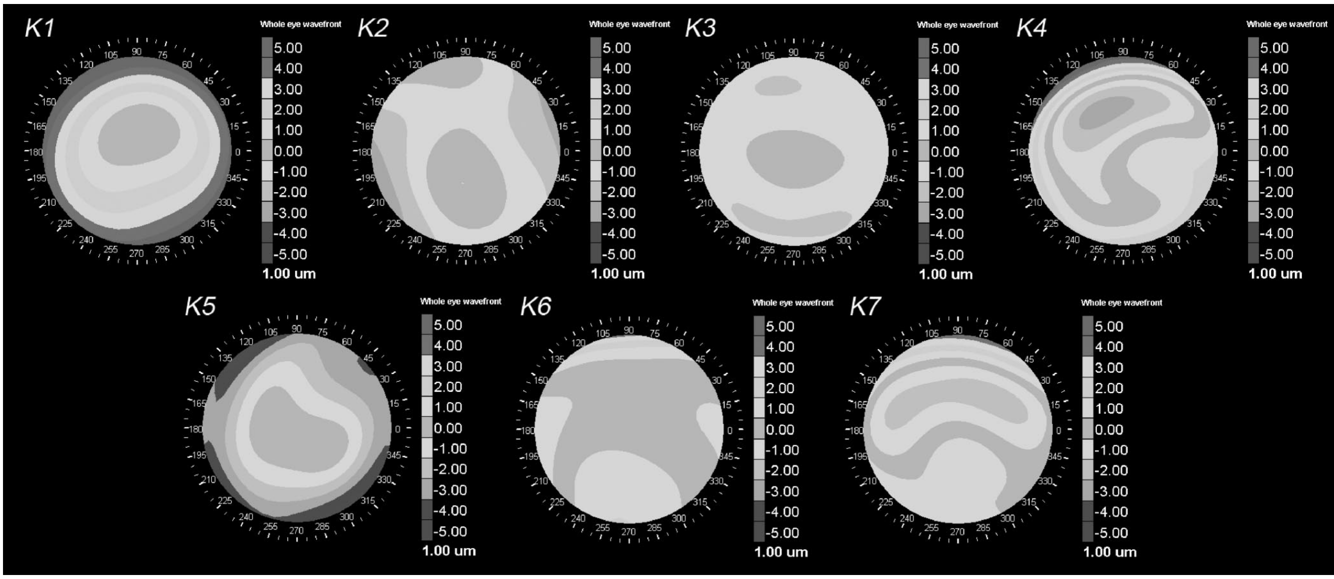

FIGURE 1.

Uncorrected ocular aberrations maps for each of the seven keratoconic eyes wearing RGP lenses. These maps are composed of the 2nd to 6th Zernike order aberration terms over a 5 mm pupil. Rotational asymmetry in the maps is a result of both high order aberrations (coma, secondary astigmatism, etc.) and low order terms (cylinder).

TABLE 4.

Individual aberration measures recorded on these keratoconic eyes during RGP wear, average keratoconic value, average normal value, interval encompassing 95% of the normals, and the number of keratoconic eyes falling outside the normal interval

	RMS (μm)				
Eye	HOA	Coma	Sec. astig.	Sec. coma	Tert. astig.
K1	0.36	0.31	0.08	0.12	0.02
K2	0.31	0.25	0.10	0.12	0.03
K3	0.29	0.08	0.10	0.08	0.02
K4	1.26	0.97	0.30	0.14	0.16
K5	0.52	0.19	0.19	0.06	0.18
K6	0.46	0.39	0.12	0.07	0.05
K7	0.90	0.74	0.13	0.17	0.06
Average KC	0.59 ± 0.36	0.42 ± 0.32	0.14 ± 0.08	0.11 ± 0.04	0.07 ± 0.07
Average normals	0.21 ± 0.07	0.10 ± 0.06	0.04 ± 0.02	0.02 ± 0.01	0.02 ± 0.01
Interval for 95% normals	0.07–0.35	0.00–0.22[a]	0.00–0.08	0.00–0.04	0.00–0.04
KC eyes outside normal interval	5	5	6	7	4

The RMS level reported here for coma, secondary astigmatism, secondary coma, and tertiary astigmatism includes both components of the aberration. Five of seven keratoconic eyes fall outside the normal range for higher order RMS. The components coma, secondary astigmatism, secondary coma, and tertiary astigmatism (previously reported as significant components of the high order aberration structure of keratoconic eyes)[4] are also elevated compared to normals, with at least four of seven eyes falling outside the normal range on each measurement.

[a]This value was reported as 0.00 because the calculated value of − 0.02 is not possible.

D50 with R^2 values for VA = 0.30, 0.47, 0.62, and 0.30 and PRCS = 0.21, 0.45, 0.75, and 0.15 respectively.

DISCUSSION

RGP contact lens correction remains the optical correction of choice for keratoconic eyes. RGP corrections are effective at improving visual performance in keratoconic patients, as seen here with all eyes in this study having monocular entrance acuity of 0.30 logMAR (20/40 Snellen equivalent) or better. This level of visual acuity allows an individual with keratoconus to perform routine visual tasks such as read a newspaper or work on a computer.

While it is tempting to examine the elevated RMS levels directly to assess visual performance loss, previous studies have shown that the manner in which these aberrations interact is crucial to understanding resultant retinal image quality.[14] Here, this is studied

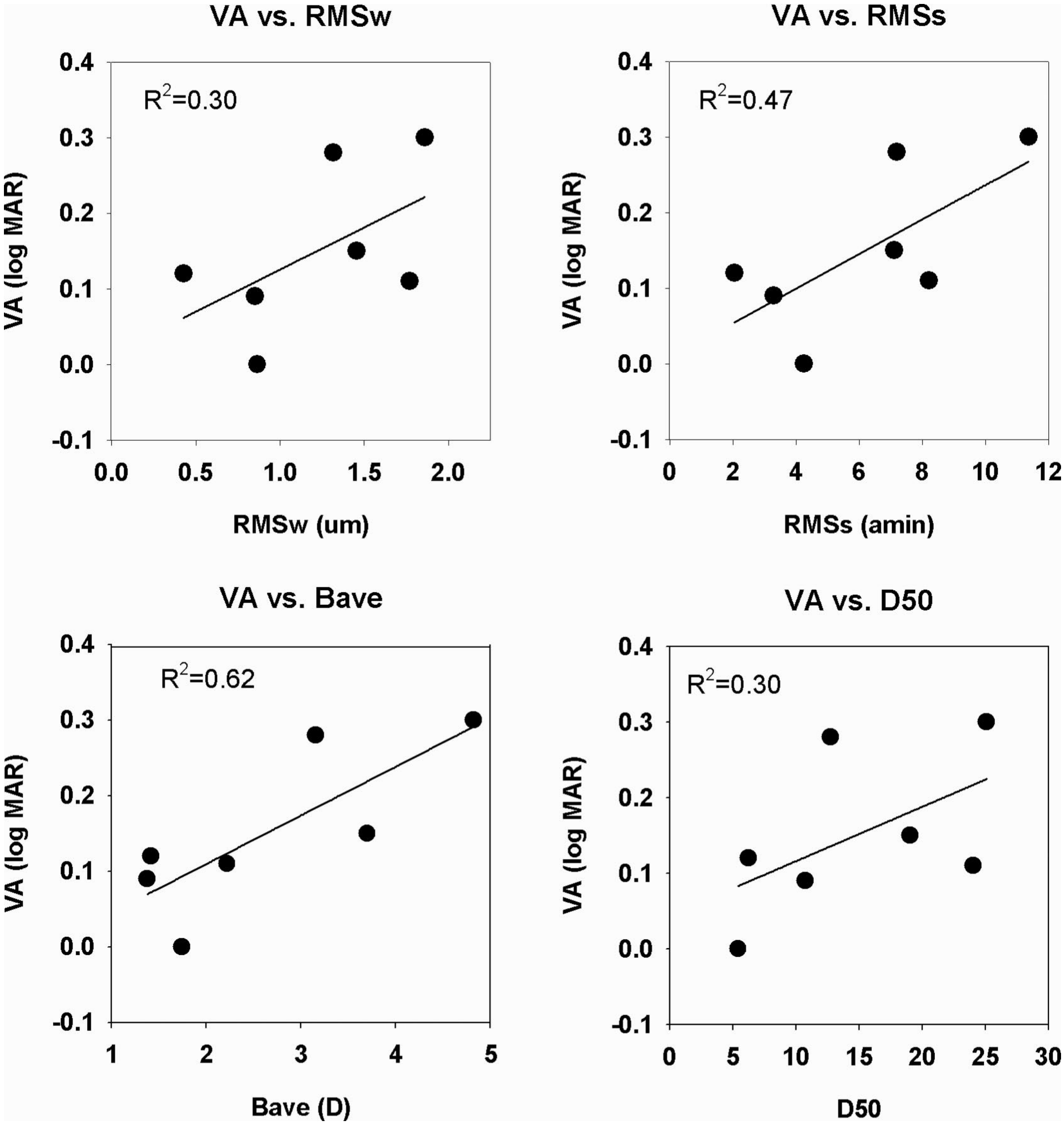

FIGURE 2.

High contrast visual acuity (VA) is plotted as a function of the four optical quality metrics studied: RMSw, RMSs, Bave, and D50. The most predictive of these metrics is Bave with an R^2 value of 0.62. The least predictive of these metrics are RMSw and D50 with an R^2 value of 0.30.

through the use of metrics. As seen in Figures 2 and 3, retinal image quality metrics determined from residual aberrations are correlated to visual performance measures.

Visual performance and higher order aberrations in RGP-wearing keratoconic eyes are compared to values for normal eyes. This is done in an attempt to examine the visual potential of keratoconic eyes. Given that a keratoconic eye generally has many years of normal vision before any significant loss, it is reasonable to assume that correcting ocular aberrations will improve visual performance. One clinical method that could be employed to compensate for residual low order aberrations would be to continue to fit different RGP contact lenses until the residual spherocylindrical corrections do not improve visual performance. Spectacles might also be worn over the RGP contact lenses. Either of these low order correcting techniques might be employed here with success for eyes K1 and K3, both of which display improved logMAR VA in the presence of an over-correction. However, Table 3 demonstrates that with either mode of correction (RGP alone or RGP + spectacle over-correction), three of the seven eyes still had reduced logMAR VA as compared to normals. Table 4 demonstrates that RGP performance alone leaves behind important high order optical aberrations in keratoconus that cannot be corrected by an over-refraction.

It is possible that high order aberrations induced by the anterior surface of the cornea are partly corrected by index matching. However, a traditional RGP would provide no such index-matching correction for higher order aberrations originating from the posterior surface of the cornea or the crystalline lens. Correction of any higher order posterior corneal or crystalline lens aberrations would require the specific introduction of a compensating aberration structure in the RGP correction. This type of wavefront-guided RGP correction is currently not available.

Previous studies have demonstrated reduced contrast sensitivity in keratoconus.[2,25–30] Perhaps the best previous evidence of decreased contrast sensitivity in contact lens wearing keratoconic eyes comes from two studies by Carney who showed in a small cohort of keratoconic eyes that contact lens correction provided better contrast sensi-

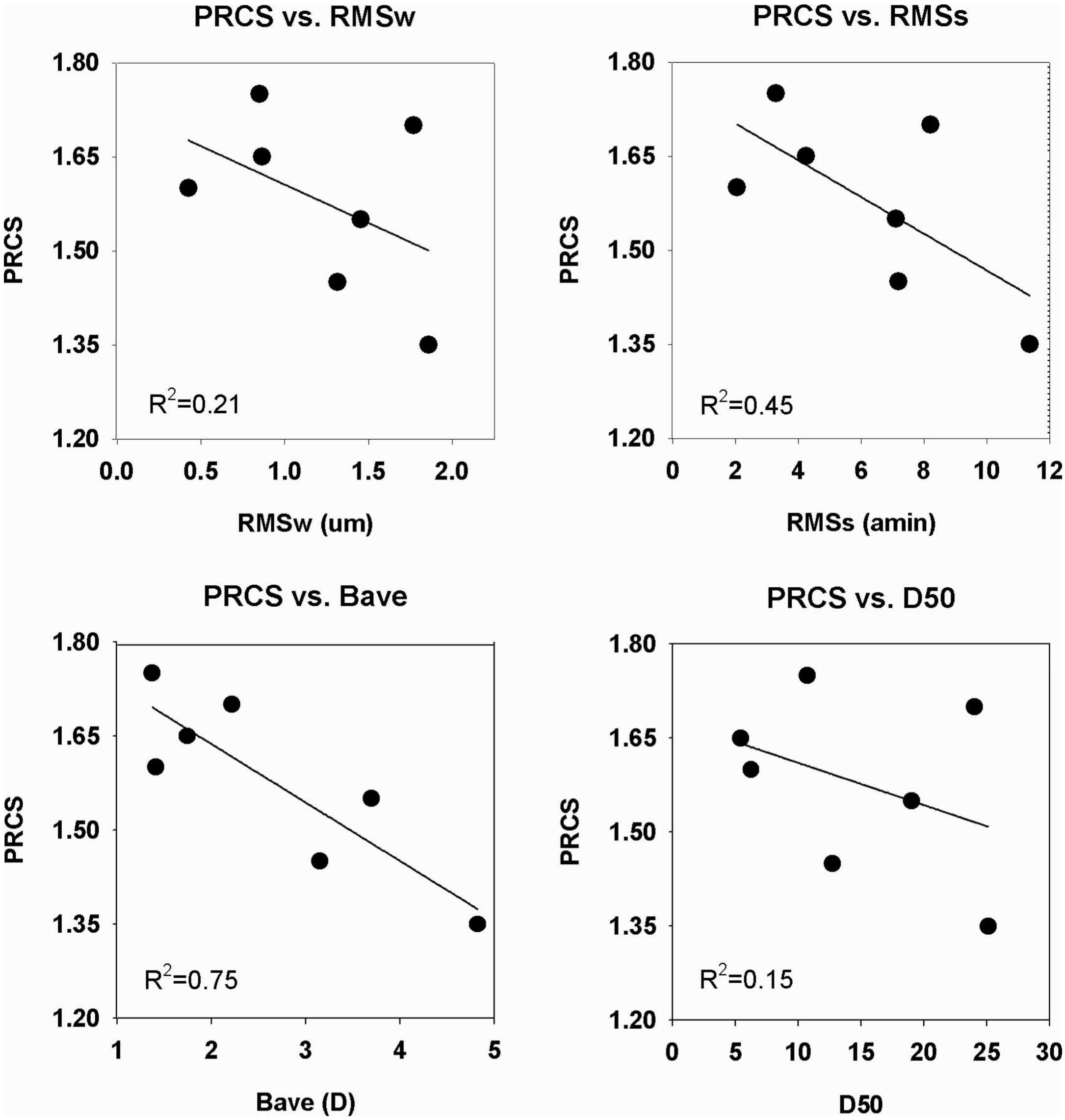

FIGURE 3.

Pelli-Robson contrast sensitivity (PRCS) is plotted as a function of the four optical quality metrics studied: RMSw, RMSs, Bave, and D50. The most predictive metric is Bave with an R^2 value of 0.75. The least predictive metric is D50 with an R^2 value of 0.15.

tivity than did spectacle correction, but that it was still below normal levels.[25,26] However, the level of residual aberrations in RGP lens wear in keratoconus has not been previously described.

These data suggest methods should be sought to further reduce the impact of uncorrected aberration in the keratoconic RGP-eye system. Possible methods for achieving better correction of aberrations include customized contact lenses incorporating a wavefront correction. Such technology is under development at several centers worldwide and has been eye to a number of patent applications. Wavefront guided spectacles over the RGP correction may also become an option in some cases.

While the present study reports on only a small sample of keratoconic eyes (six moderate, one severe), the sample illustrates the large differences in visual performance and higher order aberrations that exist between RGP-corrected keratoconic eyes and normals and the relationships between visual performance and optical quality metrics. Metrics relating residual ocular aberration to visual performance may become increasingly useful in understanding the impact of aberration on visual performance for complicated clinical eyes as well as prospectively designing corrections. These results support the growing evidence that highly aberrated eyes will benefit from a custom correction that accounts for the aberrations of that individual eye.[31–37]

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