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Optical Assessment of Soft Contact Lens Edge-Thickness

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Abstract

Purpose—To assess the edge shape of soft contact lenses using Gabor-Domain Optical Coherence Microscopy (GD-OCM) with a 2 μm imaging resolution in three dimensions, and to generate edge-thickness profiles at different distances from the edge tip of soft contact lenses.

Methods—A high-speed custom-designed GD-OCM system was used to produce 3D images of the edge of an experimental soft contact lens (Bausch + Lomb, Rochester NY) in four different configurations: in air, submerged into water, submerged into saline with contrast agent, and placed onto the cornea of a porcine eyeball. An algorithm to compute the edge-thickness was developed and applied to cross-sectional images. The proposed algorithm includes the accurate detection of the interfaces between the lens and the environment, and the correction of the refraction error.

Results—The sharply defined edge tip of a soft contact lens was visualized in 3D. Results showed precise thickness measurement of the contact lens edge profile. 50 cross-sectional image frames for each configuration were used to test the robustness of the algorithm in evaluating the edge-thickness at any distance from the edge tip. The precision of the measurements was less than 0.2 μm .

Conclusions—The results confirmed the ability of GD-OCM to provide high definition images of soft contact lens edges. As a non-destructive, precise, and fast metrology tool for soft contact lens measurement, the integration of GD-OCM in the design and manufacturing of contact lenses will be beneficial for further improvement in edge design and quality control. In the clinical perspective, the in-vivo evaluation of the lens fitted onto the cornea will advance our understanding of how the edge interacts with the ocular surface. The latter will provide insights into the impact of long-term use of contact lenses on the visual performance.

Keywords

soft contact lens; edge-thickness; optical coherence tomography; microscopy; optical metrology

Today, more than 125 million people worldwide wear contact lenses, with about 38 million in the United States alone.¹ This number is expected to gradually increase, given the various benefits that contact lenses provide in daily activities compared to eyeglasses. Contact lenses

correct refractive error of the eye without disturbing daily activities and sports. In addition, when comparing wearing glasses and contact lenses, teenagers and children particularly showed greater involvement in activities and high satisfaction with both corrected vision and their perceived appearances when corrected with contact lenses.² However, contact lens wearers might easily experience discomfort primarily caused by the interaction of the lens with the ocular surface, as supported by the reports of the TFOS International Workshop on Contact Lens Discomfort.³⁻⁵

The interaction between the contact lens and the ocular surface primarily involves the movement of the contact lens, which allows for the exchange of tears and removal of metabolic waste products when the eye blinks.⁶ Shen et al. indicated the possibility that this interaction with the contact lens, especially near the edge, largely determines the comfort of the wearer and the health of the ocular surface.⁷ The significance of the edge in terms of discomfort and quality of vision has also been supported with recent studies.^{8, 9} For instance, Shen et al. reported that the thinner edge configuration helps to form a smoother transition between the edge of the lens and the conjunctiva and thus reduces mechanical irritation of the ocular surface.⁷ In addition, the design of the contact lens edge is critically related to lens mobility that affects the exchange of tears.¹⁰ The quality control of the contact lens during and after manufacturing is a critical step to maintain the optimum comfort of the patient and the health of the ocular surface. This control usually includes the wettability and semi-permeability of the contact lens, the lens power, the diameter and base curvature, the center, junction, and edge-thicknesses, and the quality of the edge.

A dial thickness gauge designed for use with contact lenses is typically used to measure the thickness of contact lenses.¹¹ A low compressive force that usually ranges from 0.4N to 2N is applied to the lens in air when measuring the thickness. However, this technique has been found to be more accurate for rigid contact lenses, which only represent 13% of the contact lens market.¹ For soft contact lenses, which otherwise represent 87% of wearers in the US,¹ applying force during measurement impacts the accuracy of thickness measurements due to the soft characteristic of the materials (e.g., hydrogels). Furthermore, as hydrogels absorb liquids and must stay hydrated, soft contact lenses are typically measured to be thinner in air than when hydrated by the tear film of the eye. Thus, the measurement of soft contact lenses may best be performed when the lens is immersed in a solution, providing a challenging measurement task. Alternatively, physically slicing the contact lens with a razor blade is another common way of determining its thickness. The thickness can then be measured with a microscope based on the acquired cross-sectional view of the contact lens. However, this method is destructive and requires proficiency. Also, soft contact lenses dry quickly when illuminated with the microscope light. Non-destructive means of measuring thickness of soft contact lenses may provide an efficient and improved quality control.

Optical Coherence Tomography (OCT) has been demonstrated as a useful non-invasive technique to achieve micron-scale resolution imaging of deep structures in tissue.^{12, 13} With its non-invasiveness, high resolution, and speed, OCT has been widely used in ophthalmology to measure thickness of various layers of the eye, including the cornea,^{14, 15} the retina,^{16, 17} and the tear film.¹⁸⁻²⁰ More recently, the capabilities of OCT have been extended to numerous applications in materials science.²¹⁻²³ The use of OCT for contact

lens metrology has also been investigated by peers.^{24, 25} Works by Verrier et al. reported on the central thickness measurement of contact lenses and compared the accuracy of the results using two different sources (i.e., SLED and supercontinuum).²⁶ The method reported was based on one-point measurement at the center of the lens. Davidson et al. also used OCT to measure the mechanical prism of contact lenses at 0.3 mm from the edge.²⁷ The prism was defined as the maximum difference in thickness at opposing points on the lens edge and considered to be a significant metric of the quality control of a contact lens manufacturing process. The thickness at this fixed distance from the edge was measured over 360 degrees. Their automated algorithm and analysis established the capability of spectral domain OCT as a tool for non-destructive, fast, and reliable contact lens metrology. Also, a commercial OCT system Envisu S4410 (Leica Microsystems, Inc) was recently developed to perform the metrology of soft contact lens immersed in a hydration bath, but not adapted in the current development stage to the quality control of the edge tip. An improvement to the developed methods would include the ability to assess the full edge and to extend the 2D imaging to 3D. The 3D orientation of the lens should be considered for the accuracy of the measurement, especially at the edge where a higher lateral resolution is needed for a better accuracy in the thickness measurement as well as to resolve smaller features such as defects occurring at the edge tip of the lens after the molding process. Indeed, compared to the center of the lens, the edge presents a rapid variation in thickness, which needs to be sampled properly to precisely extract the thickness. For instance, commercial instruments, such as the PhaseFocus that offers standard resolution imaging of 7 microns and optional high resolution imaging of 0.7 microns for imaging the edge of the lens, cannot image the lens and the edge in one shot at the same resolution; imaging in the higher resolution mode requires a 10× greater sampling in 2D, thus results in a 100× slower measurement for the same field of view.

In this paper, we report on the investigation of the capability of a custom OCT system – Gabor-Domain Optical Coherence Microscopy (GD-OCM) – to provide precise thickness evaluation and high definition 3D imaging of the edge of the contact lens. As compared to conventional OCT where lateral resolution is limited to tens of micrometers, the 2 μm imaging resolution in three dimensions of GD-OCM is highlighted in this study for contact lens metrology.

Methods

Gabor-Domain Optical Coherence Microscopy Experimental Setup

A custom built GD-OCM system shown in Fig. 1 was utilized throughout this study.^{28, 29} GD-OCM combines the high sectioning capability of OCT and high lateral resolution of confocal microscopy to achieve high-contrast volumetric imaging resolution of ~2 μm, defined as the full width half maximum (FWHM) of the point spread function (PSF). The source in the current instrument is a super luminescent diode laser centered at 840 nm and with ~100 nm FWHM (BroadLighter D-840-HP-I, Superlum, Ireland), yielding 2.2 μm FWHM axial PSF in contact lens materials. The reference arm integrates a polarization controller and a custom dispersion compensator that allow constant resolution across the thickness of up to 2 mm.³⁰ The sample arm used in this study was equipped with a dual-axis

XY galvanometer-based scanner (6215HSM40B, Cambridge Technologies Inc.) and was configured to scan a $1\text{ mm} \times 1\text{ mm}$ field of view with a $1\text{ }\mu\text{m}$ sampling step. The microscope objective incorporates a bio-inspired liquid lens, which allows dynamic-focusing in order to image different depths of the sample while maintaining an invariant lateral resolution of $\sim 2\text{ }\mu\text{m}$ within the imaging depth.^{31, 32} A high-sensitivity custom spectrometer with a high-speed CMOS camera (spl4096 – 140 km, Basler Inc., Exton, Pennsylvania) is used to capture the spectral information.³³ The scanning probe is attached to an articulated arm that allows flexibility in imaging under multiple configurations. We recently leveraged the capability of graphic processing units (Two NVIDIA GTX Titan cards) to allow real time acquisition and visualization of high resolution images.³⁴

Experiment Design

A soft contact lens (Bausch & Lomb, Rochester NY) was investigated for this study. The lens was an experimental cast molded lens made of nesofilcon A, a new high water (78%) hydrogel contact lens material. The refractive index n of the lens was provided to be 1.3702 at the wavelength of 840 nm. The experimental evaluation of the lens-edge was performed in four configurations: (A) contact lens in air ($n=1$); (B) contact lens immersed in water ($n=1.329$ at 840 nm); (C) contact lens immersed in balanced salt solution (BSS) with a contrast agent ($n=1.362$ at 840 nm); and (D) contact lens positioned onto the cornea of a fresh porcine eyeball. A porcine eye was chosen as it is widely available and shares many similarities in size and structures with the human eye.^{35, 36}

For configuration (A), the edge of the soft contact lens was imaged in air. The lens was removed from its packaging BSS right before the experiment and placed onto a small petri dish whose shape accommodated to that of the lens. The lens was positioned in such a way that the edge was floating in air (i.e., there was no contact of the contact lens edge with the Petri dish). Note that in this configuration the lens was slightly wetted with BSS so that the shape and the dimensions remained unchanged. In the second configuration (B), the soft contact lens was taken out of BSS and placed into a small plastic storage bag filled with water and equilibrated for more than an hour. The pressure in the plastic was sufficient to maintain the contact lens in a floating position without deforming the lens. It is important to note that before using water, we first attempted to image the lens in a storage bag filled with BSS, but the contrast was insufficient to clearly detect the top surface of the lens. The bottom surface was invisible due to the low gradient of refractive index between the lens and BSS. We then investigated in configuration (C) the imaging of the lens in BSS with a biocompatible contrast agent; no extra equilibration time was needed since the lens was already in the BSS and we didn't expect any effect of the contrast agent by itself on the CL thickness. In the final configuration (D), the contact lens was placed onto the cornea of a porcine eyeball obtained from a local abattoir and the experiment was performed within three hours postmortem. A few drops of BSS were continuously applied to the top of the contact lens in order to keep the cornea and the contact lens wet during imaging.

For each configuration, the sample was positioned on a three-axis translation stage. A mark was printed on the edge to serve as reference and to ensure the imaging was performed at the same location in the four configurations. The probe fixed on an articulated arm was

manipulated to position the optical axis approximately normal to the contact lens edge. Real time 2D scanning in x and y was successively performed to localize the edge and adjust the position of the sample. In the current setting of the instrument, the alignment of the probe with the contact lens edge was performed in approximately five minutes. A 3D scan including the dual x-y axis galvanometer scanner and the z axis refocusing liquid lens was then performed at each position. Since the contact lens was about 150 μm thick, the liquid lens with 80 μm depth of focus required refocusing the lens once from nominal focus to provide high definition just around the lens,³² thus minimizing the acquisition and processing times. The acquisition time of the 3D image was 30 seconds and the visualization of the sample was made possible within 13 seconds of the acquisition time using the parallelized GPU processing.³⁴ For each measurement, 1000 frames, each containing 1000 pixels (A-scans), were saved for further image analysis.

Image Analysis

After acquisition, post-processing, fusing and rendering of contact lens images, a MATLAB (The MathWorks, Inc. Massachusetts) program was written to analyze and evaluate the edge-thickness of the contact lens in the four configurations. The acquired cross-sectional images had a width of 1 mm (1000 pixels) and depth of 0.6 mm (666 pixels with a scale of 0.9 μm , which depends on the refractive index of the lens and the number of sampling points (i.e. 8192) of the FFT processing). The main steps in the thickness measurements included locating the interfaces of the contact lens edges by a multiple peak detection method, correcting for the refractive error and computing the edge-thickness at different lateral positions from the edge tip.

For each of the 1000 frames of the volume, the image was cropped to only keep the region of Interest (ROI) around the edge of the contact lens. Figure 2(A) illustrates the ROI of a chosen frame in the configuration (D), with the resulting size of 1 mm by 0.4 mm (i.e., 1000 pixels $\times$ 444 pixels). The structures of the contact lens, the corneal epithelium and stroma, as well as the fluid gap between the contact lens edge and the corneal surface, are clearly differentiated.

Five neighboring frames were averaged to perform the peak detection. A 2-D median filter with a 3×3 kernel was applied to the segmented image. A median filter was more appropriate than other convolution kernels, as it has been known to effectively remove salt and pepper noise while protecting the edge.³⁷

Locating the Interfaces of the Lens

Locating the surfaces of the lens is a critical step in the thickness measurements. In order to precisely locate the top and bottom surfaces of the contact lens, each vertical line of the resulting filtered frame was normalized to highlight the edges. A publicly released MATLAB program to detect multiple peaks in a vector was optimized in this application to identify the top and bottom surfaces of the lens.³⁸ A binary image of peaks was then created where peaks were assigned a value of 1 and all other data points were assigned a value of 0. Figure 2(B) presents the resulting binary image from the peak detection algorithm. Among different segmentation techniques, the multi-peak detection approach appeared to be most

effective in detecting the edges from OCT data. Indeed, the edge of the contact lens will produce the highest intensity in the backscattering light relative to the gradient of the refractive index between the lens and its environment, thus yielding a most precise location of the edge. However, as shown in Fig. 2(B), the peak detection algorithm misses the bottom interface of the lens at some locations at which the reflection from the upper surface is stronger and impacts the amount of light reaching the lower surface.

In order to correct for the error in the edge location, a 5th order polynomial fitting was applied to the top and bottom surfaces of the lens to provide the continuity of the boundary. From our investigation, the 5th order was proved to be sufficient and optimal to fit the moderately curved surface of the contact lens. Figure 2(C) shows the superposition of the region of interest (ROI) grayscale image and the edge boundaries determined from the peak detection and polynomial fitting.

The thickness measurement at each lateral position from the edge tip of the lens was computed by evaluating the distance, relative to the inner surface of the lens, between the two fitted surfaces. Care must be taken when imaging the lens with OCT. Indeed, the processing and rendering of OCT data is based on the assumption that the light is travelling straight through the material. As such, each vertical line (A-scan) of the image is computed as a straight trajectory of light. In the same manner, the GD-OCM images are obtained from the transverse scan of the system, and the intensity data from each point are plotted transversely to create one frame. This assumption is true only if the incoming light is normal to the top surface. Although we attempted to position the probe normal to the contact lens, there was still a slight slope of the top surface and specifically near to the edge tip of the lens, which induces a refraction error in the measurement of the thickness. In the next section, we evaluated the effect of the refraction error on the thickness measurement.

Refraction Correction Evaluation

Because of the refraction phenomenon that occurs at the interface of the material with different refractive index, the transverse positioning of data in OCT is not always a perfect representation of the real situation. Figure 3 illustrates the principle of the refraction effect when imaging a uniform tilted layer using OCT. The incoming light strikes the first surface with the angle of incidence θ_1 and refracts to reach the bottom surface at the point B. According to OCT data, the apparent impact point of the light on the bottom surface is the point A. However, the real impact of the light with the bottom surface is produced in the point B that is localized by measuring the same optical path difference (OPD) between OA and OB. This concept was applied at each lateral position of the top surface to find the real impact point of the light with the bottom surface. The real bottom surface (hard blue line) of the material is then obtained and compared to the apparent surface from the OCT data (dashed blue line).

We define $t_{\text{corrected}}$, as the optical thickness (physical thickness times the refractive index) measured in the real situation that accounts for the refraction effect; and $t_{\text{GD-OCM}}$, as the optical thickness measured directly from GD-OCM images. From the Fig. 3, the two trigonometric relationships between the angles and the thicknesses can be described as

$$\begin{cases} t_{\text{GD-OCM}} = \text{OPD} \times \cos\theta_1 \\ t_{\text{corrected}} = \text{OPD} \times \cos\theta_2 \end{cases}, \quad (1)$$

Based on the Eq.1 and Snell's law, the relationship between the thickness from GD-OCM and refraction corrected thickness was found and is given as

$$t_{\text{GD-OCM}} = t_{\text{corrected}} \times \frac{\cos\theta_1}{\sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 \times \sin^2\theta_1}}, \quad (2)$$

where n_1 and n_2 represent the refractive indices of the surrounding environment and the material, respectively. The refraction effect and correction algorithm were first evaluated in simulation, and then validated experimentally using a microscope cover slip.

First of all, the effect of the refraction was simulated to theoretically predict the expected or apparent thickness measured from GD-OCM data, for a given material with a known thickness. The simulation requires the inputs of the real thickness of the material and its refractive index, as well as the tilt angle of the sample with respect to the incoming light. For this demonstration, we considered the surrounding environment of the material to be air ($n_1=1$). Equation 2 was used to evaluate the expected thickness from GD-OCM for different tilt angles and refractive indices. Figures 4(A) and 4(B) show the anticipated thickness from GD-OCM as a function of refractive index and tilt angle for the microscope cover slip, while the real thickness was equal to 150 μm .

Compared to the real thickness (i.e., 150 μm), the apparent thickness from GD-OCM decreases as the index of refraction increases, as shown in Fig. 4(A); the decrease becomes more significant as the tilt angle increases, as shown in Fig. 4(B). For example, a tilt angle of 30 degrees for an index of refraction n_2 of 1.3 produces a difference of 9.3 μm between the real and apparent thicknesses. From this simulation, it can be concluded that the greater the tilted angle of the sample relative to the incoming light, the larger the difference between the real thickness and the apparent thickness from GD-OCM, resulting in potentially a significant error in the thickness measurement if not corrected. The refractive index of the sample is also an important factor, but its effect is less critical in this study.

The effect of refraction was next evaluated experimentally using a thin microscope cover slip (Schott D263M) with a given thickness of $150 \pm 5 \mu\text{m}$. For this experiment we evaluated the accuracy of the GD-OCM measurement by comparing the refraction corrected thickness estimated with a tilted sample to that evaluated at normal incidence (without refraction effect and taken as our ground truth), both measured with GD-OCM. The precision of each measurement was evaluated from 50 repetitions. The refractive index of the sample was evaluated using a projection Abbe refractometer (Model 7135) and confirmed to be 1.5155 ± 0.0015 at 840 nm.³⁹ The sample was then imaged for different tilted angles using the GD-OCM system, and the apparent thickness computed for each configuration. The corrected

thickness was calculated based on Eq. 2. Figure 5 presents the results of the thickness computed for three tilt angles (0, 12 and 17.5 degrees). The case of 0 degrees (Fig. 5(A1)) corresponds to the configuration in which the incoming light is normal to the top surface of the sample, and in this case there is no effect of refraction. The thickness in this configuration was measured to be $150.7 \pm 0.1 \mu\text{m}$ and was considered as the true thickness of the sample. The apparent thicknesses obtained with 12 and 17.5 degrees tilt angles (Fig. 5(A2) and 5(A3), respectively) were $148.8 \pm 0.1 \mu\text{m}$ and $146.7 \pm 0.1 \mu\text{m}$, respectively, and were consistent with the simulation (Fig. 4(A)). The refraction correction algorithm was then applied to the GD-OCM apparent thicknesses at 12 and 17.5 degrees to obtain the real thicknesses of $150.7 \pm 0.1 \mu\text{m}$ and $150.7 \pm 0.1 \mu\text{m}$, respectively.

Results of the experimental validation are consistent with the simulation and demonstrate that the effect of refraction correction is significant in evaluating the accurate thickness of the sample using an OCT-based system. Using the peak detection and refraction correction algorithms, the thickness of the sample can be measured with a precision of less than $0.2 \mu\text{m}$, as shown in Fig. 5(B). Also comparing the thickness at 0 degree (ground truth) with the refraction corrected thicknesses at 12 and 17.5 degrees, the accuracy is evaluated to be $0.1 \mu\text{m}$. Note that the error in the measurement increases with the tilted angle mainly due to the lower back scattering of the light on a tilted surface. Because of the latter, the limit of the detection during this experiment was reached at around 50 degrees with our system. The effect of refraction is often omitted during the evaluation of the thickness from OCT data, but the impact can be significant, as quantified here, and can therefore compromise the accuracy of the measurement in many applications, such as evaluating the parameters of the cornea.⁴⁰

Results

The refraction correction algorithm was applied to the images of the four different configurations. Figure 6 presents the summary of the results obtained in the four configurations, the first column being the configuration (A) with the contact lens in air, the second column the configuration (B) with the contact lens in water, the third column the configuration (C) with the contact lens in BSS with contrast agent, and the fourth column the configuration (D) with the contact lens positioned onto the cornea of the porcine eyeball. The first row of the figure shows the 3D volumetric images in each configuration with a good definition of the contact lens edge. The second row of the figure represents the region of interest of the cross-sectional images of the chosen frames. The third and fourth rows illustrate the results of the edge segmentation using peak detection and the polynomial fitting of the contact lens boundaries, respectively.

It can be observed from the 2D images that, besides a slight deformation of the contact lens in configuration (A), the contact lens is significantly thinner in this case compared to the three other configurations. This observation is consistent with the drying of the lens in air, even though the lens was equilibrated in the BSS before imaging. Indeed, soft contact lenses dry very quickly when exposed to air and this dryness increases when light is shone on the contact lens while imaging. Figure 7 shows the thickness profile of the contact lens versus the distance from the edge tip in the four different configurations. For each lateral position

of the lens from the edge tip, the angle of incidence was evaluated and the algorithm for refraction correction was applied to 50 successive sets of cross-sectional images per configuration to evaluate the precision of the measurements.

The evaluation of the thickness confirms the thinning of the contact lens in air compared to the three other configurations. Except for a small difference observed below 0.25 mm from the edge tip, the thicknesses in configurations (B), (C) and (D) are within the tolerance and consistent with our expectation. From this evaluation, the 3D thickness map can be computed to assess the uniformity of the experimental lens and can be used to identify defects during the manufacturing of the lens.

Discussion

The ability of GD-OCM to generate high definition images lends itself to the quantitative, nondestructive assessment of soft contact lenses, which can be done at different stages of the product development and in different configurations. Specifically, the high lateral resolution of GD-OCM allows assessing the edge shape and thickness of contact lenses with precision that falls within the demand for quality control across lens manufacturers. The technology can be used either to identify defects at the edge of contact lenses after the molding process or to evaluate their swelling when immersed in solution. This study shows that the environment into which soft contact lenses are immersed during their metrology is critical for accurate thickness measurements. Thus, soft contact lens metrology should be performed when immersed in appropriate solution, which renders the metrology challenging. In this study, the contact lens was also immersed into water because the refractive index of the water is close to that of the tear film of the eye ($n=1.332$ at 840 nm), thus anticipating the performance of the lens when fitting onto the cornea. Nevertheless, imaging of a soft contact lens submerged into BSS was also attempted. The image showed lower contrast due to the smaller difference between the refractive indices of the current contact lens and BSS ($n=0.008$). One solution we proposed to solve this issue is the use of a biocompatible contrast agent in BSS to highlight the boundary of the contact lens and evaluate the thickness. For the experimental lens used in this study, results show no significant difference in lens thickness between the saline with a contrast agent and water as solutions.

For comparison purposes, we also attempted to measure the edge-thickness of the contact lens from a cross sectional view of a slice of the contact lens under the light microscope in order to have a reference comparison. The contact lens was accurately cut in two equal parts using a razor blade and folded to keep the edge straight. The edge of the contact lens deformed drastically under the microscope illumination and focusing of the objective on the edge was too subjective, making this method of measuring the edge-thickness too unreliable to be considered. Finally, computationally intensive emerging methods for thickness estimation using OCT raw spectra may be investigated in the future as a mean to further push accuracy and precision in the estimation of thickness if such capability may be leveraged by manufacturers.¹⁹ The method proposed in this paper yields a precision of 0.2 μm and an accuracy of 0.1 μm based on the microscope cover slip validation experiment, in addition to being automatic and fast (full thickness map is generated in less than one minute

after the alignment of the lens to the GD-OCM microscope is performed).³³ Results from the current study also establish a benchmark against which other methods may be compared.

Conclusions

GD-OCM combined with conventional image processing methods was shown in this paper to provide high definition of the edge of a soft contact lens, as well as measurements of its thickness with a precision of 0.2 μm at any point from the edge tip. The capability of GD-OCM to precisely and nondestructively quantify the thickness of soft contact lenses can provide various opportunities in manufacturing, development, and medical research. The system developed may be used at the end of the manufacturing line of soft contact lenses to quantify thickness as well as to examine the quality of the final product and identify potential defects created during the molding process. The ability of imaging the edges of a contact lens with high definition may help designers of the lens finely analyze the edge for further development. In the medical perspective, as GD-OCM also provides high-resolution images of microstructures of the cornea,⁴¹ it may also be used to study the interaction between the contact lens, the ocular surface, and the tear film, which may provide insights into the impact of long term use of contact lenses.

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Figure 1. Gabor-Domain Optical Coherence Microscopy (GD-OCM) setup.³³

Figure 2. Detection of the contact lens boundaries. (A) Region of interest after segmenting the original image; (B) binary image of the detected peaks; (C) boundaries identification of the contact lens edge from polynomial fitting. Red solid line corresponds to the top surface of the CL and the blue solid line corresponds to the bottom surface of the CL. Yellow line shows the fluid gap.

Figure 3. Principle of the refraction effect. The difference between a GD-OCM data point and a real impact point is presented. The diagram helps derivation of the relationship between thicknesses and angles.

Figure 4.

Plot of the apparent thickness from GD-OCM for **(A)** four different tilted angles as a function of the refractive index of the sample, and **(B)** for three different indices of refraction as a function of the tilted angle.

Figure 5. Experimental validation of the refraction correction with three different tilting angles (**A1**) 0 degrees, (**A2**) 12 degrees and (**A3**) 17.5 degrees. (**B**) Comparison of the GD-OCM apparent thickness and the refraction corrected thickness.

Figure 6. Results of imaging and edge-thickness measurement of a soft contact lens (CL) using GD-OCM in three different configurations: **(A)** CL in air, **(B)** CL in plastic bag filled with water, **(C)** CL in plastic bag filled with saline and contrast agent, and **(D)** CL onto the cornea of a porcine eyeball.

Figure 7.

Thickness profile as a function of the distance from the edge. The thickness profile was obtained from the average of 50 successive image frames for each configuration and was corrected for refraction.