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Micrometer scale contact lens movements imaged by ultra-high resolution optical coherence tomography

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Abstract

PURPOSE—To dynamically evaluate contact lens movement and ocular surface shape using ultra-high resolution and ultra-long scan depth optical coherence tomography (OCT).

DESIGN—Clinical research study of a laboratory technique.

METHODS—Four different types of soft contact lenses were tested on the left eye of 10 subjects (6 males and 4 females). Lenses edges at primary gaze and temporal and nasal gazes were imaged by ultra-high resolution OCT. Excursion lag was obtained as the distance between the lens edge at primary gaze and immediately after the eye was quickly turned either nasally or temporally. The inferior lens edges were imaged continuously to track vertical movements during blinking. Ultra-long scan depth OCT provided quantifiable images of the ocular surface, and the contour was acquired using custom software.

RESULTS—Excursion lag at the horizontal meridian was $366 \pm 134 \mu\text{m}$ at temporal gaze and $320 \pm 137 \mu\text{m}$ at nasal gaze ($P > .05$). The lens uplift at the vertical meridian was $342 \pm 155 \mu\text{m}$ after blinking. There were significant differences in horizontal lags and vertical movements among different lenses ($P < .05$). Horizontal lags were correlated with radii of curvatures and sagittal heights at 6- and 14- mm horizontal meridian radii ($P < .05$). The blink-induced lens uplift first lowered by $104 \pm 8 \mu\text{m}$, and then lifted $342 \pm 155 \mu\text{m}$ after the blink.

CONCLUSIONS—Ultra-high resolution and ultra-long scan depth OCT can assess micrometer scale lens movements and ocular surface contours. Both lens design and ocular surface shape affected lens movements.

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Introduction

Dynamic evaluation of contact lenses on the eye reveals lens movements that are critical in maintaining ocular health and comfort.¹ Lens movements are regarded as indicators of the tightness of lens fitting, and if too tight, the lens does not move very well. Proper lens movement facilitates tear exchange underneath the lens² and the removal of debris and dead cells.^{3,4} In the modern contact lens practice, lens movement is routinely evaluated by slit-lamp biomicroscopy or quantified by a digital camera with video capture.^{5,6} There may be a subjective appraisal during the measurement of the lens movement, and the assessment may not be adequate due to the lack of cross-sectional landmarks and quantification of movement at the micrometer level.^{7,8} Without a static landmark, estimates of the movement by these methods may be noisy. Using a cross-sectional landmark to track micrometer-range movements of the lens may further enhance modeling of the interaction between lens and ocular surface.

Lens fitting characteristics are impacted by many factors, such as lens material and design,⁷ blink rate,⁵ corneal shape,⁹ and post-lens tear film.^{10–13} The diameter of soft contact lenses is about 14 mm,¹⁴ and they cover the whole cornea along with the transition from the cornea to the sclera and some parts of the sclera. In the traditional lens fitting procedure, the central corneal curvature, approximately 3 mm from the apex, is used to select the appropriate base curve of the soft contact lens.⁹ Young found the central shape may not play an important role in determining overall lens fitting.⁹ This indicates that information regarding the central corneal shape may not be adequate for evaluating the lens fit. Our recent studies^{15,16} show that interaction between the lens edge and the ocular surface at the peripheral cornea plays an equally or more important role for lens fitting.

Current videokeratoscopes is able to characterize the majority of the entire cornea. However the limited usefulness of these instruments to predict soft lens fitting can be attributed to their inability to provide information about the peripheral ocular surface, especially the cornea-scleral junction.¹⁷ The impact of interaction around the periphery of ocular surface on the lens movement remains unclear, mainly due to the lack of a suitable instrument for evaluating the overall ocular surface shape. The goal of this pilot study was to demonstrate the feasibility using OCT to quantify the lens movement and overall shape of the ocular surface.

Subjects and methods

Subjects had no evidence or history of binocular vision anomalies or any pathology that would normally contraindicate contact lens wear. During screening, slit-lamp biomicroscopy evaluation was performed to confirm the lens fitting with a centration of less than 1 mm.¹⁸ After a screening test, ten subjects (6 males and 4 females; mean $\pm$ SD age, 31.2 ± 6.5 years) were recruited.

We imaged the overall ocular surface using a custom built, spectral domain, ultra-long scan depth OCT instrument. A custom spectrometer with special design was developed to achieve a scan depth of 7.3 mm in air. An internal fixation target displayed on a miniature LCD monitor was provided. To ensure proper alignment during OCT scanning, X-Y cross aiming was applied. The scan width was set to 18 mm. In our recent study,¹⁹ the overall ocular surface of human eyes was imaged and processed with custom software to yield sagittal height, corneal curvature, and peripheral shape around the corneal-scleral junction. The accuracy and repeatability of measurement for ocular surface shape was tested and validated.

A custom built, spectral domain, ultra-high resolution OCT with ~3 μm resolution was used to image each contact lens on the eyes. The ultra-high resolution OCT and its use in imaging the tear film and contact lenses in vivo were described in detail previously.^{16,18} In brief, a three-module superluminescent diode light source (Broadlighter, T840-HP, Superlumdiodes Ltd., Moscow, Russia) was used with a center wavelength of 840 nm and a bandwidth of 100 nm.

Each subject was tested in a consulting room after 10 AM to avoid the edematous cornea and the alterations of the tear film induced by sleep.^{20,21} Using ultra-long scan depth OCT, the overall ocular surface of the subjects' left eyes were imaged at the horizontal and vertical meridians (Figure 1) before lenses fitting. Then four types of commercially available soft contact lenses (Table 1) were randomly chosen and inserted into the left eye. Before ultra-high resolution OCT imaging, a 5 minute period for lens adaptation was allowed after every lens insertion.^{6,22} Subjects were asked to sit in front of the ultra-high resolution OCT instrument and look straight at the fixation target, which was placed in the front of the eye for primary gaze. OCT scanning at the horizontal meridian was conducted to image the lens excursion lag, both nasally and temporally. Excursion lag was defined as the distance between the location of the lens edge while gazing forward and its location immediately after the eye is quickly turned either nasally or temporally. The lag occurs because inertia of the lens causes it to move more slowly than the eye. The lens edge was imaged (Figure 1) at both nasal and temporal sides. When the subject looked at the fixation target placed at 45 degrees temporally (monitored with the slit-lamp angular scale), the lens edge at the nasal side was imaged. Similarly, when the subject looked at the nasally-positioned target, the edge at the temporal side was imaged (Figure 1).

To visualize lens movement induced by blinking, the inferior lens edge was imaged by ultra-high resolution OCT at the vertical meridian for 2.7 seconds continuously while blinking, during which 128 frames were acquired. Subjects were asked to have several normal blinks before image acquisition, and then the images were acquired for two or three blinks. During OCT imaging, subjects were asked to fixate on the primary-gaze position during the open eye period and immediately after every blink. The lower eyelid was pulled down a little so that the lower edge of the lens could be imaged.

Custom software was used to obtain the location of the contact lens edge on the eye. Two landmarks were chosen to determine the edge location. One was the end of Bowman's layer at the limbus, and the other was the tip of the contact lens edge (Figure 1). The lens excursion lag at the horizontal meridian was assessed as the linear distance between the ending of the Bowman's layer to the tip of lens edge in the nasal and temporal gazes compared to that in primary gaze. To display the movement, an OCT M-mode view was created to show the footprint of the lens edge during blinking (Figure 2). The M-modeview reconstruction was formed by summing the information of the lens edge in every frame of all 128 acquired images during one OCT data acquisition. In every single frame, the vertical cross-sectional image was taken at the same horizontal position. To process the OCT images obtained by ultra-long scan depth OCT, we used custom software¹⁹ to define the radii of curvature and sagittal heights of 3-, 6-, 10- and 14-mm zones on the ocular surface at the horizontal meridian and 3-, 6-, and 10-mm zones at the vertical meridian.

Data analysis was conducted using the Statistical Package for Social Sciences (SPSS version 17.0 for Windows XP; SPSS Inc., Chicago, IL). All of the data were presented as means $\pm$ standard deviations. Independent t-tests were applied to the comparison of lens excursion lags between temporal and nasal gazes. ANOVA was used to determine if there were any differences between the different lenses in movements. Post hoc tests were used to compare the movements between any two lenses. Pearson correlation was used to test correlations

between lens movements at different meridians, and the relationship between lens movements and ocular surface parameters. $P < 0.05$ was considered significant.

Results

At the horizontal meridian the lenses were located in different positions at primary gaze compared to temporal or nasal gaze. The lens excursion lag was $366 \pm 134 \mu\text{m}$ at temporal gaze and $320 \pm 137 \mu\text{m}$ at nasal gaze (Table 2). There were no differences between lens temporal and nasal gaze lags at the horizontal meridian (independent t-test, $P > .05$; Table 2). There were significant differences in lens movements, including horizontal lags and vertical movements among all of the contact lenses. The PureVision lens showed significantly larger excursion lag at the horizontal meridian compared to Acuvue 2 and O₂OPTIX lens (post hoc, $P < .05$; Figure 3). Blink-induced uplift of the PureVision lens was larger than for both the Acuvue Advance and Acuvue 2 lenses (post hoc, $P < .05$; Figure 3). Lens temporal gaze lag was correlated with the nasal gaze lag ($P < .05$; Figure 4), but there was no correlation between horizontal lags and blink-induced uplift at the vertical meridian ($P > .05$; Figure 5).

Using ultra-long scan depth OCT, we measured the curvatures and sagittal heights of the 3-, 6-, 10-, and 14-mm ocular surface zones at the horizontal and vertical meridians (Table 3). The temporal and nasal horizontal lags were correlated with the radii of curvature at the 3-, 6-, 10- and 14-mm zones of the ocular surface (Table 4). However, the temporal gaze lags were correlated only with the sagittal heights at the 14-mm zone, and the nasal gaze lags were correlated only with the sagittal heights at the 6- and 14-mm zones of the ocular surface at the horizontal meridian ($P < .05$; Table 4).

Through the M-mode views of OCT images, vertical movement of the inferior lens edge was tracked to clearly yield the movement footprint before and after blinking. The dynamic tracking at the vertical meridian showed a little lowering, $104 \pm 8 \mu\text{m}$, of the lens at the beginning of each blink and a larger lifting, $342 \pm 155 \mu\text{m}$, after the blink (Table 2). During the open eye period, the lens appeared to drop in two phases. The first phase was fast then a relative slow phase till reaching the baseline.

Discussion

The evaluation of contact lens fit is important to clinical practice. Poor fitting lenses may have negative impacts on ocular physiology and result in greater fluorescein staining and higher levels of bulbar and limbal hyperemia.²³ One of the most important causes of discomfort for patients is inappropriate lens fit.^{24–27} In the clinic, the fit is usually assessed by subjective comfort and often evaluated by slit-lamp biomicroscopy.²⁸ The assessment relies on individual judgment, and the absence of good fitting information is usually due to a lack of precision in the evaluation modality. Developing a full range of objective lens fitting evaluations may help better understanding the fitting characteristics. OCT is well suited for developing such an evaluation.

Recently, we used a custom built ultra-high resolution spectral domain OCT instrument to evaluate the fitting of soft contact lens edges.^{15,16} Additionally, spectral-domain OCT with ultra-long scan depth has the ability to quantify the entire ocular surface.¹⁹ Combining these two OCT devices enables quantitative assessment of the overall ocular surface shape and its interaction with the lens in situ. The combined use of these instruments will be beneficial in evaluating contact lens movement. This may further reveal insightful information about lens movement patterns, especially those influenced by the shape of the ocular surface.

The horizontal lags and blink-induced uplift that we evaluated by OCT were within the ranges reported by others using slit-lamp biomicroscopy with an eyepiece graticule¹ and video photography.²⁹ Young evaluated good and bad fitting lenses and suggested that both horizontal lag and blink-induced movements were related to it.¹ In the current study, the lags of the lens movements at the temporal and nasal gazes were similar to and correlated with each other. Corneal curvature at the nasal corneo-limbal junction angle and the temporal corneo-limbal junction angle are similar,³⁰ and this may explain the similarity of movements in the different gazes. The lack of correlation between lags and blink-induced lens uplift indicates that these types of lens displacements have different origins. The horizontal lag was triggered by the eyeball rotation and may be mainly influenced by the ocular shape. The vertical movement induced by blinking was triggered by the movement of the lid, and the shape of the ocular surface may resist lens displacement. Lid tension may exaggerate the action of the lid on the lens displacement during blinking, a topic that warrants further study.

Movements of the lenses may be attributable to two different origins. One is the contact lens itself and the other is the contour of eye. Among different contact lenses tested in the present study, the lens movements differed significantly. Different base curves, powers, edge designs, diameters, and materials all may play roles in determining the lens fitting, resulting in measurable lens lag and movement. For example, PureVision lenses with a high modulus and rounded edge was founded more blink-induced uplift than Acuvue Advance and Acuvue 2 lenses with low modulus of elasticities and angled edges. Similar findings have been reported by Gasson and Morris,³¹ who found that lenses with low modulus show less movement. Less movement in a lens with a low modulus might be attributed to the ease of deformation and the adherence to the ocular surface that may result in a thin post-lens tear film. PureVision lenses with the high modulus also presented more horizontal lag than Acuvue 2 lenses, however, there was also a significant difference between the PureVision lenses and the O₂OPTIX lenses which had similar elasticity. These results may indicate that other factors may play additional roles in lag movements.

The shape of the ocular surface needs to be considered when fitting contact lenses. Normally, lenses with steeper curves and larger diameters fit more tightly. Wolffsohn et al. found that the relationship between the corneal curvature and lens back optic zone radius did not affect lens movement.²⁹ In the present work, we obtained the radii of curvature and sagittal heights of the ocular surfaces up to a 14-mm zone at the horizontal meridian and up to a 10-mm zone at the vertical meridian. The curvature data of the ocular surface indicated that the cornea was steepest centrally and flattened towards the periphery, as would a prolate ellipse,^{32,33} which was in agreement with previous work.³⁰ The peripheral sagittal heights of the ocular surface were also similar to those reported previously.³⁰ The relationship between the sagittal heights at the peripheral areas and the lags at the horizontal meridian may highlight the importance of peripheral shape in fitting evaluation.

There are limitations in attempting to reconstruct the corneal surface based on curvature measurements that are not unique properties of the cornea.³⁴ The same shape can have many different “curvatures” depending on which axis is used to make the measurement.³⁴ Corneal elevation or height data provides more actual and useful information about the ocular surface. The results of our research may indicate that peripheral ocular surface shape is important in considering the process of lens fitting. Additionally, there was no correlation between blink-induced lens movement and ocular surface parameters for the vertical meridian. With regard to vertical lens movements, the action of the lid during blinking plays a much more important role than does the shape of the ocular surface.

Tracking the footprint of lens movements in micrometer dimensions can provide additional information on movement velocity and the amount of movement that results from blinking.

Dynamic tracking at the vertical meridian showed a little lowering of the lens at the beginning of each blink and a lifting of the lens after blinking. This indicated that the upper eyelid pushed the contact lens downward when it descended, followed by an upwards movement as the eyelid began to open. This effect of the upper eyelid on the lens at the moment of blink and upon eye opening was also reported by Conway et al.³⁵ Sufficient motion of the contact lens during blinking may facilitate the exchange of the tears under and around the lens² and the removal of debris from underneath the lens.^{3,4} Lens movement at an adequate speed may help to maintain normal or nearly normal physiological conditions of the cornea and conjunctiva.²⁹ Traditionally, the dynamic assessment of lens fitting has been performed by slit-lamp evaluation of the ease of displacement or recovery speed of the push-up test. Objective, non-invasive, and non-contact OCT demonstrated in this work may be very suitable for the assessing contact lens fit in both research and routine patient care.

This is the first study combining ultra-high resolution and ultra-long depth OCT to evaluate the movement of contact lenses and the contribution of ocular surface shape to that movement. While the types of study lenses and the sample size are both small, we clearly demonstrated this novel method for precisely tracking the lens movement in a micrometer scale. Even with the small sample size, significant differences among lenses were evident. Further studies with well controlled approaches will reveal additional information on lens movements.

We did not evaluate the repeatability of in vivo movement measurements and the localization of Bowman's layer as a landmark. Nevertheless, the repeatability of in vivo tracking of the lens movement appeared to be good as evident in the footprint between two blinks. We found that the Bowman's layer landmark was easily identified in each OCT image. Although image registration was not performed in the present study, the end of Bowman's layer at the limbus, the inherent landmark of the cornea, was used as a non-moving reference during the image processing. These repeatability tests will be considered in our design of future studies.

The segmentation software for determining the amount of movement and lag was semi-automated. More robust segmentation may further enhance the method for routine clinic application. In addition, evaluation in three-dimension would be valuable for establishing the contact lens fitting model in future studies. The impacting factors like conjunctival buildup¹⁵ and lens centration will be considered during the modeling. These results may lead to a significant impact on lens fitting and evaluation.

In summary, this study demonstrated the feasibility of dynamic evaluation of the lens movement associated with gazes and blinking. Combining the ultra-high resolution and ultra-long scan depth OCT devices for the determination of the lens movement may provide a new, different, and practical approach to evaluate contact lens movement at the micrometer scale and provide useful information in the characterization of the lens fitting.

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Biography

Lele Cui, MD, is currently a PhD student at Wenzhou Medical College. She graduated from Wenzhou Medical College, Zhejiang, China, majoring in general medicine. From November 2009, she spent one year at Bascom Palmer Eye Institute (Miami), doing research regarding the clinical application of optical coherence tomography. Dr Cui's current research interests include contact lens and tear dynamics.

Figure 1. Ultra-high resolution and ultra-long scan depth OCT images of PureVision lens horizontal lag excursion and ocular surface shape

Nasal and temporal PureVision lens edges were visualized in ultra-high resolution OCT images that were taken when the subject looked ahead in primary gaze and then at a target located temporally or nasally (Top). Two landmarks were used in image processing. One was the ending of the Bowman's layer at the limbus (e), and the other was the contact lens edge (t). Lens location was defined as the linear distance (d) between "t" and "e", which was different in primary gaze compared to temporal or nasal gazes. These difference values represented the horizontal lags on the temporal or nasal side. Using ultra-long scan depth OCT, the overall ocular surfaces of the subjects were imaged at the horizontal (bottom) and vertical (not shown) meridians. Bars = 500 μm .

Figure 2. Movement footprint of the PureVision lens edge by ultra-high resolution OCT
 The ultra-high resolution OCT images showed the blink-dependent PureVision lens movement on the ocular surface. Through the OCT dataset, two images were chosen, one before a blink (Left) and one after (Right). The location of the inferior lens edges in the OCT images corresponded to the movement track in the OCT M-mode view (Middle). The M-mode view (Middle) showed the footprint of contact lens movement, which lowered a little (asterisk) at the beginning of the blink and then lifted after the blink. During the open eye period, the lens dropped in two phases, a fast phase and then a slow phase, finally reaching the baseline.

Figure 3. Lens movements (horizontal lag excursion and blink-induced uplift) for the different contact lenses

(Left) Mean combined excursion lags for both temporal and nasal gazes. The PureVision lens (§) had significantly greater horizontal lag than did the Acuvue 2 or O₂OPTIX lens (* post hoc, $P < .05$) (Right) Mean blink-induced uplift at the vertical meridian. The PureVision lens (§) had significantly greater blink-induced uplift compared to Acuvue Advance and Acuvue 2 lens. (* post hoc, $P < .05$). Bars denote 95% confidence interval (CI).

Figure 4. Correlation between the nasal gaze lags and the temporal gaze lags of contact lenses
The nasal gaze lags of contact lenses were significantly correlated with the temporal gaze lags ($P < .05$).

Figure 5. Absence of correlation between the contact lens horizontal lags and the blink-induced uplifts

There was no correlation between either lens temporal or nasal gaze lags and the vertical blink-induced uplifts ($P > .05$).

Table 1

Design variables of the contact lenses.

Brand	Acuvue Advance	Acuvue 2	PureVision	O ₂ OPTIX
Manufacturer	Vistakon, Johnson & Johnson	Vistakon, Johnson & Johnson	Bausch & Lomb	CibaVision
Diameter (mm)	14.0	14.0	14.2	14.2
Base Curvature (mm)	8.7	8.7	8.6	8.6
Power (D)	−3.00D	−3.00D	−3.00D	−3.00D
Material	Galyfilcon A (SiHi)	Etafilcon A	Balafilcon A (SiHi)	Lotrafilcon B
Modulus (MPa)	0.43	0.3	1.1	1.0
Edge Shape	Angled	Angled	Rounded	Chisel
Center Thickness (mm)	0.07	0.08	0.09	0.07
Water content (%)	47	58	36	33

Table 2

Contact lens excursion lags at temporal and nasal gazes and blink-induced lens movements.

Lens	Horizontal lag ^a		Vertical movement ^a	
	Temporal Gaze Lag ^b (μm)	Nasal Gaze Lag ^b (μm)	Blink-induced Uplift (μm)	Blink-induced Lowering (μm)
Acuvue Advance	372 ± 103	367 ± 194	239 ± 122	107 ± 17
Acuvue 2	292 ± 83	266 ± 88	253 ± 122	107 ± 35
PureVision	478 ± 189	376 ± 136	394 ± 158	103 ± 17
O ₂ OPTIX	322 ± 53	271 ± 79	322 ± 112	101 ± 25
Mean ± SD (μm)	366 ± 134	320 ± 137	342 ± 155	104 ± 8

^a mean ± SD values, n=10 eyes.^b There were no differences between lens temporal and nasal gaze lag at the horizontal meridian (independent t-test, $P > .05$).

Table 3

Curvature and sagittal height of 3-, 6-, 10-, and 14-mm ocular surface zones at the horizontal and vertical meridians.

	Horizontal meridian		Vertical meridian	
	Curvature (mm)	Sagittal height (mm)	Curvature (mm)	Sagittal height (mm)
3 mm zone	7.96 ± 0.19	0.14 ± 0.01	7.68 ± 0.23	0.15 ± 0.01
6 mm zone	8.09 ± 0.24	0.58 ± 0.01	7.75 ± 0.24	0.61 ± 0.02
10 mm zone	8.28 ± 0.25	1.68 ± 0.06	7.97 ± 0.27	1.74 ± 0.08
14 mm zone	8.90 ± 0.31	3.22 ± 0.18	-	-

Table 4

Relationship between contact lens horizontal lags, blink-induced uplifts, and ocular surface parameters.

r			
	Temporal gaze lag	Nasal gaze lag	Blink-induced movement
Curvature	3 mm zone	-0.41 ^a	-0.33 ^a
	6 mm zone	-0.45 ^a	-0.43 ^a
	10 mm zone	-0.39 ^a	-0.36 ^a
	14 mm zone	-0.39 ^a	-0.34 ^a
Sagittal height	3 mm zone	0.15	-0.03
	6 mm zone	0.28	0.35 ^a
	10 mm zone	0.17	0.22
	14 mm zone	0.40 ^a	0.34 ^a
Vertical meridian	3 mm zone	-0.18	0.02
	6 mm zone	-0.27	-0.16
	10 mm zone	-0.27	-0.20
	14 mm zone	-0.27	-0.15
Sagittal height	3 mm zone	0.06	-0.12
	6 mm zone	0.07	0.08
	10 mm zone	0.14	0.17
	14 mm zone	0.14	0.11

^aSignificant correlation of P < .05.