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ORIGINAL ARTICLE

Automatic segmentation of ocular coherence tomography images of partial graft detachment following descemet membrane endothelial keratoplasty

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Abstract

Purpose: The purpose of the study was to develop a proof-of-concept image-processing algorithm for the automatic identification and area and volume quantification of partial graft detachments following descemet membrane endothelial keratoplasty (DMEK).
Materials and Methods: Multiple consecutive B-scan corneal images were acquired from four patients with post-DMEK detachment. To identify and quantify the graft detachments, an image processing algorithm was developed consisting of the following steps: Noise reduction, morphological filtering, contrast enhancement (Frangi filter), and image segmentation (using Chan-Vese and Otsu methods). The computed areas were compared to manually-delineated areas using Dice similarity coefficient.
Results: The full 21 anterior-segment optical coherence tomography image set was acquired in one patient, and 10 images captured from different cross-sections were acquired in the other three patients. Of the total 31 images, 14 included areas of graft detachment: 12 were detected by the algorithm and two were not. In one image, a detachment-like noise adjacent to the cornea's lower edge was falsely identified as a detachment. The mean Dice coefficient of the area for the 31 tested images was 0.85 (±0.25). The Dice coefficient volume, calculated in the full-image set, was 0.73.
Conclusion: Our study demonstrated the feasibility of automatically delineating and quantifying graft detachments following DMEK surgery, which can be of use in the clinical setting as well as for research purposes.

Introduction

Descemet membrane endothelial keratoplasty (DMEK) has become the gold standard for surgical treatment of corneal endothelial decompensation. Although more technically demanding than descemet stripping automated endothelial keratoplasty (DSAEK), DMEK results in better and faster visual rehabilitation and is associated with a lower postoperative graft rejection rate. The most common early post-operative complication of DMEK is graft detachment. Small peripheral detachments tend to spontaneously reattach and can be safely followed, but larger detachments can progress to total detachment and require treatment with anterior chamber rebubbling using gas or air.[1,2]

Large post-DMEK graft detachments can be identified by slit-lamp biomicroscopy. Often, however, anterior segment optical coherence tomography (AS-OCT) is used to demonstrate descemet's membrane detachment and to ascertain the correct graft orientation. With current AS-OCT modules, post-DMEK (or DSAEK) graft detachment boundaries cannot be automatically detected. Moreover, unlike macular OCT modules, AS-OCT modules do not allow for comparison of two B-scans or *en face* or volumetric reconstructed images of the cornea. Thus, graft detachments that are deemed small enough to follow-up are assessed clinically or using single B-scan AS-OCT images taken at different locations, with no real option of accurately assessing their progression or resolution.

The aim of this proof-of-concept study was to test the feasibility of performing image processing of multiple consecutive B-scan images of post-DMEK corneas to enable the detection of graft detachment edges as well as *en face* and volumetric reconstruction of the detached areas.

Materials and Methods

The study followed the tenets of the 1964 Declaration of Helsinki and the use of medical records was approved by the Ethics Committee of Rabin Medical Center. The AS-OCT images used in this study were acquired from patients who underwent DMEK at the Department of Ophthalmology of Rabin Medical Center, Israel, from March to December 2019 and were clinically diagnosed with early graft detachment.

Image acquisition

A SPECTRALIS® OCT scanner (Heidelberg Engineering, Heidelberg, Germany) was used in in all cases. The scanning area measured 15ºx10º, with 384 A-scans per B-scan. The full scan was comprised of 21 equidistant horizontal B-scans aimed at the central cornea. The distance between B-scans was 278μm; the automatic real-time tracking (ART) function was set at 23 frames. Each OCT image consisted of a line raster which provided information about the image location in the set and the distance between the images. An example is shown in Figure 1.

Image processing

Algorithm overview

The presented method was composed of several image processing and calculation steps. A schematic description of the algorithm is shown in Figure 2. The various steps are detailed below.

Extraction of corneal and graft detachment boundaries

To obtain an initial image of the cornea and detachment with minimal background noise, the Chan-Vese active contour technique was used.[3] The initial curve required by the Chan-Vese method was the boundary of a region approximating the cornea which was obtained using Otsu segmentation.[4] Hence, as not to exceed the boundaries of the cornea, the curve was slightly shrunk by applying morphological erosion with a 5 × 5-pixel square structuring element (SE) on the region obtained from Otsu thresholding, before boundary extraction.

The cornea on the binarized image contained holes and gaps that had to be filled. The correction technique was based on finding the median value of the vertical width along the cornea, and then filling this range from the upper edge of the cornea downward in each column. For further processing, separating the detachment from the cornea was required. To do so, morphological opening followed by morphological closing with the same 9 × 9-pixel square SE was applied. Subtraction of the cornea from the obtained image provided the detachment.

Extraction of the cornea's lower edge

Since the detachment forms a cavity bound on one side by the cornea's inner edge and on the other side by the graft itself, extraction of the inner boundary of the cornea can ease further processing. By scanning the image vertically, the lower bright pixel in each column was extracted, and the inner edge of the cornea could be detected. To make the cornea's inner edge continuous (i.e., without abrupt changes), morphological dilation with a 5 × 5-pixel square SE was followed by morphological erosion with a 5-pixel-long diamond-shaped SE.

Initial detection of the detachment

After the above steps, multiple detachment-like structures remained in the detachment image. To extract the desired

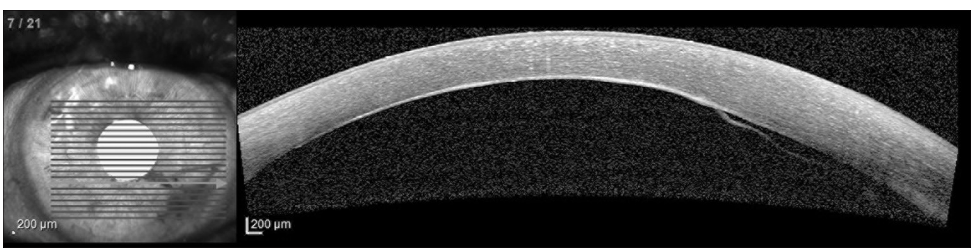

Figure 1: AS-OCT image showing partial graft detachment following DMEK. B-scan location is shown on the *en face* image (left)

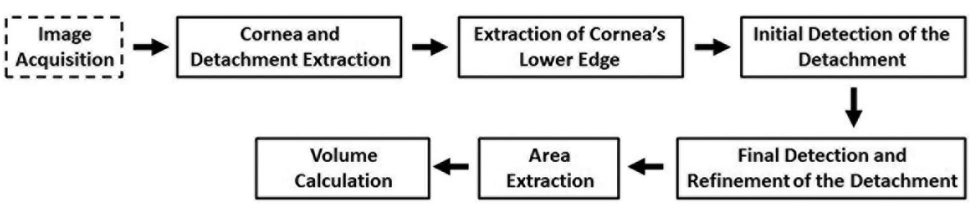

Figure 2: Schematic block diagram of an algorithm for the detection and delineation of partial graft detachment following DMEK using AS-OCT B-scan images

detachment, a few conditions were defined, as follows: (1) eliminating high solidity blobs (the solidity is the relative part of the convex hull that belongs to the object), assuming the solidity of the detachment is lower than the solidity of round-shaped noise; (2) connecting blobs with similar orientation whose centroids are close; (3) eliminating relatively small blobs; (4) keeping the blob that has a minimum number of transitions between "1" and "0."

The numerical threshold values for these conditions were based on the detachment properties. Multiple images (including some that were not part of the 21-image set) were used to ensure that the chosen thresholds fit as many images as possible and were not adapted to only a single set. The thresholds chosen were 0.8 for solidity, 65 pixels for maximal distance between blob centroids, and a minimal blob area that was half the size of the largest object in the image. The chosen blob was added to the binarised cornea, as displayed in Figure 3.

Final detection and refinement of the extent of detachment

The graft detachment's gray levels were very similar to the background noise, and consequently, parts of the detachment were considered as background in the initial detachment detection [Figure 3a]. Therefore, a more thorough investigation was conducted at the detachment surroundings. First, a rectangular region-of-interest (ROI) around the detachment was selected which was 50 pixels wider in each direction than the bounding rectangle of the detachment. This ROI was then extracted from the original gray-level image. Frangi filter[5] was applied on the ROI image, and Otsu segmentation was performed on the result. (Frangi filter is commonly used for enhancing tubular objects in a gray-level image.) The detected tubular objects were added to the initial finding of the detachment [Figure 3b]. Thereafter, the steps described above in the "Initial Detection of the Detachment" section were rerun to ensure that the most relevant structures of the graft detachment were captured.

For the gap between the cornea and the detachment to appear as a closed shape, the detachment had to be completed toward the cornea. The minimal and maximal horizontal coordinates of the detachment were located, and the detachment was continued to the left or right horizontally toward the cornea. The choice of the left- or right-side completion depended on which one was shorter.

Area extraction

Finally, the detachment was added to the cornea's lower edge, and the cavity between them was filled with "1" pixels using morphological reconstruction [Figure 4]. To disconnect the desired object (filled cavity) from the rest of the cornea's lower edge, a vertical sequence condition was applied, that is, every vertical sequence of <5 pixels was deleted. On the assumption that there was only one significant detachment in an image, the largest object in the image was identified as the desired object and its area computed.

Volume calculation

The resulting set of 2D images with identified objects as well as the set of computed areas was stored in arrays arranged according to the locations of the slices shown in the images. The 2-D image arrays were later used to generate a map of the graft detachment locations along the cornea as an *en face* image as well as a 3D display of the detachment. To eliminate wrongly detected areas, those which did not belong to a sequence were omitted.

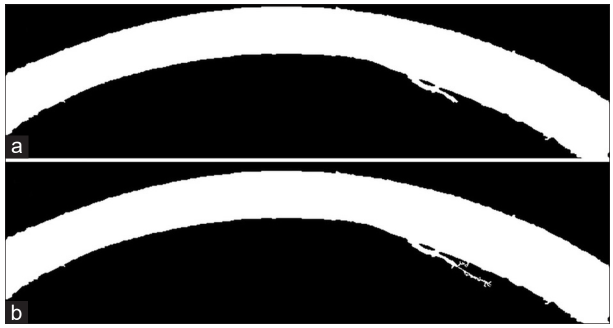

Figure 3: (a) B-scan following banalization, image enhancement, and the addition of the identified graft detachment. (b) Detachment area is further refined using Frangi filter and Otsu segmentation

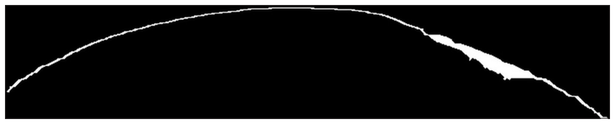

Figure 4: Graft detachment area is added to the cornea's lower edge using morphological reconstruction

The distance between adjacent images in the set was measured using the line raster shown in Figure 1. Each part of the image (grid and B-scan) contained a different pixel-to-micrometer conversion scale. The scale in the grid was used to convert the distance between adjacent images, and the scale in the B-scan was used to convert the pixels in the image plane. Hence, the conversion was calculated separately for each part of the image. Since the B-scans were equidistant, a volume unit (voxel) was calculated, and each recorded area was multiplied by the voxel size to determine the total volume.

Algorithm validation

In all processed images, the graft detachment area was manually delineated using IMAGEJ open-source software and then calculated using MATLAB software (Mathworks, Natick, MA). Delineation was approved by a cornea specialist (Y.N.). The Dice coefficient was used to calculate the similarity between the area delineated manually and that identified by the algorithm. The Dice coefficient is a spatial overlap index, which is a measure for the relative overlap between images. It is equal to the ratio of twice the number of overlapped pixels between the images and the total number of pixels in both images.

Results

B-scan AS-OCT images were acquired from four patients. In one patient, the full 21-image set of parallel equidistant B-scans was used for area and volume calculation. In the other three patients, a total of 10 images were captured and used only for area calculation and validation.

Of the total 31 images, 14 included areas of graft detachment. In the 21-image set, there were nine images that included graft detachment; eight of them were successfully detected and quantitatively analyzed. The other 12 images did not include any detachment of the graft, although in one, detachment-like noise adjacent to the lower edge of the cornea was falsely identified as a detachment.

Among the other 10 images, five included a graft detachment; four of them were successfully detected and analyzed. The other five images did not include a graft detachment and no false detections were made.

A reconstructed *en face* image is shown in Figure 5. The red marks in the figure represent the locations of the detected detachments along the cornea.

The mean Dice coefficient for the area calculation was 0.85 ± 0.25. For the full image set, the Dice coefficient was calculated for the volume as well and was 0.73.

Discussion

Our results demonstrate the feasibility of delineating and calculating the area and volume of graft detachments following DMEK. Several approaches have been used for this purpose in the past, first for DSAEK, and then for DMEK. Dhommati *et al.*[6] described an algorithm for automatic analysis of post-DSAEK graft detachments using four radial OCT B-scans. Its major steps included cornea localization, detachment segmentation, and 3D mapping. Later, Treder *et al.*[7] presented an algorithm utilizing a convolutional neural network (CNN)-based classifier to locate a graft detachment -- or lack thereof -- on OCT B-scans. Heslinga *et al.*[8] also used CNNs to automatically localize and quantify post-DMEK graft detachments on OCT radial B-scans. Scleral spur (junction of cornea and sclera) localization was used to center and extract the boundaries of the cornea from the B-scans, followed by segmentation. The length of the obtained detachment was determined by skeletonization, and an *en face* projection of the detached areas was constructed.

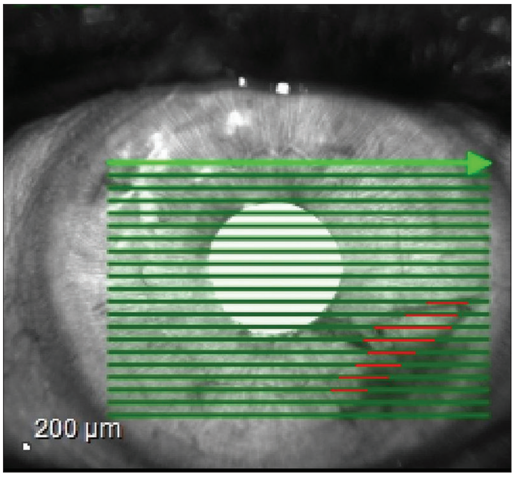

Figure 5: *En face* projection of areas with graft detachment following DMEK. Red marks represent the detected detachment locations along the cornea as identified by the algorithm in 21 separate B-scan images

In this work, we present an algorithm based on classical and simple image processing methods. Unlike CNN-based algorithms, our method does not require algorithm training or the use of large amounts of data, and it is easily reproducible.

Our algorithm missed graft detachment in two images and falsely identified a detachment in one image. While developing the algorithm, we found that a major obstacle for automatic identification of detached areas was the background noise level. Our ability to produce the highest quality images during the acquisition stage was limited by factors inherent to the examination. Specifically, we used the Spectralis ART real-time mean function to filter out background noise. However, this resulted in a longer acquisition time for each frame which was uncomfortable for the patients, leading to their movement during the examination and consequently lower image quality. Therefore, although the Spectralis produces a denser scanning profile, we used only 21 B-scans for the complete set to shorten the examination. Further studies are needed to optimize acquisition variables and standardize image acquisition for that purpose. Furthermore, other dedicated AS-OCT platforms might provide better quality images of the cornea. During the study, we considered using the Cassia platform (Tomey GmbH, Nürnberg, Germany), but it only provides sets of radial B-scans that were unsuitable for our algorithm.

Another challenge in graft detachment detection is the presence of detached remnants of the recipient's Descemet's membrane at the edge of the descemetorhexis. A possible solution could be the identification of the line orientation separating detachments emanating from the recipient side from graft detachments.

Our algorithm did not compensate for cyclotorsion movements during image acquisition. We believe that for the purpose of delineating the detachment area, these movements could be disregarded due to their small magnitude, and with averaging done during acquisition of each B-scan using the ART function in our OCT platform.

In addition to automatic detection of DMEK graft detachment, other approaches can be applied, such as manual or semiautomatic segmentation. Another simple solution is suggested by the more edematous nature of the corneal stroma above a detached area than above an attached area. Thus, comparative thickness maps showing increases or decreases of corneal thickness in different locations might provide a surrogate marker for the progression or resolution of graft detachment. However, this method is limited by several factors. First, the corneal epithelium is sometimes removed during DMEK surgery, so that areas devoid of epithelium might be identified as thinner before complete epithelization occurs. Second, even when the graft is fully attached, stromal dehydration occurs gradually, so that thickened stroma can be seen also above an attached graft. Third, as intrastromal fluids can flow laterally, thickness maps may differ from detachment maps at the edge of the detached areas.

In conclusion, this work demonstrates the feasibility of automatically delineating and quantifying graft detachments following DMEK. We believe that this method can be further refined to aid in the clinical follow-up of graft detachments. In addition, its use may enable the standardization of reporting post-DMEK graft detachments in clinical research.

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Declaration of Conflicting Interests

The authors declare that there is no conflict of interest.

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