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Corneal Graft Detection for Descemet's Stripping Automated Endothelial Keratoplasty using Optical Coherence Tomography

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Abstract—**The cornea is the window of the eye and when it is severely damaged or diseased, vision is impaired. Descemet's Stripping Automated Endothelial Keratoplasty (DSAEK) is a surgical procedure to replace the malfunctioned Descemet's membrane with a healthy one in order to restore the patient's sight. After the operation, ophthalmologists need to monitor the grafted membrane to check for signs of detachment, rejection, etc. and take appropriate actions before graft failure occurs. In this paper, we introduce the COrneaL GrAft Thickness Evaluation (COLGATE) System that we developed for ophthalmologists for the evaluation of the transplanted corneal graft. We discuss the various components in our system and methods we developed. Experiments are conducted and the results are m_1 = 7.5% and m_2 = 7.2%.**

I. Introduction

THE cornea is a clear, transparent window of the eye and contributes to two thirds of our eyes focusing power. A healthy cornea should be clear and free of impurities. When cornea tissues are damaged or diseased, the cornea became cloudy and vision clarity is reduced. Cornea transplant is a surgical procedure to replace the damaged or diseased cornea with a healthy one from a donor. DSAEK [1] is an advanced procedure where the diseased Descemet's membrane is removed and replaced by the donor's healthy one. The procedure kept over 90% of the patient's cornea intact and thus has a smaller risk of rupture [2] compared to the traditional Penetrating Keratoplasty (PKP).

Optical Coherence Tomography (OCT) [3] is a technique using near infrared light to capture three dimensional images, effectively behaving like "optical ultrasound." OCT imagery can be used to examine the graft [4] after a cornea transplant is performed using the DSAEK procedure. The graft is defined to be the newly transplanted Descemet's membrane. It is of utmost interest for the ophthalmologists to observe the graft's thickness and signs of detachment. It also provides a means to detect any signs of graft rejection. Failure to detect such symptoms early may cause potential damage to the patient's eyes.

The current state of the art system is the Visante® omni OCT Anterior Segment Imaging System [5]. It provides a way for ophthalmologists to measure the thickness of the graft by manually adjusting calipers in their area of interest. It is rather tedious process and some form of automation is desired.

In this paper, we introduce the COLGATE System which is a semi-automated system we developed to facilitate the evaluation of the corneal graft based on OCT images. It aims to assist ophthalmologists to examine the graft in details and is heavily driven by their practical needs. In this paper we will discuss the methods we used to detect the graft, our experiments and their results.

The steps taken to segment the graft in a corneal OCT image are shown in Fig. 1. The system first extracts the boundary of the cornea and detects the corners of the graft. We then extract a few control points on the graft boundary and fit them to a curve. A profile of the graft thickness is then displayed to allow the user to better evaluate the graft. After the automated graft detection process is done, the user can further refine the detected graft by adjusting the control points on the graft.

II. Methodology

A. Boundary Extraction

The main challenge in extracting the boundary of the corneal OCT image lies in the removal of noise which exists in two forms. Firstly, noise from the intensity spike usually occurs near the highest point of the cornea. Secondly, interference noises can be present on any part of the image producing a region without any pixels. Fig. 2 shows a sample OCT image with the above mentioned noise. The combined effects of these two image noise leads to erroneous edge detection if we simply apply the Canny edge detector.

To address these problems, the OCT image was first filtered and converted to a binary image through the Canny

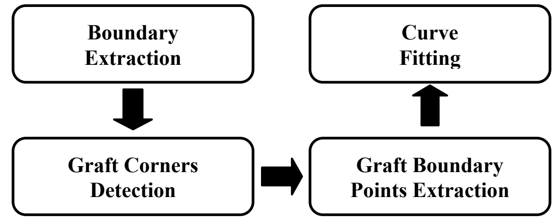

Fig. 1. System Flow in COLGATE.

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edge detector. Subsequently, the output was separated to the top and bottom aspects and sampled in steps of 10 pixels. This allows us to cut down effects of the interference noise on the on the extracted boundary. The effects of the center intensity spike are minor on the top portion of the segmented boundary so it is simply masked. For the bottom portion, linear interpolation is used to fill in the center portion affected by the intensity spike. The resulting points are then fitted to a spline enabling the extraction of a smoother and more accurate boundary essential for graft segmentation. Fig. 3 shows a comparison of our method and Canny edge.

B. *Graft Corners Detection*

In order to segment the transplanted graft, we need to locate the 4 corner points as shown in Fig. 4. We detect corners based on global and local curvature properties [6]. The boundary detected has rough edges, so the corner detector tends to return false corners for the given images. In the DSAEK procedure, a circular disc of the donor's Descemet's membrane is grafted to the patient's cornea. Examining the OCT images and consulting with the ophthalmologists confirms that corner points occur at specific regions in the images. Thus, we applied corner detectors to specific windows to at which the corner points are localized. The windows are selected based on clinical input. The 2 most likely corners within the windows are selected. Fig. 4 shows the corner points and the windows used.

C. *Graft Boundary Points Extraction*

The main task in this step is to extract the points that lie on the boundary between the patient's original cornea and the graft. This boundary has little contrast to the neighborhood so it is difficult to detect the boundary accurately. Sonar noise and the increased intensity at the center of the image further worsen the lack of contrast at anterior aspect of the boundary of the graft. We have attempted four methods to detect points on the posterior aspect of the corneal grafts and they are outlined as follows.

In the first method, we noticed that after the DSAEK procedure, a large portion of the patient's cornea is left intact. The graft is machine cut and is of roughly equal thickness in the center and gradually increasing in thickness at both ends. Fig. 5 shows the thickness of the patient's original cornea, P and the graft, G and T is the combined cornea thickness, P + G. We expect that the P/T ratio at the center region of cornea be rather consistent and gradually increases when it reaches both ends. Going through the set of ground truth OCT images, we found out that the mean P is 44.2 pixels with standard deviation of 5.6 pixels and the mean P/T ratio is approximately 0.76 with standard deviation of 0.05 in the center region. We select the P/T ratio since it has a smaller standard deviation. After that we assumed that P is of uniform thickness of 0.76T and mark the region outside P as the graft. We name this the baseline method due to its fundamental approach to the problem. The

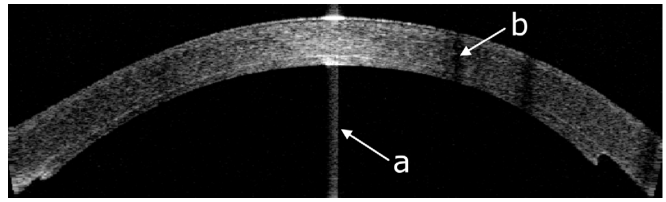
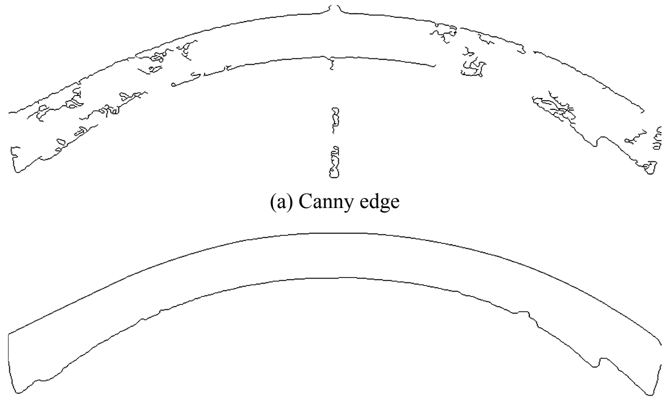


Fig. 2. Noise in corneal OCT images:
a. center intensity spike, b. interference noise.



(a) Canny edge

(b) Our method

Fig. 3. A comparison of the boundary detection methods.

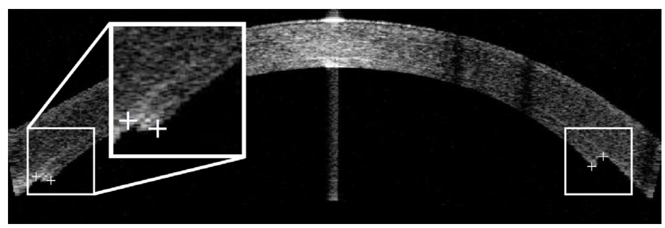


Fig. 4. The corner points detected and windows used.

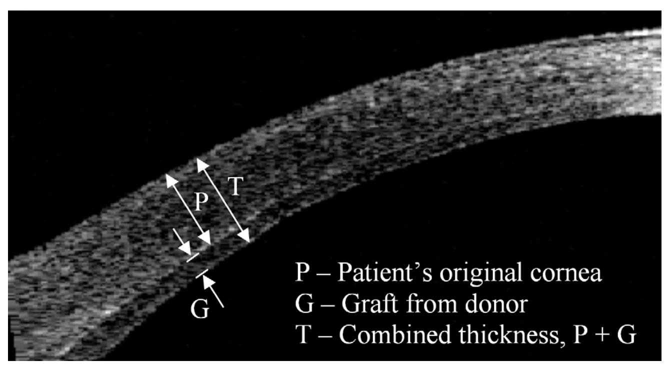


Fig. 5. The patient's original cornea and the graft.

P/T ratio could also be dependent on factors such as ethnicity, races, gender, etc. This method is also a good way to find an initial estimate of the boundary.

In the second method, we extend the first method further with the use of heuristic. We observed that the thickness of the graft slowly increase from the center region towards the edge. So, we set the value of P in the center as 0.76T and estimate the value of P at the edge to be 0.76T × (1 + c), where c range from 0.05 to 0.25. From our test, the value of c is about 0.25. The graft region is then worked out accordingly.

In the third method, we employ a Canny edge detector using threshold with hysteresis [6]. This is to enhance the detection in images as there is no fixed intensity gradient which defines an edge. This allows us to adjust the threshold values while applying the Canny edge detector to control the precision of the detection. With high threshold values, the edge detection is very precise and thus would only detect edges close to the actual boundary of the entire cornea in the OCT image. With low threshold values, the detection is less precise and thus edges detected include faint lines on the posterior aspect of the cornea graft. Performing an image subtraction of these two images allow us to extract points on the anterior aspect of the corneal graft. This method is shown to work well for center portions of the images.

In the last method, we perform Canny detector first and then apply heuristic on the region around the edge. We observed that the Canny edge detector performs badly on both end of the graft due to the large amount of noise located there. We observed that the baseline method worked better near the edges so we decided to use heuristic for these zones. First, we obtain the value of P_0 from the center region using Canny edge, and then estimate the P_0 at the end zone as $P_0 \times (1 + c)$. Using results from the second method discussed earlier, c = 0.25.

These points combined with the corner points extracted in the graft corners detection module and the information from the posterior aspect of the corneal graft in the boundary detection module, gives us enough information to segment the corneal graft.

D. Curve Fitting

In an initial inspection of the image, one would infer that the shape of the boundaries of the corneal graft would correspond to a circle or a second degree polynomial. However, fitting the data to the above mentioned graph types do not yield desirable results. Further investigations leads to the finding that different sections of the curve do not correspond to a single parameter describing the curve types mentioned.

B-spline fitting was chosen due to its polynomial nature and its ability to accommodate the irregular nature of the boundaries of the corneal graft as show in the following equation [7]:

$$P(u) = \sum_{k=0}^{n} p_k B_{k,d} \ , u_{\min} \leq u \leq u_{\max}, 2 \leq d \leq n+1$$

$$B_{k,d}(u) = \frac{u - u_k}{u_{k+d-1} - u_k} B_{k,d-1}(u) + \frac{u_{k+d} - u}{u_{k+d} - u_{k+1}} B_{k-1,d-1}(u)$$

$$B_{k,1}(u) = \begin{cases} 1 \ \ if & u_{\min} \leq u \leq u_{\max} \\ 0 & otherwise \end{cases}$$

where n is the number of control points and u is the parameter of the control points.

The set of detected control points can be further fine tuned in the manual adjustment module in COLGATE.

E. Evaluation Metric

In order to mark the ground truth for the cornea thickness of the patient and graft, we perform the following procedures. 4 lines are drawn on the OCT images and the 3 points of interest that intersects the line are marked as the ground truth as shown in Fig. 6. 2. 2 of these lines are in the middle region and the other 2 lines are drawn one on each side near the edges. These lines are stored and correspond to each image. When we run our graft detection methods, we load in the equation of the ground truth lines and then use our program to mark our detected points on those lines.

To evaluate our accuracy of the detected points, we adopt the metrics used in one of MICCAI grand challenge [8] and modify it for line segment evaluation. The modified metrics are as follows:

(a) Line overlap (m_1)

$$m_1 = \left[1 - \frac{L_g \cap L_d}{L_g \cup L_d} \right] \times 100\%$$

where L_g, L_d are the ground truth and detected line segment respectively.

(b) Relative absolute length difference (m_2)

$$m_2 = \left[\frac{|D_g - D_d|}{D_g} \right] \times 100\%$$

where D_g, D_d is the length of the ground truth and detected line respectively.

Note that both metrics would have value 0 for perfect detection.

III. Experiments and Results

To evaluate the performance of the COLGATE System, we conduct a set of experiments using a set of 27 patient's data obtained from the Singapore Eye Research Institute (SERI). The data are hand picked by an ophthalmologist in SERI so as to have a good coverage of the various types of transplanted corneal grafts that are commonly encountered in DSAEK.

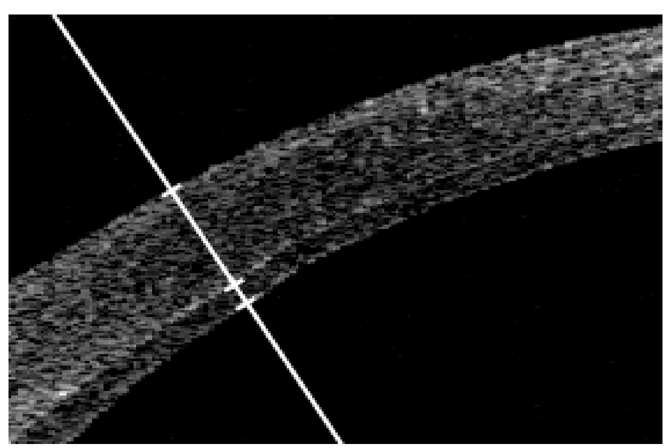


Fig. 6. The ground truth line and the 3 points of interest.

The curves outlining the total cornea thickness is automatically detected using the boundary detection method outlined earlier. We then locate the 3 points of interest on each of the 4 comparison lines and compare them with the ground truth and the results are shown in Table 1. This shows that we have a very good segmentation of the cornea detection. Table 2 shows the results we obtained in the center region. The detection for the patient's original cornea and the combined thickness is quite good. From the results, the baseline method works slightly better than Canny edge. This could be because the Canny edge algorithm is unable to locate the graft boundary accurately.

Table 3 shows the results we obtained in the region near the edge. We observed that adding heuristic improved both the baseline and Canny edge method. Amongst them, the baseline with heuristic method has the best performance.

IV. Conclusions

We have developed the COLGATE System to assist ophthalmologists for the evaluation of the transplanted graft after the DSAEK operation. Experimental results show that the system provide a reasonably good detection of the patient's original cornea, though the graft detection can be improve further. The user can further fine tune the detected curves for a more accurate graft evaluation. In our further works, we will work on better graft detection and test on a larger patient's data set.

TABLE 1
Comparison of the graft detection algorithms at the edge and center regions.

Zones	Combined, T = P+G			
	m_1		m_2	
	mean	*SD*	*mean*	*SD*
Center	9.5%	4.9%	6.5%	4.8%
Edge	8.0%	5.2%	6.0%	5.2%

TABLE 2
Comparison of the graft detection algorithms at the center regions.

Methods	Patient's original cornea, P			
	m_1		m_2	
	mean	*SD*	*mean*	*SD*
Canny Edge Only	14.1%	13.7%	8.4%	8.3%
Baseline Only	12.5%	11.8%	7.8%	7.3%

TABLE 3
Comparison of the graft detection algorithms at the edge regions.

Methods	Patient's original cornea, P			
	m_1		m_2	
	mean	*SD*	*mean*	*SD*
Heuristic + Canny	11.4%	7.4%	9.0%	9.4%
Canny Edge Only	14.0%	7.1%	9.5%	7.5%
Baseline + Heuristic	7.5%	4.5%	7.2%	4.5%
Baseline Only	12.6%	7.7%	12.7%	11.6%

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