HHS Public Access
Author manuscript
Optom Vis Sci. Author manuscript; available in PMC 2019 April 01.

Published in final edited form as:
Optom Vis Sci. 2018 April ; 95(4): 391–398. doi:10.1097/OPX.0000000000001205.

LogMAR and Stereoacuity in Keratoconus Corrected with Spectacles and RGP Contact Lenses

Vinay Kumar Nilagiri, BSOpt,
Bausch and Lomb School of Optometry, Brien Holden Institute of Optometry and Vision Sciences, L V Prasad Eye Institute, Hyderabad, Telangana, India; Prof. Brien Holden Eye Research Centre, Hyderabad Eye Research Foundation, L V Prasad Eye Institute, Hyderabad, Telangana, India

Sangeetha Metlapally, PhD, FAAO,
Vision Science Group, School of Optometry, University of California Berkeley, Berkeley, California

Parthasarathi Kalaiselvan, BSOpt,
Bausch and Lomb School of Optometry, Brien Holden Institute of Optometry and Vision Sciences, L V Prasad Eye Institute, Hyderabad, Telangana, India; Bausch and Lomb Contact Lens Centre, L V Prasad Eye Institute, Hyderabad, India

Clifton M. Schor, PhD, FAAO, and
Vision Science Group, School of Optometry, University of California Berkeley, Berkeley, California

Shrikant R. Bharadwaj, PhD
Bausch and Lomb School of Optometry, Brien Holden Institute of Optometry and Vision Sciences, L V Prasad Eye Institute, Hyderabad, Telangana, India; Prof. Brien Holden Eye Research Centre, Hyderabad Eye Research Foundation, L V Prasad Eye Institute, Hyderabad, Telangana, India

Abstract

Significance—This study showed an improvement in 3D depth perception of subjects with bilateral and unilateral keratoconus with RGP contact lens wear, relative to spectacles. This novel information will aid clinicians to consider RGP contact lenses as a management modality in keratoconic patients complaining of depth-related difficulties with their spectacles.

Purpose—To systematically compare changes in logMAR acuity and stereoacuity from best-corrected sphero-cylindrical spectacles to RGP contact lenses in bilateral and unilateral keratoconus, vis-à-vis, age-matched controls.

Methods—Monocular and binocular logMAR acuity and random-dot stereoacuity were determined in subjects with bilateral (n=30; 18–24yrs) and unilateral (n=10; 18–24yrs) keratoconus and 20 controls using standard psychophysical protocols.

Results—Median (25^{th}–75^{th} IQR) monocular (right eye) and binocular logMAR acuity and stereoacuity improved significantly from spectacles to RGP contact lenses in the bilateral keratoconus cohort ($p<0.001$). Only monocular logMAR acuity of affected eye and stereoacuity improved from spectacles to RGP contact lenses in the unilateral keratoconus cohort ($p<0.001$). There was no significant change in the binocular logMAR acuity from spectacles to RGP contact

Corresponding author: Shrikant R. Bharadwaj, bharadwaj@lvpei.org.

lenses in the unilateral keratoconus cohort. The magnitude of improvement in binocular logMAR acuity and stereoacuity was also greater for the bilateral compared to the unilateral keratoconus cohort. All outcome measures of cases with RGP contact lenses remained poorer than controls ($p<0.001$).

Conclusion—Binocular resolution and stereoacuity improve from spectacles to RGP contact lenses in bilateral keratoconus while only stereoacuity improves from spectacles to RGP contact lenses in unilateral keratoconus. The magnitude of improvement in visual performance is greater for the binocular compared to the unilateral keratoconus cohort.

Keywords

bilateral; keratoconus; interocular average; interocular difference; logmar acuity; rgp contact lens; stereoacuity; unilateral

---

Keratoconus is a progressive, non-inflammatory disease of one or both eyes characterized by thinning, anterior protrusion, increased asphericity and an eventual scarring and opacity of the cornea.[1] There is a significant deterioration of visual performance (e.g. high-contrast visual acuity) and the individual's quality of life with this disease.[2, 3] Many optical correction modalities including sphero-cylindrical spectacles, soft toric contact lenses, rigid gas permeable (RGP) contact lenses, scleral contact lenses and customized wavefront correcting contact lenses are currently available for managing keratoconus and all these modalities aim to improve the patient's visual performance by reducing the eye's low and/or higher order wavefront aberrations.[1] In general, there is agreement in the literature that monocular high and low-contrast visual acuities and contrast sensitivity of eyes with keratoconus are better with conventional RGP contact lenses than with sphero-cylindrical spectacles or soft contact lenses, all relative to performance under uncorrected conditions.[4, 5] Monocular visual acuity appears to improve even further when these eyes are corrected using customized wavefront correcting contact lenses or using a lab-based adaptive optics set-up.[6–9]

While changes in monocular visual acuity with keratoconus are well documented, there is little known about the binocular vision status of these subjects. Habitual viewing is a binocular process and many visual functions are crucially dependent on the matching of corresponding features in the two eyes (e.g. fine depth perception).[10] Deterioration of image quality in one or both eyes (e.g. due to anisometropia or aniseikonia) has deleterious effects on binocular vision parameters like stereoacuity and contrast summation.[11–13] Stereoacuity also deteriorates with an increase in the average and interocular difference in higher-order wavefront aberrations of the eye following LASER refractive surgery[11, 14] or following unilateral corneal transplantation, with the stereo performance improving in this cohort with RGP contact lens wear.[15]

Eyes with keratoconus are known to have increased magnitudes of lower-order (defocus and astigmatism) and higher-order wavefront aberrations.[16–19] Even while the lower-order aberrations can be corrected with sphero-cylindrical spectacles or RGP contact lenses, the elusiveness in the endpoint of subjective refraction may result in significant magnitudes of these aberration terms remaining uncorrected in keratoconic eyes.[20, 21] Qualitatively, the higher-order aberrations in keratoconic eyes are similar to those observed in eyes after corneal transplantation or after LASER refractive surgery.[15, 22–24] In addition, there may also be an increase in the interocular difference in wavefront aberrations depending on whether the disease manifests unilaterally or bilaterally, and depending on the stage of the disease in the two eyes for bilateral keratoconus. Patients with keratoconus may therefore also experience an associated loss of binocular visual functions, with some of this loss being potentially restored following optical interventions like spectacles or RGP contact lenses. The one study we found on this topic reported an improvement in motor fusion, suppression status and stereoacuity of subjects with long-standing keratoconus following scleral contact lens wear, relative to uncorrected conditions.[25]

The present study systematically investigated changes in the monocular and binocular logMAR acuity and binocular stereoacuity of individuals with unilateral and bilateral keratoconus with their best-corrected sphero-cylindrical spectacles and RGP contact lenses.

METHODS

Thirty subjects [median (25^{th}– 75^{th}IQR) age: 19yrs (18 – 24yrs)] with clinically diagnosed keratoconus in both eyes (bilateral keratoconus cohort) and ten subjects [20yrs (18–24yrs)] with clinically diagnosed keratoconus in one eye (unilateral keratoconus cohort) were recruited for the study from the Bausch & Lomb Contact Lens centre, LV Prasad Eye Institute (LVPEI), Hyderabad, India. Twenty controls [20.5yrs (20 – 21yrs)] who were free from any ocular pathology and with best-corrected visual acuity of 20/20 or better were also recruited from among the staff and students of LVPEI for comparison with the data on subjects with keratoconus. The study adhered to the tenets of Declaration of Helsinki and was approved by the Institutional Review Board of LVPEI. All subjects participated after signing a written informed consent form.

Corneal curvature and power of all subjects with keratoconus were obtained in this study using the topography scans in the Wavelight OculyzerII (Pentacam HR technology, Texas, http://www.alconsurgical.ca/Wavelight-Oculyzer-II.aspx). Based on the power at the apex of the cornea obtained from this device[26], all subjects with keratoconus who participated in this study were deemed to have mild to moderate forms of the disease. All these subjects were experienced RGP contact lens users, with more than one year of wearing experience, average wearing duration of 8hrs per day, no complaints with the current contact lenses and those who maintained their lenses using the proper care regimen as advised by their eye specialist. All subjects with keratoconus underwent a comprehensive eye examination evaluating all the aforementioned parameters before being enrolled into the study and the standard clinical management was followed for all of them, with no influence of the study on their care. Subjects with signs of corneal scarring, superficial punctate keratitis, frequent blinking, intolerance to RGP contact lens wear, monocular best-corrected high-contrast acuity worse than 20/30 with RGP contact lens and any other ocular co-morbidities were excluded from the study.

Each subject’s sphero-cylindrical refractive error with spectacles or over-refraction with RGP contact lenses was first estimated using retinoscopy and then finalized using the maximum plus for maximum visual acuity criterion of clinical subjective refraction. Refraction procedures were performed by a single examiner and refractive corrections incorporated using trial lenses at ~12 – 14mm vertex distance for all study procedures. All subjects with keratoconus wore tri-curve, back aspheric design RGP contact lenses (Flouroperm 90, CLASSIC Contact Lens Laboratory, Bangalore, India) and over-refractions were incorporated using trial lenses, as described above.

Monocular and binocular logMAR acuity was determined under unaided, best sphero-cylindrical spectacle corrected and best RGP contact lens corrected conditions at 3m viewing distance using a calibrated, computerized logMAR optotype presentation system (COMPlog; http://www.complog-acuity.com/). Optotypes were presented on a LCD screen (1680 × 1050 pixel resolution) under photopic lighting conditions (monitor luminance: 80cd/m^2). In this paradigm, a series of 5 Sloan optotypes were randomly displayed and their angular subtense decreased using a staircase thresholding algorithm until 3 out of these 5 optotypes were incorrectly identified.[27] LogMAR acuity was recorded as the number of optotypes correctly identified at termination, with 0.02 logMAR units allotted per optotypes.[27] Stereoacuity was also measured under unaided, best sphero-cylindrical spectacle corrected and best RGP contact lens corrected conditions at 40cm using a custom-designed program in the Psychophysics-3 interface of Matlab.[28, 29] Near vision of all subjects were corrected in this test using a +2.5D near-addition lens before both eyes that was appropriate for the viewing distance of the task. Subjects identified the orientation of a long cyclopean rectangular bar presented in crossed disparity in a random-dot field subtending 7° × 7° on the LCD screen. The disparity patterns were presented using a mirror stereoscope, the angle of which was adjusted to overcome any horizontal heterophoria of the subject. None of the subjects complained of vertical misalignment of the monocular images, indicating the absence, or minimal vertical heterophoria. The disparity stimulus was scaled to the subject's IPD and modulated in 10% steps from a starting value of 400arc sec in step size of 15arc sec using a two alternate forced choice one-up, one-down staircase that terminated after 11 reversals. Stereoacuity was defined as the average disparity of the last 8 reversals. A minimum disparity of 15arc sec could be achieved in this test based on the display resolution of the computer monitor (1680 × 1050 pixel resolution) and sub-pixel resolution algorithms used during stimulus display in the study.

All subjects were instructed to discontinue contact lens wear the evening prior to the scheduled experiment. They wore their habitual spectacles on the day of the study and carried their contact lens along with them. On the day of the study, all data were first collected with spectacles followed by RGP contact lenses to avoid any short-term changes in corneal topography following RGP contact lens wear.[30] Post the data collection with spectacles, subjects wore their RGP contact lenses and rested for one-hour prior to start of the second experimental session. This ensured that any form of temporary discomfort with the contact lens was removed prior to data collection. All psychophysical data were also obtained after the eyes were cyclopleged with 1% Cyclopentolate eye drops. Cycloplegia was confirmed by a drop in near visual acuity below 2.0M units on Bailey-Lovie word reading chart at 50cm viewing distance. A 6mm diameter artificial aperture was placed before the eyes on the trial frame during these measurements.

RESULTS

Data was successfully collected in all study participants. Table 1 provides details of the median (25th – 75th IQR) age, gender balance, corneal curvature, interpupillary distance (IPD) and objective and subjective sphero-cylindrical refractive error (represented in power vector notation[31]) of all subjects that participated in this study. The Shapiro-Wilk test indicated that most outcome variables in this study did not follow a normal distribution. A non-parametric Wilcoxon Sign Rank test and Mann Whitney U-tests were therefore applied to compare data within and across groups, with statistical significance set at a p-value of p<0.05.

The median (25th – 75thIQR) unaided logMAR acuity of the bilateral keratoconus cohort in the right eye, left eye and binocular viewing conditions was worst under unaided conditions, followed by spectacles and then with RGP contact lenses (Z=4.62; n=30; p <0.0001) (Figure 1A and B, Table 2). The median interocular difference in logMAR acuity for these subjects was larger with spectacles than with RGP contact lenses (Z=4.14; n=29; p<0.001) (Figure 1A and B, Table 2). As evident from the IQR's, there was also a reduction in the inter-subject variability of binocular logMAR acuity of these subjects with RGP contact lenses, vis-à-vis, spectacles (Figure 1A and B, Table 2).

The median unaided logMAR acuity of the unilateral keratoconus cohort was expectedly worse in the affected eye than in the fellow unaffected eye and the acuity remained similar to the unaffected eye's acuity under binocular viewing conditions (Table 2). The median logMAR acuity of the affected eye improved significantly from best corrected spectacles to RGP contact lenses (Z=2.62; n=10; p=0.008) while the binocular acuity remained unchanged between the two modalities of optical management (Z=1; n=5; p>0.05) (Figure 1C and D, Table 2). Like the binocular cohort, the median interocular difference in logMAR acuity (Z=2.73; n=10; p=0.008) and the inter-subject variability of binocular logMAR acuity also reduced from spectacles to RGP contact lens wear in the unilateral keratoconus cohort (Figure 1C and D, Table 2).

All measures of logMAR acuity in age-matched controls were significantly better than the spectacle and RGP contact lens corrected conditions of subjects with bilateral and unilateral keratoconus (H=31.03; df=2; p <0.001 for all) (Figure 1E, Table 2). The binocular logMAR acuity of the bilateral and the unilateral keratoconus cohort correlated more with the eye that had better of the two monocular logMAR acuities (i.e. the unaffected fellow eye, in the unilateral cohort) than with the worse logMAR acuity eye for both spectacle and RGP contact lens correction (Table 3).

Subjects with bilateral and unilateral keratoconus did not appreciate the stereo pattern displayed on the computer monitor with disparities as high as 1000arc sec under unaided viewing conditions (Table 2). The median stereoacuity improved significantly from spectacle-corrected to and RGP contact lens corrected conditions for both the bilateral and the unilateral keratoconus cohort (Z=4.76; n=30; p<0.001) (Figure 2, Table 2). Like logMAR acuity, the IQR's were smaller for the RGP contact lens wear than for spectacles, suggesting a reduction in the inter-subject variability of stereoacuities with the former modality of management, relative to the latter, in both the bilateral and unilateral keratoconus cohorts (Figure 2, Table 2). The RGP contact lens and the spectacle corrected stereoacuity of all subjects were significantly worse than the best-corrected stereoacuity of controls ($H=28.9$; $df=2$; $p=<0.001$ for both) (Figure 2, Table 2).

Figure 3 shows the median change in binocular visual acuity and stereoacuity from spectacles to RGP contact lenses for the bilateral and the unilateral keratoconus cohort. Since calculating such a change for logMAR acuity can be challenging due to presence of zeros in its numerical values (zero logMAR = 20/20 acuity), all logMAR values were converted into their MAR equivalents for this calculation. In this analysis, larger values of MAR and stereoacuity indicated poorer spatial and depth-related visual performance, respectively. A ratio of unity therefore indicated no change in performance from spectacles to RGP contact lenses while a ratio of greater than unity indicated worse performance in spectacles related to RGP contact lenses (in other words, an improvement in performance with RGP contact lenses, vis-à-vis, spectacles). The median and upper IQR data clearly indicated that the magnitude of change from spectacles to RGP contact lenses was greater for stereo than for MAR acuity (Figure 3). For unilateral keratoconus, there was little or no improvement in binocular MAR acuity from spectacles to RGP contact lenses but there was a significant improvement in stereoacuity (Figure 3).

Discussion

This study determined the high-contrast logMAR and stereoacuity of subjects with bilateral and unilateral keratoconus when corrected with sphero-cylindrical spectacles and RGP contact lenses. The results obtained here are in line with the previous literature and with the clinical expectations of an improvement in monocular high-contrast logMAR acuity from spectacles to RGP contact lenses in eyes with unilateral and bilateral keratoconus.[4, 5] The present study extends these findings to show improvement in binocular logMAR and stereoacuity in the bilateral keratoconus cohort (Figure 1A and B, Figure 2, Tables 2 and 3) and for stereoacuity in the unilateral keratoconus cohort (Figure 1C and D, Figure 2, Tables 2 and 3). In fact, the switch from spectacles to RGP contact lenses appears relatively more beneficial for depth vision than for spatial vision in both cohorts, as evidenced from the magnitude of change in visual performance from the former to the latter management modality (Figure 3). There is also a reduction in the intersubject variability of logMAR acuity and stereoacuity when switching from spectacles to RGP contact lenses, indicating that there is some homogenization of visual performance across subjects when wearing RGP contact lenses (Figure 1 and 2, Table 2). The intersubject variability in performance was, in general, larger for both keratoconus cohorts compared to age-matched controls and this is expected given the wide variation in disease severity in these subjects (Figure 1 and 2). Such a homogenization in visual performance with RGP contact lenses, vis-à-vis, spectacles, has also been observed in subjects who undergo corneal transplantation for treating non-keratoconic corneal pathology.[15] Overall, from a clinical management standpoint, patients with keratoconus may gain more depth vision than 2D spatial resolution when wearing RGP contact lenses and the patient cohort may perform more uniformly and predictably with RGP contact lens wear than with spectacles. Patients with bilateral disease may perceive an improvement in both 2D resolution and depth vision under naturalistic binocular viewing conditions with RGP contact lenses, vis-à-vis, spectacles, while those with unilateral disease may see an apparent benefit only for depth related visual tasks and not for binocular 2D spatial resolution tasks.

Interestingly, the monocular uncorrected logMAR acuity of the bilateral and the unilateral keratoconus cohorts were somewhat better than what would be expected from a non-keratoconic with equivalent amount of blur from spherical refractive error. The acuity ranges obtained in this study were in line with previous reports on a similar cohort of subjects. [32, 33] A relatively better acuity may be the result of a phenomenon akin to simultaneous vision while wearing multifocal lenses that arise from an interaction between the lower- and higher-order wavefront aberrations of the eye.[34, 35] Alternatively, the relatively better visual acuities seen in these eyes could also be a reflection of some form of neural adaptation to the long-standing presence of these wavefront aberrations.[7, 36] Further experiments are required to discern these possibilities.

In this study, the median spectacle-corrected stereoacuity of the bilateral keratoconus cohort (587.6arc sec) was somewhat poorer than that of the unilateral cohort (446.8arc sec) (Figure 2 and Table 2). Stereoacuity improved to comparable levels in both cohorts with RGP contact lens wear (221.4arc sec for bilateral cohort Vs. 187.8arc sec for unilateral cohort) (Figure 2 and Table 2), indicating that the greater enhancement of performance in stereoacuity from spectacles to RGP contact lenses in the bilateral cohort was primarily because of poorer spectacle-corrected stereoacuity to begin with. The stereoacuity with RGP contact lenses was still significantly poorer than the median stereoacuity of controls (42.2arc sec), suggesting that there may be upper limits to performance enhancement that can be achieved with RGP contact lenses in these subjects (Figure 2 and Table 2).[22, 23] The improvement in stereoacuity from spectacles to RGP contact lenses may be explained by several factors including a reduction in the overall magnitude and interocular difference in wavefront aberrations of the two eye with RGP contact lenses, leading to better and similar quality of retinal images in the two eyes that facilitates binocular matching of corresponding features to extract depth[11, 14, 15], reduction in aniseikonia with RGP contact lenses[12] and an improvement in the accuracy of binocular vergence eye movements with RGP contact lenses[37, 38]. A systematic evaluation of these factors is currently underway in the laboratory. Even while the optical fidelity of the keratoconic eye may improve with RGP contact lenses, they may not reach the level of the control population as RGP contact lenses still leave a portion of the higher-order aberrations uncorrected.[22] This may explain why the stereoacuity in keratoconus continued to remain poorer than those of controls even with RGP contact lens wear. In addition, the slow and progressive nature of image quality loss in keratoconus may lead to some form of amblyopia in the worse eye – especially in long standing unilateral keratoconus – and this may also impose a limit on the magnitude of improvement in visual performance that can be achieved with optical correction.[7] The possibility of amblyopia in keratoconic eyes is quite opposite to the possibility of neural adaptation to optimize visual performance noted above. These apparently conflicting points of view need to be reconciled through further experimentation.

Two observations made in this study suggest that the eye that provides better of the two visual inputs may drive binocular 2D spatial visual performance. First, the binocular logMAR acuity of the unilateral keratoconus cohort did not show any improvement from spectacles to RGP contact lenses and it was only marginally better than their unaided binocular logMAR acuity (Figure 1 and 3). Second, the correlation of binocular logMAR acuity was higher with the eye that had the better of the two monocular logMAR acuities (i.e. the unaffected eye in unilateral keratoconus and the eye with the lesser disease severity in bilateral keratoconus) (Table 2). The first observation suggests that the unaffected eye largely determined the binocular logMAR acuity in the unilateral keratoconus cohort, given that this eye's visual acuity remained unaltered and better than the affected eye's acuity even with RGP contact lenses (Figure 1C and D). Similar observations of the visual input from one eye dominating the binocular spatial performance have been observed in patients following unilateral corneal transplantation.[15] Both observations are also akin to the phenomenon of "blur suppression" described with monovision contact lenses and intraocular lenses for management of presbyopia, wherein one eye is optically corrected for distance and the fellow eye is purposely made myopic to focus at near.[39, 40] Dominance of the eye that produces clearer of the two images may also be logically derived from studies that show the binocular contrast summation to become negligible beyond a certain magnitude of induced anisometropia.[41] While the relative dominance of one eye's visual input over another may make binocular spatial resolution immune to the presence of unilateral blur, other visual functions like depth vision that are critically dependent on the similarity of inputs from both eyes are bound to deteriorate in the presence of an interocular difference in image quality.[42, 43]

This study had two limitations. First, the visual performance of keratoconic subjects reported here are with a large pupil diameter (6mm) and this may have artificially worsened the visual performance of these eyes relative to naturalistic viewing conditions. This pupil diameter used in this study represents a scenario when the wavefront aberrations of their eye are likely to have maximum negative impact on the retinal image quality.[22] Arriving at the endpoint of subjective refraction in these eyes may also be harder with such large pupil diameters, thereby increasing the chances of sphero-cylindrical refractive errors remaining uncorrected in these eyes. Second, artificial pupils of 6mm diameter were placed before both eyes of the subject during all psychophysical testing to ensure that the viewing experience was uniform across all subjects that participated in the study. Even while care was taken to align the pupil to the visual axes of the subject from time to time during the experiment, slight misalignments may have crept in between the visual axes and the artificial pupils during the experiment. This may have some undesired effect on the subject's retinal image quality and contributed to some magnitude of worsening of visual performance reported here. Taken together, both limitations suggest that the overall visual performance of the keratoconus cohort reported here with spectacles and RGP contact lenses may be worse than what is found under naturalistic viewing conditions with smaller pupil diameters.

Acknowledgments

The authors would like to thank all the participants of this study, Dr. Preeji Sudharman and members of the Bausch & Lomb Contact Lens Centre, L V Prasad Eye Institute, Hyderabad for their inputs during the initiation of the project. The authors would also like to acknowledge the support of Mr. Preetam Kumar from the Bausch & Lomb Contact lens Centre, L V Prasad Eye Institute, Hyderabad providing the ocular photograph of a patient with keratoconus.

References

1. Krachmer JH, Feder RS, Belin MW. Keratoconus and Related Noninflammatory Corneal Thinning Disorders. Surv Ophthalmol. 1984; 28:293–322. [PubMed: 6230745]
2. Jones-Jordan LA, Walline JJ, Sinnott LT, et al. Asymmetry in Keratoconus and Vision-Related Quality of Life. Cornea. 2013; 32:267–72. [PubMed: 22825402]
3. Gothwal VK, Reddy SP, Fathima A, et al. Assessment of the Impact of Keratoconus on Vision-Related Quality of Life. Invest Ophthalmol Vis Sci. 2013; 54:2902–10. [PubMed: 23518765]
4. Jinabhai A, Radhakrishnan H, O'Donnell C. Visual Acuity and Ocular Aberrations with Different Rigid Gas Permeable Lens Fittings in Keratoconus. Eye Contact Lens. 2010; 36:233–7. [PubMed: 20543704]
5. Negishi K, Kumanomido T, Utsumi Y, Tsubota K. Effect of Higher-Order Aberrations on Visual Function in Keratoconic Eyes with a Rigid Gas Permeable Contact Lens. Am J Ophthalmol. 2007; 144:924–9. [PubMed: 17949670]
6. Yang B, Liang B, Liu L, et al. Contrast Sensitivity Function after Correcting Residual Wavefront Aberrations During Rgp Lens Wear. Optom Vis Sci. 2014; 91:1271–7. [PubMed: 24770353]
7. Sabesan R, Yoon G. Visual Performance after Correcting Higher Order Aberrations in Keratoconic Eyes. J Vis. 2009; 9(6):1–10.
8. Jinabhai A, O'Donnell C, Tromans C, Radhakrishnan H. Optical Quality and Visual Performance with Customised Soft Contact Lenses for Keratoconus. Ophthalmic Physiol Opt. 2014; 34:528–39. [PubMed: 24758229]
9. Marsack JD, Parker KE, Applegate RA. Performance of Wavefront-Guided Soft Lenses in Three Keratoconus Subjects. Optom Vis Sci. 2008; 85:1172–8.
10. Frisby, JP., Stone, JV. Seeing with Two Eyes, Part I and Part II. In: Frisby, JP., Stone, JV., editors. Seeing: The Computational Approach to Biological Vision. 2nd. Cambrige, MA: MIT Press; 2010. p. 419-96.
11. Jimenez JR, Castro JJ, Jimenez R, Hita E. Interocular Differences in Higher-Order Aberrations on Binocular Visual Performance. Optom Vis Sci. 2008; 85:174–9. [PubMed: 18317332]
12. Lovasik JV, Szymkiw M. Effects of Aniseikonia, Anisometropia, Accommodation, Retinal Illuminance, and Pupil Size on Stereopsis. Invest Ophthalmol Vis Sci. 1985; 26:741–50. [PubMed: 3997423]
13. Sabesan R, Zheleznyak L, Yoon G. Binocular Visual Performance and Summation after Correcting Higher Order Aberrations. Biomed Opt Express. 2012; 3:3176–89. [PubMed: 23243568]
14. Sarkar S, Bharadwaj SR, Reddy JC, Vaddavalli PK. Optical Quality and Visual Performance after Lasik, PRK or Relex Smile Refractive Surgery for Myopia. Submitted. 2017
15. Bandela PK, Satgunam P, Garg P, Bharadwaj SR. Corneal Transplantation in Disease Affecting Only One Eye: Does It Make a Difference to Habitual Binocular Viewing? PLoS One. 2016; 11:e0150118. [PubMed: 26938450]
16. Alio JL, Shabayek MH. Corneal Higher Order Aberrations: A Method to Grade Keratoconus. J Refract Surg. 2006; 22:539–45. [PubMed: 16805116]
17. Gordon-Shaag A, Millodot M, Ifrah R, Shneor E. Aberrations and Topography in Normal, Keratoconus-Suspect, and Keratoconic Eyes. Optom Vis Sci. 2012; 89:411–8. [PubMed: 22311193]
18. Marsack JD, Parker KE, Pesudovs K, et al. Uncorrected Wavefront Error and Visual Performance During Rgp Wear in Keratoconus. Optom Vis Sci. 2007; 84:463–70. [PubMed: 17568315]
19. Marsack JD, Rozema JJ, Koppen C, et al. Template-Based Correction of High-Order Aberration in Keratoconus. Optom Vis Sci. 2013; 90:324–34. [PubMed: 23458981]
20. Davis LJ, Schechtman KB, Begley CG, et al. Repeatability of Refraction and Corrected Visual Acuity in Keratoconus. The Clek Study Group. Collaborative Longitudinal Evaluation of Keratoconus. Optom Vis Sci. 1998; 75:887–96. [PubMed: 9875994]
21. Raasch TW, Schechtman KB, Davis LJ, et al. Repeatability of Subjective Refraction in Myopic and Keratoconic Subjects: Results of Vector Analysis. Ophthalmic Physiol Opt. 2001; 21:376–83. [PubMed: 11563425]

22. Marsack JD, Parker KE, Pesudovs K, et al. Uncorrected Wavefront Error and Visual Performance During Rgp Wear in Keratoconus. Optom Vis Sci. 2007; 84:463–70. [PubMed: 17568315]
23. Marsack JD, Rozema JJ, Koppen C, et al. Template-Based Correction of High-Order Aberration in Keratoconus. Optom Vis Sci. 2013; 90:324. [PubMed: 23458981]
24. Sarkar S, Vaddavalli PK, Bharadwaj SR. Image Quality Analysis of Eyes Undergoing Laser Refractive Surgery. PLoS One. 2016; 11:e0148085. [PubMed: 26859302]
25. Sherafat H, White JE, Pullum KW, et al. Anomalies of Binocular Function in Patients with Longstanding Asymmetric Keratoconus. Br Journal Ophthalmol. 2001; 85:1057–60.
26. Buxton, JN., Buxton, DF., Dias, AK., Scorsetti, DH. The CLAO Guide to Basic Science and Clinical Practice. 3rd. Dubuque, IA: Kendall/Hunt; 1996. Keratconus basic and clinical features; p. 101-22.
27. Shah N, Laidlaw DA, Shah SP, et al. Computerized Repeating and Averaging Improve the Test-Retest Variability of Etdrs Visual Acuity Measurements: Implications for Sensitivity and Specificity. Invest Ophthalmol Vis Sci. 2011; 52:9397–402. [PubMed: 22003109]
28. Brainard DH. The Psychophysics Toolbox. Spat Vis. 1997; 10:433–6. [PubMed: 9176952]
29. Pelli DG. The Videotoolbox Software for Visual Psychophysics: Transforming Numbers into Movies. Spat Vis. 1997; 10:437–42. [PubMed: 9176953]
30. Tyagi G, Collins MJ, Read SA, Davis BA. Corneal Changes Following Short-Term Rigid Contact Lens Wear. Cont Lens Anterior Eye. 2012; 35:129–36. [PubMed: 22361013]
31. Thibos LN, Wheeler W, Horner D. Power Vectors: An Application of Fourier Analysis to the Description and Statistical Analysis of Refractive Error. Optom Vis Sci. 1997; 74:367–75. [PubMed: 9255814]
32. Choi J, Wee WR, Lee JH, Kim MK. Changes of Ocular Higher Order Aberration in on-and Off-Eye of Rigid Gas Permeable Contact Lenses. Optom Vis Sci. 2007; 84:42–51. [PubMed: 17220777]
33. Gemoules G, Morris KM. Rigid Gas-Permeable Contact Lenses and Severe Higher-Order Aberrations in Postsurgical Corneas. Eye Contact Lens. 2007; 33:304–7. [PubMed: 17993826]
34. Madrid-Costa D, Tomás E, Ferrer-Blasco T, et al. Visual Performance of a Multifocal Toric Soft Contact Lens. Optom Vis Sci. 2012; 89:1627–35. [PubMed: 23034336]
35. Kang P, Wildsoet CF. Acute and Short-Term Changes in Visual Function with Multifocal Soft Contact Lens Wear in Young Adults. Cont Lens Anterior Eye. 2016; 39:133–40. [PubMed: 26482903]
36. Sabesan R, Yoon G. Neural Compensation for Long-Term Asymmetric Optical Blur to Improve Visual Performance in Keratoconic Eyes. Invest Ophthalmol Vis Sci. 2010; 51:3835–9. [PubMed: 20130284]
37. Ukwade MT, Bedell HE, Harwerth RS. Stereothresholds with Simulated Vergence Variability and Constant Error. Vision Res. 2003; 43:195–204. [PubMed: 12536141]
38. Ukwade MT, Bedell HE, Harwerth RS. Stereopsis Is Perturbed by Vergence Error. Vision Res. 2003; 43:181–93. [PubMed: 12536140]
39. Evans BJ. Monovision: A Review. Ophthalmic Physiol Opt. 2007; 27:417–39. [PubMed: 17718882]
40. Ravikumar S, Bradley A, Bharadwaj S, Thibos LN. Expanding Binocular Depth of Focus by Combining Monovision with Diffractive Bifocal Intraocular Lenses. J Cataract Refract Surg. 2016; 42:1288–96. [PubMed: 27697246]
41. Legras R, Hornain V, Monot A, Chateau N. Effect of Induced Anisometropia on Binocular through-Focus Contrast Sensitivity. Optom Vis Sci. 2001; 78:503–9. [PubMed: 11503939]
42. Qian J, Adeseye SA, Stevenson SB, et al. D(Max) for Stereoscopic Depth Perception with Simulated Monovision Correction. Seeing Perceiving. 2012; 25:399–408. [PubMed: 21774871]
43. Fernandez EJ, Schwarz C, Prieto PM, et al. Impact on Stereo-Acuity of Two Presbyopia Correction Approaches: Monovision and Small Aperture Inlay. Biomed Opt Express. 2013; 4:822–30. [PubMed: 23761846]

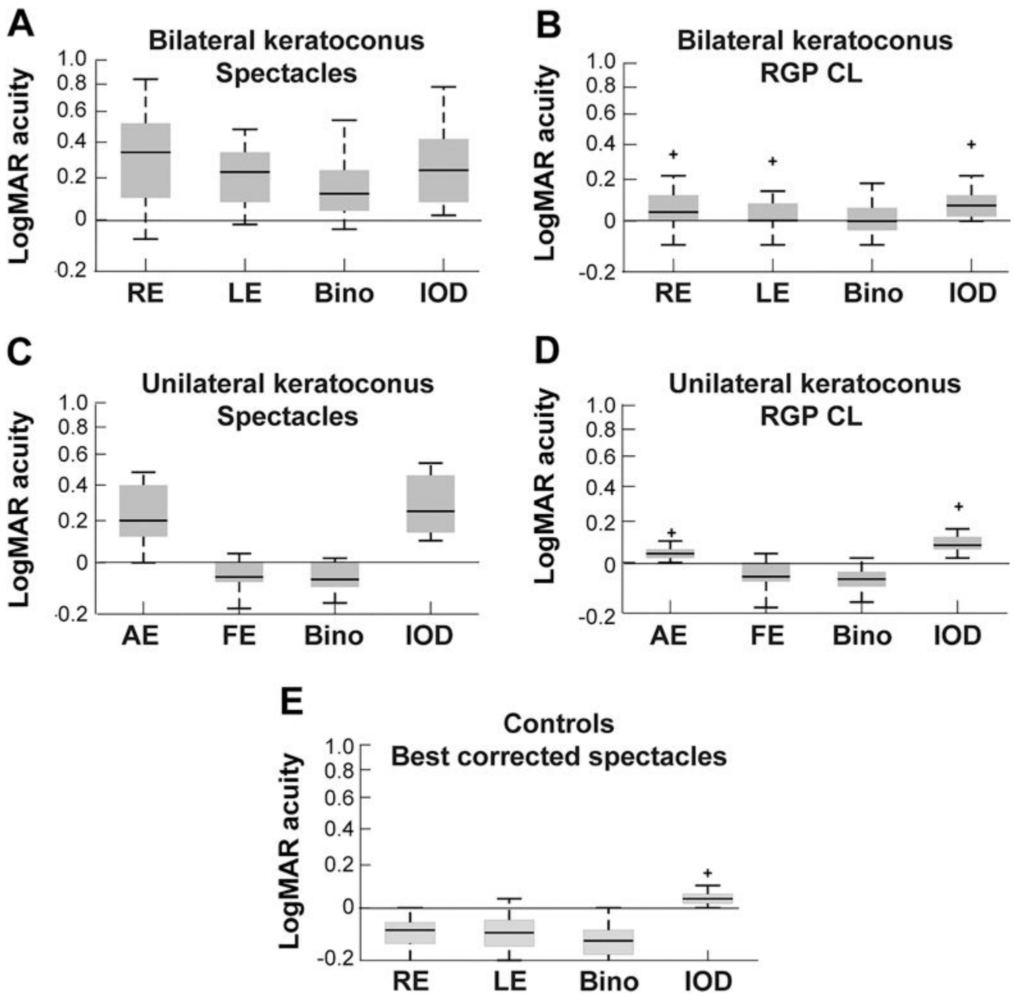

Figure 1.

Box and Whisker plots of high-contrast monocular and binocular logMAR acuities and interocular differences in logMAR acuity of subjects with bilateral (panels A and B) and unilateral (panels C and D) keratoconus with best-corrected spectacles (panels A and C) and with best-corrected RGP contact lenses (panels B and D). Panel E shows the same data from best-corrected conditions of age-matched controls. The solid horizontal line within the box indicates median value, lower and upper edges of the box indicate the 25th and 75th interquartile range (IQR), lower and upper whiskers show the 1st and 99th quartiles and plus symbols indicate outliers.

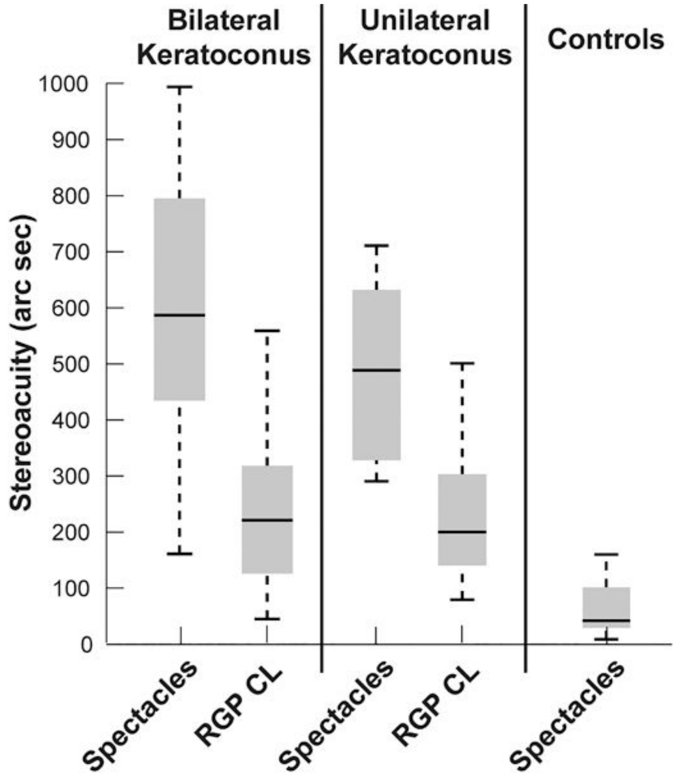

Figure 2.

Box and Whisker plots showing the spread of binocular random-dot stereoacuities of subjects with bilateral (left) and unilateral (middle) keratoconus corrected with spectacles and with RGP contact lenses. Best-corrected stereoacuity from controls is also included in this figure (right). All other details of the Box and Whisker plots are the same Figure 1.

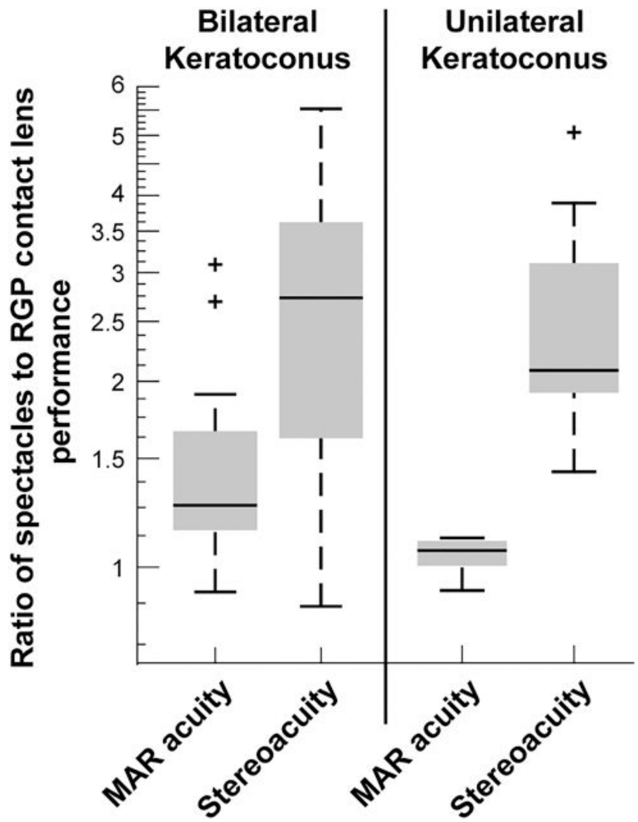

Figure 3.

Ratio of binocular high-contrast visual acuity and binocular stereoacuity with best-corrected spectacles to that with best-corrected RGP contact lens in subjects with bilateral (left panel) and unilateral (right panel) keratoconus. All other details of the Box and Whisker plots are the same as Figure 1. A ratio of unity indicates that visual acuity and stereoacuity of these subjects were the same with both corrections, while a ratio greater than unity indicates that visual acuity and stereoacuity was better with RGP contact lenses than with spectacles.

Table 1

Demographic and refractive outcome measure details of subjects with keratoconus and controls that participated in the study. RE and LE indicates right eye and left eye, respectively, of controls or of subjects with bilateral keratoconus. AE and FE indicate affected eye and fellow eye, respectively, of subjects with unilateral keratoconus. M, J0 and J45 represent power vector notations of spherical equivalent refraction, astigmatism with a cross-cylinder axis at 180° and astigmatism with a cross-cylinder axis at 45°, respectively.[31] The uncorrected subjective refraction values were used as the spectacle correction for all subjects in this study. The subjective refraction values over the best-corrected RGP contact lens were introduced as trial lenses to correct the subject's residual refractive error over the RGP contact lenses.

	Bilateral keratoconus	Unilateral keratoconus	Controls	p-value
Subjects (n)	30	10	20	–
Age (years)	19.0 (18.0 – 22.0)	20.0 (18.0 – 24.0)	20.5 (20.0 – 21.0)	0.14
Male: Female	17 : 13	7 : 3	7 : 13	–
Corneal power	RE: 52.2 (47.2 – 53.7)	AE: 50.1 (47.4 – 52.1)	–	0.41
(D)	LE: 49.5 (46.9 – 52.9)	FE: 44.9 (43.8 – 45.4)	–	0.002
IPD (cm)	6.0 (5.8 – 6.2)	6.0 (5.8 – 6.2)	6.0 (5.7 – 6.2)	0.93
Uncorrected objective refraction				
M (D)	RE: −5.50 (−7.50 – −3.25)	AE: −3.00 (−3.50 – −1.50)	RE: −0.25 (−1.19 – 0.25)	<0.001
	LE: −4.75 (−6.75 – −3.25)	FE: −2.62 (−3.25 – −0.50)	LE: −0.25 (−1.25 – 0.00)	<0.001
J0 (D)	RE: 1.80 (0.75 – 2.35)	AE: 0.56 (0.47 – 1.88)	RE: 0.00 (−0.21 – 0.35)	<0.001
	LE: 1.20 (0.23 – 1.91)	FE: 0.24 (0.19 – 0.60)	LE: 0.00 (−0.25 – 0.22)	0.55
J45 (D)	RE: 1.53 (0.85 – 1.97)	AE: 0.33 (0.00 – 1.08)	RE: 0.00 (−0.16 – 0.11)	0.08
	LE: −1.18 (−1.77 – −0.43)	FE: −0.30 (−1.48 – 0.09)	LE: 0.00 (−0.26 – 0.16)	0.93
Uncorrected subjective refraction				
M (D)	RE: −4.00 (−6.88 – −2.81)	AE: −4.13 (−4.50 – −3.00)	RE: −0.13 (−0.56 – 0.00)	<0.001
	LE: −4.38 (−6.25 – −3.25)	FE: −0.63 (−2.38 – −0.09)	LE: 0.00 (−0.47 – 0.00)	<0.001
J0 (D)	RE: 0.70 (0.28 – 1.79)	AE: 0.83 (−0.19 – 1.43)	RE: 0.00 (0.00 – 0.14)	0.003
	LE: 0.16 (−0.49 – 1.49)	FE: 0.21 (0.01 – 0.44)	LE: 0.00 (0.00 – 0.15)	<0.001
J45 (D)	RE: 1.42 (0.55 – 2.34)	AE: −0.12 (−1.55 – 0.39)	RE: 0.00 (0.00 – 0.00)	0.008
	LE: −1.19 (−1.93 – −0.38)	FE: 0.11 (0.00 – 0.25)	LE: 0.00 (0.00 – 0.00)	0.59
Objective refraction over the best-corrected RGP contact lens				
M (D)	RE: 0.25 (−0.25 – 1.25)	AE: −0.37 (−1.25 – 0.13)	–	0.04
	LE: 0.50 (−0.25 – 1.00)	FE: −0.50 (−1.50 – 0.13)		0.01
J0 (D)	RE: 0.00 (−0.25– 0.25)	AE: 0.22 (−0.19 – 0.50)	–	0.08
	LE: −0.12 (−0.29 – 0.00)	FE: −0.12 (−0.47 – 0.23)		0.02
J45 (D)	RE: 0.00 (−0.41 – 0.17)	AE: 0.14 (0.00 – 0.34)	–	0.10
	LE: 0.00 (−0.16 – 0.16)	FE: 0.00 (−0.17 – 0.11)		0.01
Subjective refraction over the best-corrected RGP contact lens				
M (D)	RE: 0.00 (−0.19 – 1.19)	AE: −0.25 (−0.59 – 0.47)	–	0.27
	LE: 0.38 (0.00 – 1.19)	FE: −0.63 (−2.38 – −0.09)		0.08

	Bilateral keratoconus	Unilateral keratoconus	Controls	p-value
J0 (D)	RE: 0.00 (−0.14 – 0.00)	AE: 0.00 (−0.35 – 0.00)	–	0.76
	LE: 0.00 (0.00 – 0.00)	FE: 0.21 (0.01 – 0.44)		0.52
J45 (D)	RE: 0.00 (0.00 – 0.00)	AE: 0.00 (0.00 – 0.00)	–	0.34
	LE: 0.00 (0.00 – 0.00)	FE: 0.11 (0.00 – 0.25)		0.42

Table 2

Median (25th – 75th IQR) logMAR acuity and stereo acuity of subjects with bilateral and unilateral keratoconus under unaided viewing conditions and when corrected with spectacles and RGP contact lenses and that of controls under the best-corrected conditions. For the unilateral keratoconus cohort, numbers in the column labeled "Right eye" represent data from the affected eye and those in the column labeled "Left eye" represent data from the fellow unaffected eye.

	Right eye	Left eye	Binocular	Interocular difference
Bilateral keratoconus				
logMAR– Unaided	0.57 (0.40 - 1.06)	0.63 (0.40 – 0.90)	0.43 (0.30 – 0.68)	0.33 (0.20 – 0.48)
logMAR – Spectacles	0.34 (0.10 – 0.52)	0.23 (0.08 – 0.34)	0.12 (0.03 – 0.24)	0.24 (0.08 – 0.42)
logMAR – RGP contact lens	0.04 (0.00 – 0.12)	0.00 (−0.03 – 0.08)	0.00 (−0.04 – 0.07)	0.07 (0.02 – 0.12)
Stereo – Unaided (arc min)	–	–	immeasurable	–
Stereo – Spectacles (arc min)	–	–	587.0 (434.5 – 795.0)	–
Stereo – RGP contact lens (arc min)	–	–	221.4 (126.0 – 318.3)	–
Unilateral keratoconus				
logMAR– Unaided	0.52 (0.33 – 0.80)	0.04 (0.02 – 0.36)	0.02 (0.00 – 0.23)	0.29 (0.20 – 0.44)
logMAR – Spectacles	0.20 (0.09 – 0.44)	−0.06 (−0.12 – 0.01)	−0.07 (−0.10 – 0.00)	0.25 (0.14 – 0.46)
logMAR – RGP contact lens	0.04 (0.01 – 0.10)	–	−0.07 (−0.10 – −0.04)	0.08 (0.06 – 0.12)
Stereo – Unaided (arc min)	–	–	immeasurable	–
Stereo – Spectacles (arc min)	–	–	446.8 (307.6 – 623.6)	–
Stereo – RGP contact lens (arc min)	–	–	187.8 (124.0 – 223.0)	–
Controls				
logMAR– Best corrected	−0.09 (−0.14 – −0.06)	−0.10 (−0.18 – −0.09)	−0.13 (−0.18 – −0.09)	0.04 (0.02 – 0.08)
Stereo –Best corrected (arc min)	–	–	42.15 (29.5 – 101.3)	–

Author Manuscript

Author Manuscript

Author Manuscript

Table 3

Spearman's correlation coefficients indicating relationships between binocular and monocular logMAR acuities under spectacle and contact lens corrected condition for bilateral and unilateral keratoconus.

	Bilateral Keratoconus	Unilateral Keratoconus
Worse eye acuity vs. Binocular acuity		
Spectacle corrected condition	0.46	0.18
Contact lens corrected condition	0.53	−0.34
Better eye acuity vs. Binocular acuity		
Spectacle corrected condition	0.92	0.66
Contact lens corrected condition	0.71	0.82