Correcting anterior corneal aberration and variability of lens movements in keratoconic eyes with back-surface customized soft contact lenses

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Customized contact lenses are limited in their correction performance, especially on irregular corneas, owing to decentration and rotation of the lenses. To overcome this limitation, we proposed to customize the back surface of soft contact lenses to match the anterior irregular corneal surface. These lenses were designed to correct anterior corneal aberrations and to improve lens stability. Although in keratoconic eyes the anterior corneal aberrations were effectively corrected, significant residual aberrations were observed. The internal optics, especially the posterior surface of the cornea, was the main source of these residual aberrations. Compared with conventional soft contact lenses, lens stability, on average over three eyes, was improved by a factor of 2 for horizontal and vertical decentrations and a factor of 5 in rotational orientation with the back-surface customized lenses. © 2007 Optical Society of America

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Correcting higher-order aberrations (HOAs) in abnormal eyes, in addition to lower-order aberrations, defocus, and astigmatism, provides a significant improvement in visual performance [1,2]. Front surface customized soft contact lenses (CSCLs) have been proposed as a practical, nonsurgical solution for correcting ocular HOA in abnormal eyes [3,4]. However, the residual higher-order wavefront error was still nearly double what is typically observed in normal eyes because of the instability of decentration and rotation of the lens on the cornea as shown by Guirao *et al.* [5]. In this Letter, we propose to overcome these limitations of conventional lenses by employing CSCLs whose back-surface profiles are sculpted to match the anterior corneal surface of KC eyes. The feasibility of this novel methodology in correcting aberrations and improving lens stability on KC cornea was demonstrated.

The schematic of the basic procedure for designing and fabricating the back-surface CSCLs is shown in Fig. 1. Anterior and posterior corneal topographies of three moderate KC eyes (BT, SC, and MB), classified based on the CLEK recommendation [6], were first measured by using the Orbscan IIz Corneal Analysis System (Bausch and Lomb). The anterior corneal topography data for a central 5 mm diameter was used to design an ablation profile for the same diameter around the contact lens center. The cone apices of the anterior corneal topography of MB, SC, and BT, relative to the topography center, were 0.8, 1.2, and 1.4 mm, respectively, which were well covered by the customized area. The inner 5 mm diameter circle of a soft contact lens back surface was ablated with a 193 nm excimer laser that has been proved to be effective in shaping an optical surface [7]. A laser beam size of 500 μm and an energy fluence of 0.2 mJ, providing an ablation rate of 0.05 μm/pulse, were chosen to optimize the ablation performance. Before ablation, the back surface of the soft contact lens was temporarily flipped over and placed on a plastic spherical dome. An annular holder was placed on top of the lens to avoid lens movement during laser ablation. A conventional pupil camera was installed to image the lens, and this system allowed precise alignment of lens centration to the ablation axis. Once the centration and orientation of the lens on the mount was achieved, the laser spot was scanned onto designated locations on the back surface of the lens with a dual-axis steering mirror. Prism ballasted conventional soft toric contact lenses manufactured with 45% water content hydrogel material had 14 mm diameter and 182 μm center thickness. Lenses used in the study had marks to indicate the axis of prism ballast, and these marks were used to align the lens orientation. The customized lenses tested on the KC eyes were exactly same in all respects as the conventional lenses, except for the ablation. Different base curves, 8.2, 8.4 and 8.4 mm, were employed for subjects BT, SC, and MB respectively. The lens base curve for each subject was chosen by reaching a balance between the lens conformity to the anterior cornea and the patients' wearing comfort. Before and af-

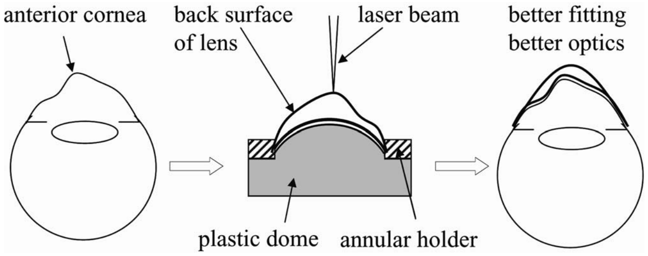

Fig. 1. Schematic principle and manufacturing process of the back-surface CSCL. Note that the back surface of a conventional soft contact lens was flipped over for ablation.

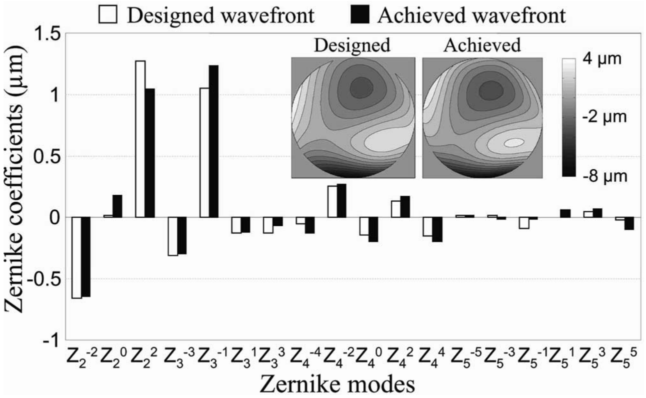

Fig. 2. Designed and achieved (manufactured) wavefront aberrations of back-surface CSCL for subject BT for a 5 mm pupil. The interval between contours is 1 μm.

ter the laser ablation, soft contact lenses were immersed in saline solution, and the wavefront aberrations were measured with a Shack–Hartmann wavefront sensor [8]. Manufacturing error from the ablation of the irregular back-surface profile was evaluated by calculating the total root mean square (RMS) and higher-order RMS (HORMS) of the difference map between designed and ablated wavefronts. The wavefront map for the aberrations of the designed and manufactured back-surface CSCL for subject BT is shown in Fig. 2. The total RMS and HORMS wavefront errors in the designed contact lens were 1.85 and 1.17 μm, respectively. Manufacturing errors were 0.39 and 0.27 μm, respectively, indicating that the back surface of the lens was reliably customized by laser ablation. Surface roughness induced by ablation of back-surface CSCL was also evaluated by measuring the peak intensity of individual Shack–Hartmann spots within the 5 mm optical zone. The average peak intensity of the Shack–Hartmann spots was reduced by 20% for the ablated CSCL compared with the conventional soft contact lens because of scatter induced by the surface roughness after ablation and the aberration created within each lenslet.

On-eye performance of the back-surface CSCL was evaluated by measuring the aberration correction performance and lens stability on the KC eyes. Aberrations of the three KC eyes were measured by a Shack–Hartmann wavefront sensor with and without the back-surface CSCL ~2 s after blinking. The eye's pupils were not dilated for the wavefront aberration and lens stability measurements. Eight frames after each of three blinks were recorded to measure the aberration. The wave aberrations over a 5 mm pupil were expressed by using 65 Zernike coefficients, corresponding to tenth-order Zernike polynomials. The Zernike coefficients are expressed according to the ANSI Z80.28-2004 standard [9]. The aberrations for subjects BT and SC without the defocus term are shown in Fig. 3. The HORMS of the naked eye was 0.70±0.03, 1.17±0.04, and 1.66±0.06 μm for subjects BT, MB, and SC, respectively. With the back-surface CSCL, the HORMS was reduced to 0.69±0.08, 0.61±0.04, and 1.30±0.1 μm for BT, SC, and MB, respectively. This residual aberration was induced by the overcorrection of most Zernike modes with the back-surface CSCL, as indicated in Fig. 3. Although the back-surface CSCL compensated for most of the anterior corneal aberrations, significant residual HOA contributed by the posterior cornea and the crystalline lens still remained. Other sources of residual aberration may be the lens manufacturing error and the refractive index mismatch between the soft contact lens ($n_{\mathrm{CSCL}} \approx 1.423$) and cornea ($n_{\mathrm{cornea}} \approx 1.376$). Here, we modeled the internal optics aberrations as the summation of aberrations contributed by posterior cornea, crystalline lens, lens manufacturing error, and refractive index difference between the CSCL and cornea. The combined aberrations of the posterior cornea and crystalline lens were calculated by subtracting the anterior corneal wavefront from the measured naked eye wavefront. The aberrations induced by the index mismatch were calculated by multiplying the refractive index difference between the lens and cornea times the anterior corneal surface profile. Internal optics aberrations thus calculated are shown in Fig. 3 for subjects BT and SC. The overcorrection of Zernike modes can be explained by the consistency between the internal optics aberrations and the eyes' aberrations with the back-surface CSCL. In particular, the posterior cornea and crystalline lens contributed 56% and 41%, respectively to the measured overcorrection of vertical coma in eyes with the back-surface CSCL on average.

Previous measurements for normal eyes [10] have indicated the partial compensation of anterior cor-

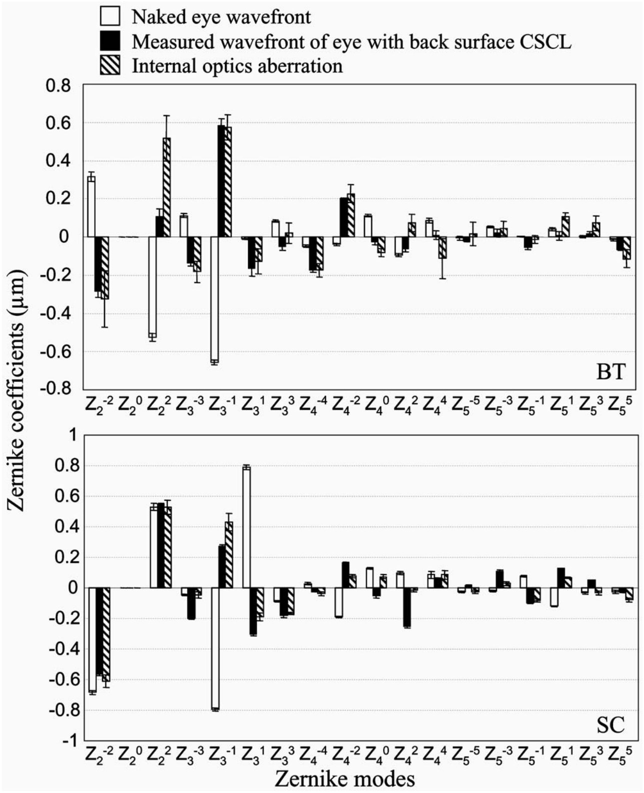

Fig. 3. Measured wavefront aberrations of naked eyes, eyes wearing back-surface CSCL, and calculated internal optics aberration for subjects BT and SC over a 5 mm pupil. Error bars represent ± 1 standard deviation.

neal aberrations by the internal ocular components. In KC eyes, with the increase in anterior corneal aberrations, the compensation by the posterior cornea is also observed to be correspondingly higher. Although correction of the anterior corneal aberration only in KC eyes improves optical quality of the eye, it might not provide the maximum visual benefit because of the residual internal optics aberrations. Rigid gas-permeable lenses use a similar mechanism based on masking the corneal irregularities with the tear film between the posterior lens and the anterior corneal surface. As our finding suggests, the residual internal optics aberrations might limit the visual benefit attainable with these lenses [11].

Lens stability was also evaluated with the back-surface CSCL on the eye. To determine the soft contact lens's movements on the eye, black dots were marked on its front surface throughout the periphery with a surgical marker. Pupil images superimposed by images of the contact lenses on the cornea were recorded for ~2 min at 15 frames/s, including around 20 blinks. The movement of the soft contact lens was measured by tracking the movements of the black dots on the lens surface, using a cross-correlation algorithm. Contact lens movements with respect to the pupil center and its rotational orientation in each image were quantified from the recorded frames. The standard deviation of lens decentration and rotation, measured after each blink, was calculated as a metric to quantify the variability in lens movements which represents lens stability. The stability of a conventional soft contact lens with the same lens parameters as the CSCL was also measured in the same manner for comparison. Table 1 shows the measured lens stability for the three subjects wearing a conventional lens and the back-surface CSCL. For subject BT, relatively variable lens movements with conventional soft contact lens were significantly stabilized with the back-surface customization. Although the conventional lenses for subjects MB and SC were relatively more stable than for subject BT, improvement in lens stability was still achieved with the back-surface CSCL. The back-surface CSCL improved lens stability by a factor of 2 each in horizontal and vertical directions and a factor of 5 in rotational orientation on average compared with the conventional soft contact lens. The stability of corrective optics and its accurate alignment to the visual axis is indispensable for HOA correction [5]. More Zernike modes with larger magnitudes can be corrected with a stabilized lens. Effective correction of aberrations with back-surface CSCL is, however, limited by uncompensated internal optics aberrations from the posterior cornea and the crystalline lens. An ideal hybrid solution might be the combination of back-surface customization to provide lens stability and front-surface customization to correct the residual internal optics aberration.

We have demonstrated the preliminary feasibility of using the back-surface CSCL to improve lens stability in KC eyes. A compensatory mechanism between anterior corneal aberrations and the internal optics, especially from posterior cornea, in KC eyes was also demonstrated. Long-term physiological and biomechanical effects of the lens on the cornea need to be investigated to make the lens clinically available for abnormal corneal patients. Stabilizing the lens movement on irregular corneas by back-surface customization has significant potential in corrective methodologies to provide abnormal eyes with normal visual performance.

Table 1. Stability (Standard Deviation) of Decentration in x and y Directions and Rotation of Conventional Soft Contact Lens and Back-Surface CSCL for Subjects BT, SC, and MB [a]

	BT		SC		MB	
Stability	CL	BCSCL	CL	BCSCL	CL	BCSCL
x (μm)	109	47	36	27	52	20
y (μm)	133	35	26	26	68	47
Rotation (deg)	21.2	5.1	5.8	0.9	9.4	2.5

[a] CL, conventional soft contact lens; BCSCL, back-surface CSCL.

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