Ophthal. Physiol. Opt. 2009 **29:** 1–9

Customized hydrogel contact lenses for keratoconus incorporating correction for vertical coma aberration

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Abstract

Purpose: To study the effects on visual performance of a novel custom hydrogel contact lens, which employs a correction for vertical coma aberration, in keratoconic eyes.

Methods: Six subjects (8 eyes) with mild or moderate keratoconus were recruited for the study. Preliminary measurements included corneal topography, wavefront aberrometry, subjective refraction, visual acuity (VA) and 50% contrast VA. Based on the aberrometry data, customized lenses were made and fitted to the subjects. Evaluation of the on-eye performance of the lenses was carried out, including wavefront aberrometry, over-refraction, VA and 50% contrast VA. In two of the subjects, both eyes were fitted with the customized lenses, and binocular performance was evaluated.

Results: Monocular visual performance with a 4 mm pupil, with the lenses worn was improved, and reached the mean values of −0.003 (LogMar units) of 100% high contrast VA, and 0.049 (in LogMar units) of 50% contrast VA. Vertical coma aberration and total higher-order aberrations (HOAs) were reduced (naked eyes: -0.64 ± 0.21 root mean square (rms) of vertical coma and 0.86 ± 0.15 rms of total HOAs; with the lenses worn: -0.29 ± 0.23 rms of vertical coma and 0.57 ± 0.17 rms of total HOAs, all for a 4 mm pupil). Binocular VA results from two of the subjects were on average −0.040 (LogMar units) 100% high contrast acuity and −0.060 (LogMar units) 50% contrast visual acuity.

Conclusions: Customized hydrogel contact lenses implementing correction of vertical coma, have been found to improve both monocular and binocular visual performance of eyes affected with mild or moderate keratoconus.

Keywords: customized contact lenses, keratoconic hydrogel lenses, keratoconus, vertical coma aberration

Introduction

Keratoconus is a progressive, non-inflammatory degeneration of the cornea, which is characterized by thinning and ectasia (outward bulging) (Yanoff and Duker, 2003). It belongs to a family of diseases which also includes pellucid marginal degeneration (PMD) and keratoglobus. Many genetic and biochemical mechanisms for the development of keratoconus have been proposed, a fact that suggests that keratoconus might be an expression of variable underlying pathologies, and not a single clinical entity (Rabinowitz, 1998).

Keratoconus is usually bilateral, but unilateral forms might exist, although the healthy eyes have also progressed to keratoconus over time (Li *et al*., 2004) or after refractive surgery (Reznik *et al*., 2008), a fact that implies that keratoconus leads to structural weakening of both corneas, even in the subclinical forms. The stage of the disease may also differ between the eyes, and the progression might also show great variability. The development of corneal topography, slit-scanning methods, Scheimpflug imaging and wavefront aberrometry,

Received: 27 October 2008
Revised form: 14 January 2009
Accepted: 17 January 2009

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 doi: 10.1111/j.1475-1313.2009.00645.x

has given new insight into the disease, and revealed many cases of mild or subclinical keratoconus (Maguire 3 and Bourne, 1989 and Wilson *et al*., 1991). In the latter, the ectasia is so mild that it cannot be detected by topography, and imaging of the posterior corneal surface is necessary in order to arrive at a definite diagnosis. In cases of subclinical keratoconus, the anterior ectasia is so mild that it is smoothed out by the six-layer epithelium. However, the endothelium consists only of one layer, and thus it cannot mask the posterior ectasia, which can then be detected by modern 4 instrumentation (Gobbe and Guillon, 2005).

The progression of keratoconus leads to excessive amounts of myopia and irregular astigmatism. However, vision in the keratoconic eye, is not only impaired by low-order sphero-cylindrical errors, but also by high-order aberrations (HOAs), due to the irregularity of the cornea. Aberrometry studies in keratoconus have shown that these eyes exhibit a large amount of such aberrations, and that the dominant one is vertical coma, which in these eyes has a negative sign (Maeda *et al*., 2002; Shah *et al*., 2003; Kosaki *et al*., 2007; Pantanelli *et al*., 2007).

In the early stages of keratoconus, or in the subclinical form, vision is good or satisfactory with spectacles. However, as the disease progresses and the ectasia becomes more prominent, spectacle lenses cannot provide good vision anymore, as they cannot correct HOAs, whose magnitude increases in respect to low-order aberrations (defocus-sphere and astigmatism). As keratoconus enters the moderate or advanced stage, current contact lens options include rigid gas-permeable (RGP) lenses; keratoconic hydrogel lenses (spherical or toric); and scleral and hybrid lenses (Woodward and 5 Rubistein, 2007). RGPs are considered the standard for fitting keratoconic eyes and irregular eyes in general, as the tear lens that is formed between the posterior lens surface and the cornea optically neutralizes the anterior cornea, and drastically reduces aberrations arising from that surface (Hong *et al*., 2001). The same advantages apply for hybrid and scleral lenses, but the latter are much more difficult to fit, and require considerable expertise from the practitioner. Hydrogel lenses, on the other hand, are of increased thickness compared to conventional designs, and depend on this thickness to mask corneal aberrations, as a thinner lens would conform on the distorted cornea and mimic its shape. Hence, hydrogel keratoconic lenses can partially but not fully correct HOAs arising from the anterior corneal surface.

As anterior corneal ectasia is accompanied by posterior ectasia in keratoconus, the posterior surface is a source of positive vertical coma, which has been shown to partly neutralize the negative coma from the anterior corneal surface. In a recent study (Chen and Yoon, 6 2008), posterior positive vertical coma was found to compensate for 22%, 24% and 14% of anterior negative vertical coma, in advanced, moderate and mild keratoconic cases respectively. The authors hypothesized that when RGP lenses are worn, anterior corneal aberrations from this surface are almost extinguished, and posterior corneal aberrations are revealed. This could explain the results reported by other authors (Marsack *et al*., 7 2007a,b; Negishi *et al*., 2007), who found that HO aberrations during RGP wear in keratoconus, are still higher than those in normal eyes.

Comfort issues are also a concern regarding contact lens fitting in keratoconic eyes. There is a belief in the clinical community that RGPs are not as comfortable as hydrogel lenses, although arguably an optimal fit can drastically reduce lens sensation. The issue here is that, in a keratoconic eye, the ideal fit might never be achieved, due to the deformation of the cornea, and the practitioner may have to settle with a compromise fit, which will lead to increased corneal and lid sensitivity (Betts *et al*., 2002; Edrington *et al*. 2004). Additionally, hydrogel keratoconic lenses are thicker that their conventional counterparts (Zhou *et al*., 2003), and thus comfort decreases, compared to standard hydrogels. Oxygen transmissibility is also an issue, as given the same lens material the lens will transmit less oxygen as it becomes thicker. This may result long term in corneal edema, reduced sensation, and contact lens intolerance (Holden *et al*., 1983). Newer silicon hydrogel materials may provide a solution to this, as they have increased permeability to oxygen (Fonn *et al*., 2002).

In keratoconic patients a peculiar situation occurs. Such patients tend to overwear their lenses, as they are dependent on them despite comfort issues. In other words, they wear their lenses far beyond the point that other wearers might consider intolerable. This may lead (besides discomfort) to irritation, ptosis of the upper eyelid, epithelial defects; or even corneal ulcers, if side effects are not managed appropriately.

It may be concluded, that in order to achieve the maximum in visual performance and comfort, a new type of lens should be introduced that combines the advantages of both worlds. These lenses are hydrogels of regular thickness, with high-order aberration (HOA) correction. The simulated performance of such lenses has been demonstrated, and it has been shown that they can provide a visual benefit to the wearer, if fitted within the standard tolerance limits of hydrogel toric lenses (De Brabander *et al*., 2003). The HOA correction can be implemented either in the anterior or in the posterior 8 lens surface. In one study, (Marshack *et al*. 2000) one lens with anterior HOA correction was fitted in a keratoconic eye, and it was found that it improved both high- and low-contrast vision. In another study (Sabesan *et al*., 2007), a series of anterior surface

HOA-correcting lenses were fitted in a series of keratoconic eyes, and the authors concluded that these lenses reduced HOAs by an average factor of 3, and yielded an improvement in acuity of about two lines, compared to standard sphero-cylindrical hydrogels. In a subsequent [9] study (Chen *et al.*, 2007a,b), a series of posterior surface customized lenses, were fitted in keratoconic eyes, and it was found that rotation and decentration were improved compared with standard hydrogels, but aberrations from the internal optics of the eyes were revealed. In a even more recent study (Marsack *et al.*, 2008), the vision of three keratoconic subjects wearing wavefront customized hydrogel lenses, was compared with the vision with their habitual RGP lenses, in terms of high-contrast VA and residual HOAs. The authors found out that vision with the novel wavefront hydrogel lenses compared favorably with the RGPs in both terms.

As the dominant aberration in keratoconic eyes is vertical coma, it can be assumed that a hydrogel lens which includes correction of vertical coma in the anterior surface, may provide significant visual benefit, if coupled with the appropriate sphero-cylindrical component. As the vertical coma in keratoconic eyes is negative, the vertical coma in the hydrogel lens should be positive. In other words, assuming a toric lens with prism stabilization and positive vertical coma,then in order to implement the coma the thicker part of the optical zone (OZ) of the lens should be the upper one, and the thinnest part should be the lower one (the one containing the prism on the edge). Such lenses are expected to improve the vision in keratoconic eyes, compared with spherical or toric keratoconic lenses. Moreover, they are much easier to manufacture and test than wavefront-customized hydrogel lenses, which employ full HOA correction.

In this study, we designed, manufactured and fitted a series of customized coma-implementing hydrogel keratoconic lenses. Our aim was to test the hypothesis that such lenses can sufficiently correct vision to provide a visual benefit to the keratoconic patient.

Materials and methods

Six keratoconic patients were recruited for this study. All of the patients were informed about the nature and the possible consequences of the study, according to the tenets of the Declaration of Helsinki, and signed an informed consent form. All of the eyes were affected with moderate keratoconus, except eyes 5 and 8, which were affected with mild keratoconus. In four of the patients, one eye was fitted with a coma-correcting hydrogel lens, and two of the patients were fitted in both their eyes (total: eight eyes). The patients were recruited from a contact lens practice. Eligibility criteria included mild to moderate paracentral keratoconus, whereas exclusion criteria were central keratoconus, severe paracentral keratoconus, corneal scarring, corneal opacities, and any other co-existing ocular pathology.

The protocol was as follows: corneal topography was performed with each of the subjects, to verify the presence and stage of keratoconus. Then monocular unaided visual acuity (UVA) was taken as a reference. Subjective refraction followed, along with best spectacle corrected visual acuity (BSCVA). Monocular low contrast (50%) VA was also taken, with the best spectacle correction in place. In two of the subjects, in whom it was planned to fit both their eyes with the custom lenses, binocular measurements of the above were added.

Three consecutive wavefront aberrometry measurements were taken and averaged on each of the eyes, with the complete ophthalmic analysis system (COAS) Wavefront Analyzer (WaveFront Sciences, Albuquerque, NM, USA), which operates on the Scheiner–Hartmann–Shack principle (Liang *et al.*, 1994; Thibos [10] and Xin, 1999; Thibos, 2000) and whose effectivity in clinical use is documented (Pesudovs *et al.*, 2007). The analysis was up to the sixth order, for a 4 mm pupil, and the completeness of the spot pattern was verified in each of the measurements, to ensure that there were no missing points due to the keratoconus. A 4 mm pupil size analysis was chosen, as this diameter is more representative of the subject's everyday vision, than the (dilated) 6 mm diameter usually reported in the literature.

Based on the aberrometry measurements, a coma-correcting hydrogel contact lens was made. The sphero-cylindrical component was chosen based on the defocus and astigmatism of aberrometry, and the amount of positive coma was chosen also on the basis of the aberrometric results. The positive vertical coma implemented, was chosen to be about 75% of the negative vertical coma measured from aberrometry. The fit was based on trial fitting, with toric lenses of similar geometrical characteristics.

A CNC lathe (Optheq; Contamac, Saffron Walden, Essex, UK) and the accompanying software (Calculens v2.7; Contamac, UK) were modified in order to design and produce non-rotationally symmetrical surfaces, such as comatic ones. All of the lenses manufactured were made from GM3 material from Contamac, UK (49% water content, 15.9 Dk), and had an optical zone (OZ) of 6 mm in order to cover the subject's pupil in all instances, a total diameter of 14.5 mm, 0.12 mm central thickness and a prismodynamic stabilization modality. The lenses were verified with a Rotlex Contest plus instrument, which operates on the principle of Moiré [11] deflectometry (Kafri and Glatt, 1982) and with a Clearwave Contact Lens Precision Aberrometer (WaveFront Sciences), which operates on the Scheiner–Hartmann–Shack principle.

After the manufacture, hydration, verification, and sterilization of the lenses, they were fitted on the subjects. The quality of the fit was ensured with the push-up test and the slit lamp. As the lenses had a toric and a comatic component, it was also ensured that the rotation did not exceed 5°. Then, aberrometry was performed with the COAS in order to measure the residual low and high order errors. The position of the OZ of the lens in respect to the pupil was also verified in this stage. As we did not want the pupil to become larger than, or fall outside of, the OZ of the lenses, since this would have resulted in possible data contamination from data points lying out of the OZ, the lighting in the examination room was manipulated. The target was a pupil positioned consistently inside the lens' OZ during the measurements, and also at least 4 mm in diameter.

Three consecutive measurements with the COAS were again taken and averaged, as the lenses were worn. Analysis was again at a pupil size of 4 mm, and Zernike analysis was up to the sixth order. Then subjective over-refraction was performed. BCVA and 50% contrast visual acuity were taken with an overcorrection, if this yielded an improvement, or without the overcorrection if it did not. Finally, the results with the lenses being worn were compared with the results without the lenses or those with the best spectacle correction. Notation of spherical aberration (SA) and coma is according to the ANSI standards.

Results

Figure 1 depicts the results of vertical coma aberration of the naked eyes compared with that of the same eyes with the coma-implementing lenses, whereas *Figure 2* shows the results for total HO aberrations in a 4 mm pupil. It can be seen that both vertical coma aberration and total HO aberrations were reduced (means and standard deviations, naked eyes: −0.64 ± 0.21 μm rms of vertical coma and 0.86 ± 0.15 μm rms of total HOAs, with the lenses worn: −0.29 ± 0.23 μm rms of v.coma and 0.57 ± 0.17 μm rms of total HOAs). In two instances (eyes 5 and 6) vertical coma was overcorrected, in the sense that it changed from negative to positive.

In *Figure 3*, a double COAS map is shown, which depicts the wave aberrations of the left eye of patient 1, without any correction worn, whereas in *Figure 4* a double COAS map of the same eye of the same patient is shown, with the coma-correcting contact lens worn.

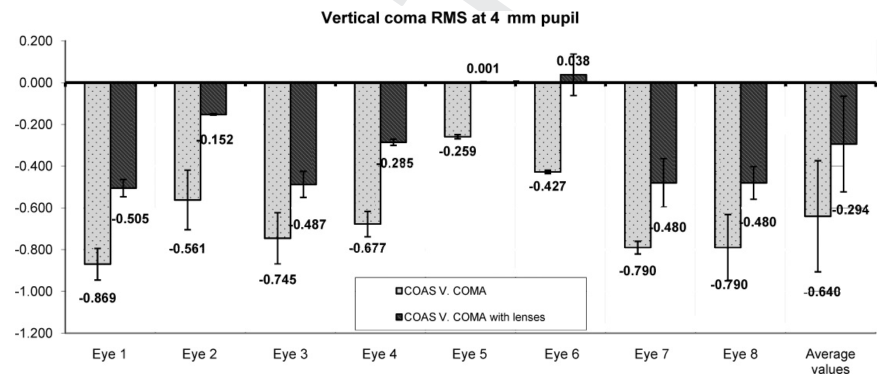


Figure 1. COAS measurements of the vertical coma aberrations without and with the custom contact lenses in place for a 4 mm pupil. Bars represent mean values, error bars represent standard deviation. The units are microns.

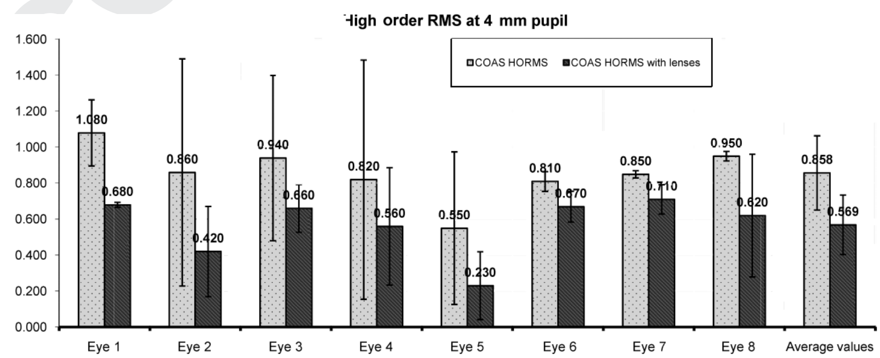
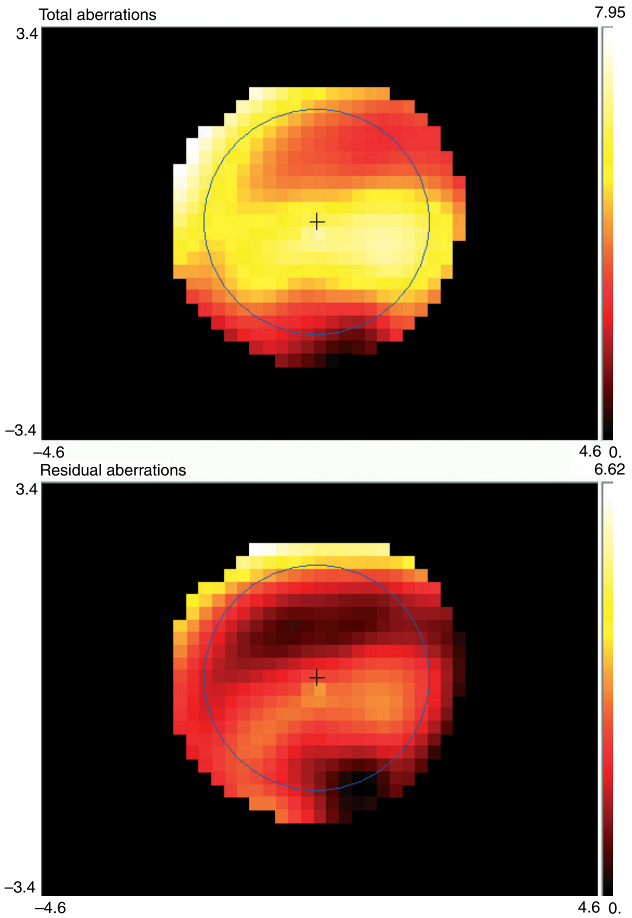
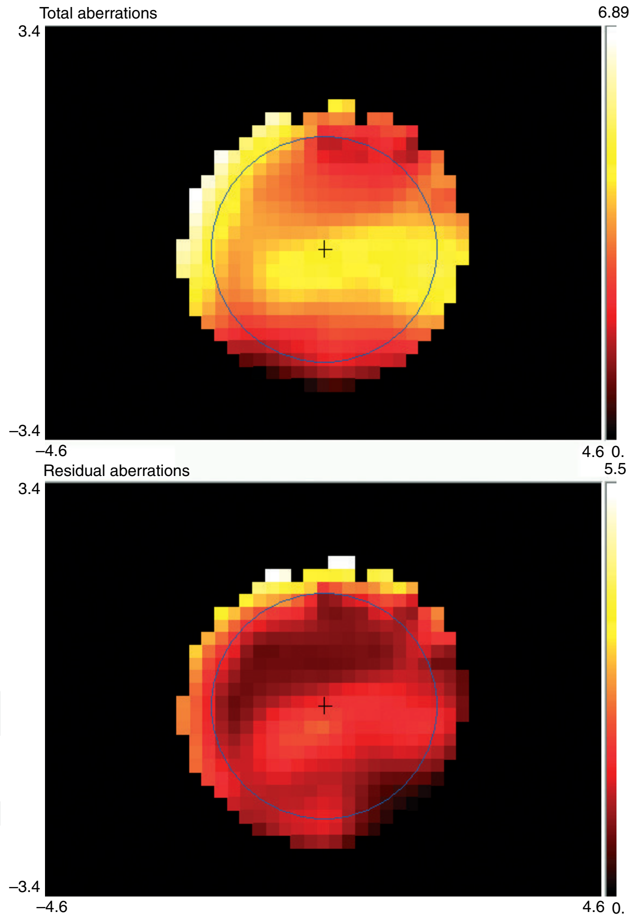


Figure 2. COAS measurements of the total high order root mean square (HO RMS) aberrations up to the sixth order, for a 4 mm pupil, without and with the custom contact lenses in place. Bars represent mean values, error bars represent standard deviation. The units are microns.

LOW RESOLUTION COLOUR FIG



16 **Figure 3.** COAS maps of the aberrations of the left eye of patient 1 without any correction worn (naked eye). The upper map is the total aberrations map, the lower map is the high order (HO) aberrations map.



17 **Figure 4.** COAS maps of the aberrations of the left eye of patient 1 with the customized lenses worn. The upper map is the total aberrations map, the lower map is the high order (HO) aberrations map.

LOW RESOLUTION COLOUR FIG

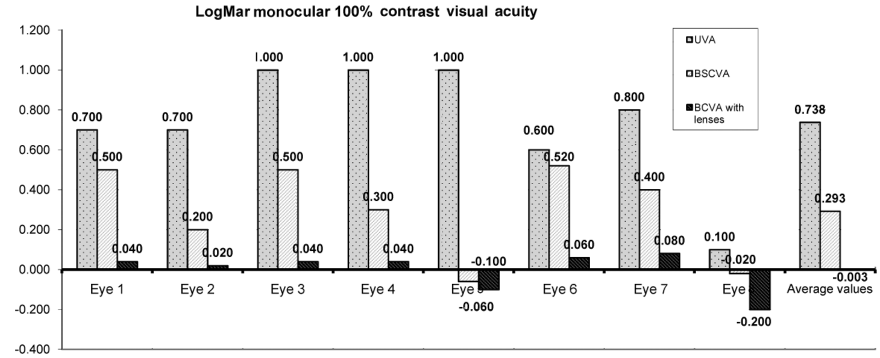
Figure 5 shows the results concerning monocular acuity in LogMar units, and in *Figure 6* the results of monocular low-contrast 50% VA in LogMar units can be seen. The results concerning 100% high contrast VA are impressive, as all of the eyes reached logMAR acuities of 0.080 or better with the custom lenses, and two of them achieved acuities of 0.0 or better. Specifically, eyes 5 and 8, which were affected with mild keratoconus, and already had good spectacle vision, reached acuities of −0.060 and −0.200 respectively, with the custom hydrogel contact lenses. Equally impressive are the results from the monocular 50% contrast VA, as all of the eyes reached values of 0.150 LogMAR or better. Eyes 5 and 8 in particular, which had already good 50% contrast VA with the spectacle correction, reached values of −0.060 and 0.00 respectively with the custom contact lenses. Total monocular average results were −0.003 of LogMar high contrast visual acuity, and 0.049 LogMar 50% contrast visual acuity.

In table 1 the binocular LogMar 100% contrast VA and the binocular LogMar 50% contrast VA results of subject 1 (eyes 1 and 2) and subject 2 (eyes 3 and 4) can be seen. As expected, binocular visual performance is better than the monocular one in both high and low contrast VA for both subjects, who had average LogMar 100% high contrast acuities of −0.040, and 50% contrast VA was on average −0.060, when the custom lenses were worn.

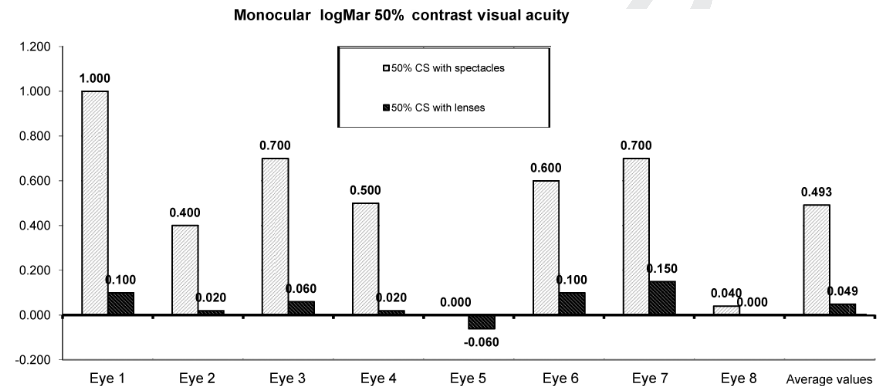
Due to the small sample size, and the relatively small number of measurements of each eye, the Wilcoxon rank sum test was performed on the vertical coma measurements, without and with the coma correcting lenses. The test derived a *p*-value of $0.005 > p > 0.001$, which indicates that there is a statistically significant difference between the coma values of the naked eyes and the coma value of the eyes plus lenses combination, and the lenses were effective in reducing vertical coma.

Discussion

We have demonstrated that customized, vertical coma-implementing, hydrogel lenses, combined with the



18 **Figure 5.** Monocular LogMar 100% high contrast visual acuity. Unaided visual acuity (UVA) is plotted in addition to best spectacle corrected visual acuity (BSCVA), and best corrected visual acuity (BCVA) with the custom contact lenses.



19 **Figure 6.** Monocular LogMar 50% contrast visual acuity. Best spectacle corrected visual acuity (BSCVA) is plotted together with best corrected visual acuity (BCVA) with the custom lenses.

appropriate spherocylindrical correction, can be used for the correction of vision in keratoconic eyes. Our results are very encouraging, and demonstrate that such lenses can restore normal vision, in mild and moderate cases of keratoconus.

In all of the eyes that were included in this study, the improvement in visual performance, compared to unaided vision or to spectacle correction, was remarkable, and reached levels that were previously attainable only with RGP lenses. These results show that vertical coma-implementing customized lenses can be a viable alternative to conventional hydrogel keratoconic or RGP lenses for the correction of keratoconus, combining the best from both worlds and avoiding many disadvantages of both.

In particular, the Wilcoxon rank sum test, which is a non-parametric test applicable to small sample sizes, showed that there is a trend for the lens plus eye combination, to have less vertical coma aberration than the naked eye alone. The value of $0.005 > p > 0.001$, although statistically significant, indicates however that a bigger sample size is more appropriate. A future possible modification of this study could be the separation of the patient group into mild, moderate and severe keratoconus, and the study of the effects of the coma-correcting lenses in each of these groups, instead of grouping them all together.

Previous research has demonstrated, both theoretically and in a clinical setting (De Brabander *et al.*, 2003; Chen *et al.*, 2007a,b; Marsack *et al.*, 2007a,b; Sabesan *et al.*, 2007), the feasibility of a custom-wavefront hydrogel CL correction in abnormal eyes, and also investigated the required extent (in Zernike orders) of such a correction (Marsack *et al.*, 2006). As mentioned above, such eyes present with large amounts of HOAs, mainly coma (if the conus is located paracentrally) and spherical aberration (in cases of central keratoconus). RGPs, hybrids and scleral lenses, have previously been considered to be the best correction modalities for such patients. However, recent studies have demonstrated that when anterior corneal aberrations are neutralized with the RGP lens, posterior corneal aberrations are revealed. This could explain the phenomenon of reduced visual performance of RGP wearing keratoconic eyes, compared to normal ones, even when the former are best corrected with such lenses (Marsack *et al.*, 2007a,b; Negishi *et al.*, 2007).

On the other hand, customized hydrogels contact lenses may avoid such pitfalls, as they can be designed to compensate for the majority of total ocular aberrations, external and internal. The recent study by Marsack *et al.* (2008), indicated for the first time that wavefront customized hydrogel lenses may compare and even surpass RGP lenses in terms of visual performance, at least in terms of high contrast VA and residual HOAs. These results indicate that customized lenses provide a feasible method for correcting the vision in keratoconic eyes, in levels previously unattainable even with RGPs. A slightly alternative approach in the case of keratoconus and corneal ectasias, is to implement an amount of positive vertical coma in order to correct the total ocular negative vertical coma present in such eyes, as this study has demonstrated. This concept can be further enhanced by adding more Zernike aberration components to the custom lenses, if deemed appropriate. For example, as most paracentral conuses are located not only inferiorly, but also temporally or nasally, the custom hydrogel lenses may additionally incorporate a correction for horizontal coma. Moreover, in cases of central keratoconus, where there are extreme values of corneal eccentricities, the custom lens may additionally implement correction for spherical aberration.

It is well known that, once fitted properly, a hydrogel CL conforms to the corneal surface, in a manner which depends on the corneal topography, the geometry and the design of the lens, the material of the lens and the interaction with the tears. In a study (Jiang *et al.*, 2006), it was found that different types of hydrogel CLs alter the wavefront profile of the eye in a manner that differed considerably from one lens type to another. They hypothesized that this can be attributed to the optical quality and the design of the lenses, the lens centration, the tear film quality and the level of deformation of the lenses on the cornea. In another study, (Lu *et al.*, 2003), it was discovered that hydrogel CLs had a trend in inducing HO aberrations when worn. However, more research is essential in order to investigate the alteration in the shape of the customized contact lens surfaces, anterior or posterior, when worn on the eye, as they do not have uniform thickness and any deformation will affect visual performance. Variable patterns of deformation, combined with decentration and rotation, may explain the fact that the lenses deviated from the intended correction of 75% of vertical coma. However, another error source might be the limitations of the Scheiner–Hartmann–Shack sensor, which will be discussed later on.

Regarding rotation and/or decentration, it was purposely decided not to include calculations of Zernike coefficient transformations based on lens rotation and translation, as we wanted to test the hypothesis, that customized dispensing can be performed without the tedious measurements and mathematical procedure associated with the above. However, we did ensure that the fitting was at least clinically acceptable, which means that the lens was well centred, and did not rotate more than 5° or decentre by more than 1 mm on blink. De Brabander *et al.* (2003) have demonstrated through simulations, that these criteria are more than acceptable for obtaining a benefit from a wavefront correction. Our results, and especially horizontal coma measurements (*Figure 3*), without and with the lens worn, reveal that there was decentration of the lens in respect to the eye's optical axis, but this decentration was not enough in order to preclude normal vision. As it is shown in *Figure 3*, horizontal coma did not change sign in the eye-lens combination, in respect to the naked eye only, and thus it can be concluded that that horizontal decentration was minimal, besides the variability between the subjects. We believe that these results support the hypothesis made by De Brabander *et al.* (2003).

Supposing that a lens that would eliminate all ocular third-order coma if properly centered could be manufactured, decentration will induce secondary (fifth order) coma, whereas rotation will leave residual coma, its magnitude depending on the rotation of the correction and the order of the aberration (Guirao *et al.*, 2001). In this study, a computational method for estimating the correction was derived, by taking into account translation and rotation. However, in another study which utilized an adaptive optics (AO) system (Guirao *et al.*, 2002), it was found that the lens rotation and decentration normally found in practice (and which are clinically acceptable), still produce better visual results compared to conventional, non-wavefront customized contact lenses. The same results were found in another theoretical study by the same authors, which employed computations of the performance of an ideal wavefront CL after decentrations and rotations (Guirao *et al.*, 2000). Based on our work and the studies described above, the authors believe that customized CL dispensing can be performed in the standard clinical practice, employing the current standards of a good clinical fit, without the steps of measuring the lens position and rotation and recalculation of the coefficients, especially if only one HO Zernike coefficient is used, such as vertical coma in our case.

The validity of the COAS' measurements in abnormal eyes was another issue that was encountered in this study. The wavefront measurements made by the COAS in these keratoconic eyes, and especially the measurements of sphere, cylinder, vertical coma and total HO aberrations, were highly variable (as indicated by the large standard deviation). Moreover, the significant residual spherocylindrical refractive error, measured by the COAS with the lenses worn, was neither reflected nor verified in the subjective over-refraction, which in most of the cases revealed minor spherical error in order to maximize BCVA. We believe that this can be attributed to the inherent inability of the Scheiner–

Hartmann–Shack wavefront sensors to measure highly aberrated eyes, and especially keratoconic ones. In such eyes, coma results in a shift of the position of the spots collected by the sensor, and might result in crossing of the spots, and hence in invalidated measurements. It can be concluded that aberrometers based on the Scheiner–Hartmann–Shack principle are not appropriate for measuring eyes with large amounts of coma, and alternative techniques, such as large dynamic range Scheiner–Hartmann–Shack sensors, or ray tracing methods should be employed.

The perceptual ability of each individual should be taken into account when designing a customized correction. When a person reads a visual acuity chart, he translates the point-spread function (PSF) at the retina (formed by the eye's optics) into familiar words or numbers. This PSF is unique to each individual, and its basic shape remains basically unchanged through age. There are two possibilities when correcting most of the eye's HO aberrations. The first is to reduce the total RMS error (as measured by the aberrometer) and increase the Strehl ratio, but at the same alter the shape and/or direction of the PSF on the subject's retina. For example, one could slightly overcorrect a large amount of coma and change its sign from positive to negative or vice versa, and at the same time the total RMS error could be less than the previous uncorrected state and the Strehl ratio increased. The second possibility is to reduce the RMS error and not alter the shape of the PSF. In the above example, this can be achieved by carefully avoiding overcorrection of coma. If this is achieved, the total RMS error is reduced; the Strehl ratio increased, and the shape and the direction of the PSF remain basically the same.

If by employing a custom wavefront correction the first scenario is realized, it is possible that the person will lose BCVA, despite seeing through better optics, as he is not accustomed to translating the new image shape in his retina. It has been discovered with the help of adaptive optics, that subjects had a sharper impression of a certain stimulus when they viewed it with their own aberrations, than with a rotated version of their aberration pattern (Artal *et al*., 2004). In a consequent study (Chen *et al*., 2007a,b) 57 it was found that the best subjective image quality did not coincide with the best possible retinal image quality, and neural adaptation occurred, although the 'intensity' or duration of this phenomenon was not investigated. In our study, the subjects with moderate keratoconus achieved reasonably good levels of visual performance, both in terms of VA and 50% contrast VA, despite the large residual aberrations, when compared to normal eyes. In our opinion, this implies that it might not be necessary to fully correct all HO aberrations in abnormal eyes. Reducing HO aberrations to a level where neural perception takes over, might be sufficient.

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