Vision improvement by correcting higher-order aberrations with customized soft contact lenses in keratoconic eyes

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Higher-order aberration correction in abnormal eyes can result in significant vision improvement, especially in eyes with abnormal corneas. Customized optics such as phase plates and customized contact lenses are one of the most practical, nonsurgical ways to correct these ocular higher-order aberrations. We demonstrate the feasibility of correcting higher-order aberrations and improving visual performance with customized soft contact lenses in keratoconic eyes while compensating for the static decentration and rotation of the lens. A reduction of higher-order aberrations by a factor of 3 on average was obtained in these eyes. The higher-order aberration correction resulted in an average improvement of 2.1 lines in visual acuity over the conventional correction of defocus and astigmatism alone.

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Higher-order aberrations (HOAs) have a significant impact on vision in normal and abnormal eyes.[1] Keratoconus is an abnormal corneal disorder that is diagnosed by the presence of a thinning of the central cornea and anterior protrusion of a conical cornea, leading to a decrease in vision quality due to HOA.[2] Eyes with abnormal corneal conditions such as corneal transplant and keratoconus have larger amplitudes of HOA than normal eyes,[2] which implies that the visual benefit of HOA correction will be correspondingly larger.[1,3] Optical and surgical methods, such as adaptive optics,[3,4] phase plate,[5] and customized laser refractive surgery,[6] have been proposed to compensate for HOA in such eyes to provide improvement in vision. Customized soft contact lenses with aspheric and asymmetric surface profiles were also shown to have potential in correcting HOA in abnormal eyes.[7] Such a scheme of correction in two keratoconic (KC) eyes has recently been described in Ref. 7. The lens was designed according to the aberration profile of the KC eye over a 5 mm pupil, and the reduction in HOA and improvement in vision were relatively small.[7] One possible explanation for the small average reduction in HOA could be the failure to account for the decentration and rotation of the contact lens on the eye. Static contact lens movements critically affect the correction performance of HOA, as the lens is not aligned to the center of the visual axis, especially in eyes with abnormal corneal surface profiles.[5,8] In this Letter, we proposed to minimize the effect of these two factors by the simultaneous measurement of HOA as well as decentration and rotation, with a trial lens on the eye. A customized lens was then designed taking into account the measured HOA, lens decentration, and rotation with the lens on the eye. This novel method for correcting HOA and improving visual acuity in KC eyes by use of customized soft contact lenses is demonstrated.

Aberrations of three KC eyes (SC and MB, advanced; MT, moderate) wearing conventional soft contact lenses were measured using a Shack–Hartmann wavefront sensor. Prism ballasted soft toric contact lenses with 45% water content hydrogel material were used to stabilize rotational orientation and manufactured using a double-lathe technique. All lenses had a spherical back vertex power equal to −1.50 D. Using a surgical marking pen, 10 black points were marked on the front surface of the lens throughout the periphery and used to determine its movements on the eye. The pupil of each subject's eye was dilated using 1% tropicamide ophthalmic solution. Three trial lenses, each with a different base curve (8.2, 8.4, and 8.6 mm) were tested on each KC eye, and the most stable lens on the cornea was se-

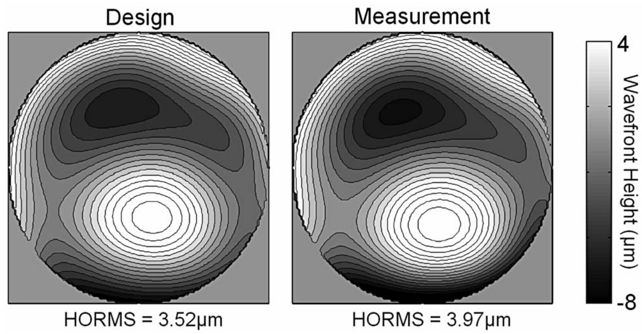

Fig. 1. Designed and measured (or manufactured) HOA with a wet-cell Shack–Hartmann wavefront sensor of a customized soft contact lens for subject MB for a 6 mm pupil. The interval between contour lines is 1 μm.

lected for the design of the customized contact lens. Shack–Hartmann spot patterns and pupil images were recorded simultaneously for approximately 1 min at 10 frames per second. This measurement session included 5–6 blinks. Once the lens position on the eye stabilized after each blink, the static x and y decentration and rotation with respect to the pupil center was evaluated from the pupil images. The position and rotation of the lens were measured by tracking the black markings on the lens surface using a cross-correlation algorithm. HOAs up to the 10th Zernike order over the maximum pupil size were measured. The lens surface profile was designed by recalculating the measured wavefront aberrations with respect to the decentered lens center.

A lathing machine (Model no. Precitech Optoform 50) with oscillating tool capability was used to sculpt the front surface of the lenses. This was followed by the typical steps of hydration and sterilization for soft contact lens manufacturing. A Shack–Hartmann wavefront sensor equipped with a wet cell was used to measure the wavefront aberrations of the customized lens to evaluate the precision of fabrication.[9] Residual HOA of the same three KC eyes for a 6 mm pupil wearing the customized contact lenses was subsequently measured. Visual acuity was measured using a tumbling letter E displayed on a computer projector (Sharp Model no. PG-M20X) at high (100%) and low (20%) contrast. The letter target was viewed through a 6 mm artificial pupil placed in a plane conjugate to the pupil of the eye.[3] A residual sphere (1.5 D) and cylinder (1.8 D) averaged over three KC eyes with customized contact lens were corrected by a Badal system and a phoropter in the letter acuity measurements, since refractive errors were not optimized in the design of the lens. A psychometric function based on 40 trials was derived, and visual acuity was determined as the line thickness of the letter for which at least 62.5% of responses were correct. The optical and visual performance of a prescribed rigid gas permeable (RGP) lens on an advanced KC eye (SC) was also evaluated in exactly the same manner to draw a comparison with the performance of the customized lens.

The average magnitude ± standard deviation of static x and y decentration and rotation with the conventional lens on the eye calculated from the three subjects was 369.3 ± 99.3 μm, 281.3 ± 78.9 μm, and 7.7 ± 13.3 deg, respectively. Large intersubject variability in stabilized lens positions indicates abnormal corneas with varying shape profiles among the three subjects. This lens movement was incorporated in the design and manufacturing process as mentioned before. Figure 1 shows the higher-order wavefront maps for the designed and the manufactured customized lens for subject MB. The higher-order root-mean-square (HORMS) wavefront error in the designed contact lens was 3.52 μm for a 6 mm pupil. Manufacturing error, defined as the HORMS difference between the designed and manufactured lens, was 0.77 μm. Figure 2 shows the optical performance of the HOA correction by the customized lens in comparison to the conventional lens for moderate (MT) and advanced (MB) KC subjects. Negative vertical coma, the most dominant HOA in KC eyes,[2] was the most effectively corrected aberration in both cases. Reduction of HORMS error from 3.28 μm with the conventional lens to 0.97 μm with the customized lens was observed for subject SC. The average ± standard deviation HORMS wavefront error for the three KC eyes with the conventional and the customized contact lenses was 2.75 ± 0.90 and 0.93 ± 0.19 μm, respectively. Poor correction of other aberrations such as trefoil led to a relatively larger residual HORMS wavefront error compared with normal eyes.[2] The high- and low-contrast visual acuity for the three subjects with the conventional and the customized contact lenses is shown in Fig. 3. The HOA correction resulted in improvement of both high- and low-contrast visual acuity by an average of 2.1 lines for

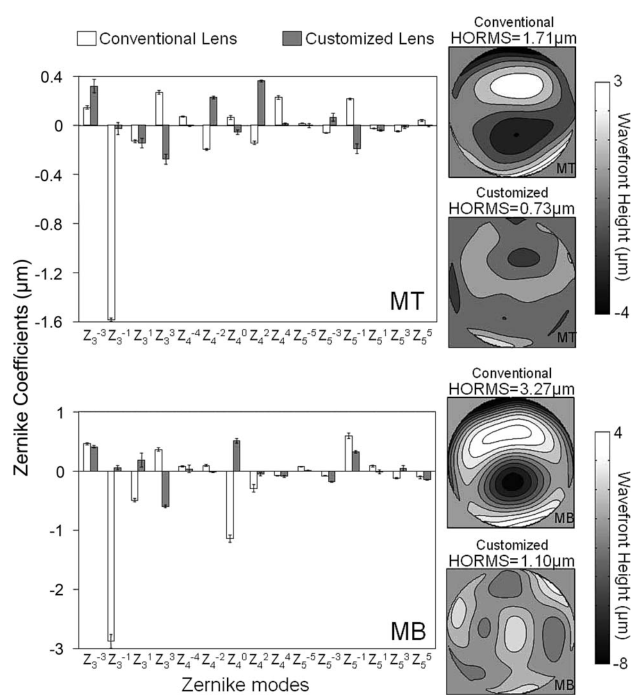

Fig. 2. HOA of moderate (MT) and advanced (MB) KC eyes wearing conventional and customized soft contact lenses. The Zernike coefficients are expressed according to the ANSI Z80.28-2004 standard. The error bars represent ±1 standard deviation. The interval between all contour maps is 1.5 μm. All plots are over a 6 mm pupil.

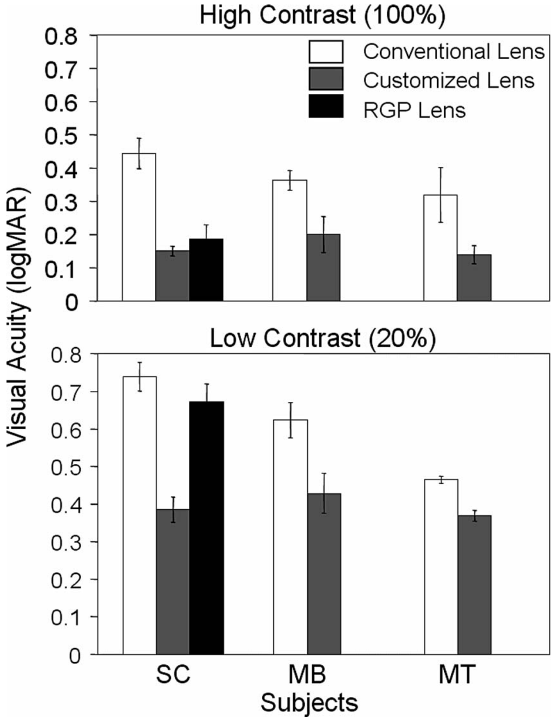

Fig. 3. High- and low-contrast visual acuity for three KC eyes wearing conventional and customized soft contact lenses measured over a 6 mm pupil. High- and low-contrast visual acuity wearing RGP lens was shown for an advanced KC eye (SC).

the three subjects. All three subjects also reported significant subjective improvement in their vision with the customized lens.

At present, RGP lenses are considered one of the most feasible solutions to correct KC eyes by masking corneal irregularities with the tear lens between the posterior lens surface and the anterior corneal surface. The optical and visual performance of an advanced KC subject (SC), wearing his own RGP lens prescribed by an optometrist and wearing the customized lens, was measured to compare both schemes of correction. The residual HORMS with the customized and the RGP lens was similar, 0.97 ± 0.01 and 1.05 ± 0.02 μm, respectively. Correction of spherical aberration was observed as the most significant discrepancy in the optical performance between two cases. Residual spherical aberration with the customized lens was nearly zero, in contrast with 0.75 μm with the RGP lens. Improvement in the high-contrast visual acuity over the conventional lens was similar with both lenses, as shown in Fig. 3. However, the customized lens provided a substantially higher improvement in low-contrast visual acuity of ~3.5 lines in comparison with an improvement of ~0.7 lines with the RGP lens. One possible explanation for this could be the difference in magnitude of residual spherical aberration with both lenses and its high impact on visual acuity.[10] In addition to providing better low-contrast visual acuity the subject preferred the customized lens, as soft contact lenses in general provide a better level of wearing comfort.[11]

The customized lens thus provided substantial correction of HOA, leading to improvement in visual acuity in all three KC eyes. However, the residual higher-order wavefront error is still nearly double of what is observed in normal eyes. This residual error can be explained to a reasonable extent by the manufacturing error, the magnitude of deviation from the designed x and y decentration, and rotation of the lens on the cornea, which were 257.3 μm, 114.7 μm, and 9.7 deg on average, respectively. Variability of lens position on the eye between blinks is unpredictable, especially in abnormal eyes. The error in manufacturing can be minimized by identifying systematic errors in the fabrication process or by using high-precision laser technology to obtain submicrometer accuracy and repeatability of fabrication. Selective and partial compensation of aberrations in the presence of lens movements also has potential to provide better optical performance by customized contact lenses, as shown in the theoretical model by Guirao and co-workers.[8,12]

We have demonstrated, using our novel technique, the significant reduction of HOA by customized soft contact lenses in KC eyes, resulting in substantial improvement in high- and low-contrast visual acuity, even in the presence of imperfections in lens fabrication and typical amounts of lens decentration. This indicates that customized soft contact lenses have the potential to provide abnormal corneal patients with a normal level of vision.

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