Novel Approach for Anterior Chamber Angle Analysis

Anterior Chamber Angle Detection With Edge Measurement and Identification Algorithm (ACADEMIA)

Objective: To describe a novel approach to measuring anterior chamber angle dimensions and configurations.

Methods: Sixty-nine images were selected randomly from the ultrasound biomicroscopic image database to develop the algorithm. Thirty images were selected for further analyses. The value of each pixel of the 8-bit grayscale ultrasound biomicroscopic images was quantized into 0 (black) or 1 (white), and the edge points outlining the angle were detected and fitted with straight lines. The dimensions and profiles of anterior chamber angles were then measured.

Results: The algorithm failed to identify the edge points correctly in 8 (11.6%) of 69 images because of strong background noise. Three basic types of angle configuration were identified based on the derived angle profiles: constant, increasing, and decreasing, which corresponded to flat, bowed forward, and bowed backward iris contours, respectively. The angle measurements demonstrated high correlation with trabecular-iris angle and angle opening distance 500 (calculated as the distance from the corneal endothelium to the anterior iris surface perpendicular to a line drawn at 500 µm from the scleral spur). The strongest association was found between the averaged angle derived from the angle profile and the angle opening distance 500 ($r = 0.91$).

Conclusion: The proposed algorithm has high correlations with angle opening distance and trabecular-iris angle configuration with the added advantages of being fully automated, reproducible, and able to capture the characteristic angle configuration. However, good-quality ultrasound biomicroscopic images with high signal-to-noise ratio are required to identify the edge points correctly.

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posed by Pavlin et al, requires subjective interpretation and localization of the anatomical landmark scleral spur, and the measurement was found to have low interobserver and intraobserver reproducibility. Therefore, a more reliable and reproducible method for measuring the anterior chamber angle is warranted. The present study introduces a novel approach to measuring the anterior chamber angle. Through an automated edge detection algorithm, the boundaries of the anterior chamber angle are outlined in UBM images. The anterior chamber angle, measured in degrees, can then be evaluated based on the configuration of the outliners.

METHODS

The study was conducted in accordance with the ethical standards stated in the Declaration of Helsinki. Approval was obtained from the local clinical research ethics committee to review the UBM ocular images obtained from UBM model 840 (Paradigm Medical Industries, Salt Lake City, Utah) with a 50-Mhz transducer probe. Sixty-nine images from 50 eyes were selected randomly from the image database for the development of the algorithm and 30 were selected for further analysis. Because the objective of this study was to design an algorithm for measurement of the anterior chamber angle in UBM images, clinical information about the age, diagnosis, and refractive error was not recorded.

ANTERIOR CHAMBER ANGLE DETECTION WITH EDGE MEASUREMENT AND IDENTIFICATION ALGORITHM

The procedure for determining the anterior chamber angle involves the following automated steps: (1) image preprocessing to facilitate subsequent detection of edge; (2) detection of the edges lining the corneal endothelium and scleral-corneal and anterior iris surfaces at the iridocorneal angle; (3) fitting of the edges at the scleral-corneal and iris boundaries by straight lines to a defined distance; (4) determination of the angle by the intersection of the 2 edges. Figure 2 outlines the steps of the procedure.

Image Preprocessing

The original UBM pictures are 8-bit grayscale images. As such, the edges in many cases are not well-defined. We im-

Figure 1. Measuring trabecular-iris angle (TIA) and angle opening distance 500 (AOD 500). A, Trabecular-iris angle is defined as an angle measured with the apex in the iris recess and the arms of the angle passing through a point on the trabecular meshwork 500 µm from the scleral spur and the point on the iris perpendicularly. B, Angle opening distance 500 is defined as the distance from the corneal endothelium to the anterior iris surface perpendicular to a line drawn along the trabecular meshwork at 500 µm from the scleral spur.

Figure 2. Steps for measuring anterior chamber angles with the ACADEMIA (anterior chamber angle detection with edge measurement and identification algorithm). UBM indicates ultrasound biomicroscopic.
ported the images in PCX format directly from the UBM. The images were then converted to black and white bitmap format using the Paint program provided in Windows XP. To facilitate the detection of edges, the value of each pixel in an image was quantized into 0 (black) or 1 (white). The cutoff between black and white was determined during the conversion of the 8-bit grayscale to black and white. It converted pixels with gray values above the middle gray level (128) to white and converted pixels below the middle gray level to black. The result was a very high contrast, black and white representation of the image. In most cases, because of the removal of noises and the enhancement of contrast, the edge points became well-defined (Figure 2A and B).

Detecting the Edge Points

An edge point is the location in which there is a strong intensity contrast, ie, the transition between a pure white and a pure black region. At such a point, there are consecutive 1s in one direction and consecutive 0s in the other direction. To determine the edge points, the image was scanned line by line in a direction toward the angle apex. Within each line, the pixels were scanned in the direction from the cornea toward the iris, ie, from top to bottom (Figure 2B). The edge between the corneal endothelium/trabecular meshwork and anterior chamber (the upper edge) was defined as the transition from a white region (5 consecutive 0s) to a black region (5 consecutive 1s), as indicated by the green dots in Figure 2C. Similarly, the edge between the anterior chamber and the anterior iris surface (the lower edge) was defined as the transition from a black region to a white region (blue dots in Figure 2C). The process of detecting the edge points terminated when 2 edge points from each side met sufficiently close to the apex (within 3 pixels). Five consecutive 0s or 1s were set for the edge identification because it was tested to be the optimal pixel number in the selected UBM images. When the pixel number was set too small, the search stopped at random patches instead of the edge points. Nevertheless, these would not affect the accuracy of the robust edge-fitting if only a few of these false detections existed. When the pixel number was set too large, it would not get close enough to the apices of narrow angles.

Defining the Edges

The next step was to define the edge by fitting the edge points with a mathematical equation. This step was necessary to calculate the anterior chamber angle and was required because of inherent noise in the data. The simplest approach was to fit the edge points with a straight line. The upper edge outlining the corneal endothelium and the trabecular meshwork was relatively easy to fit with a straight line for a short distance (Figure 2D) whereas the lower edge, the anterior iris surface, was more irregular. It was impractical to fit the surface with a curve, which itself was not useful for determining the angle. Instead, a straight line was fitted to a user-defined number of edge points in the direction from the apex to the anterior chamber. Because least squares estimators are relatively sensitive to outliers in the data, we applied an error-resistant technique, namely the least absolute distances optimization technique, which gives less weighting to outliers. To construct the lines, we first determined the number of edge points to be used. Defining \((y_1, y_2, y_3)\) and \((y_1, y_2, y_3)\) to be the vertical positions of the selected upper (cornea-anterior chamber) and lower (anterior chamber-iris) edge points, respectively, we found 2 straight lines to fit the points in such a way that large errors in a few edge points can be tolerated. Let \(y_1 = a_1x + b_1\) be the line for the upper part and \(y_2 = a_2x + b_2\) be that for the lower part.

where \(x\) represents the horizontal locations of the points. We solved for the optimization problem with the following coefficients:

\[
(a_1, b_1), (a_2, b_2) = \arg \min_{a_{1,2}, b_{1,2}} \sum_{i=1}^{m} |y_i - y'_i|, \quad \arg \min_{a_{1,2}, b_{1,2}} \sum_{i=1}^{m} |y_i - y'_i|.
\]

where \(a\) is the coefficient of \(x\), \(b\) is the constant of the linear equation, \(u\) represents the upper point, and \(l\) represents the lower point. The results of fitting the edges are shown in Figure 2D.

Determining the Anterior Chamber Angle

Because the edge points were taken very close to the apex (within 5 pixels), extending the 2 straight lines until they intersect approximated the apex angle. This angle was generated automatically by an algorithm based on elementary geometry. We visually inspected the results before acceptance to make sure that the edges, and therefore the angles, were detected correctly. In the current study, the upper edge was fitted with a straight line at an arbitrary distance of 30 pixels. Because the anterior iris surface was less well-defined, different numbers of edge points were used to construct the lower edge lines, and as a result, slightly different values of anterior chamber angles were generated in a single image. Each of these values represented the anterior chamber angle averaged to a particular distance. Because angles derived using a very small number of data points are vulnerable to relatively big errors, the results were calculated based on at least 10 pixels or data points and the angle profile consisted of 40 continuous measurements with a step of 1 pixel away from the apex.

MEASURING AOD AND TIA

Although AOD 500 and TIA can be measured manually in the operation software of UBM, we specifically wrote another program using Matlab version 6.5 (The Math Works, Natick, Mass) to measure these 2 parameters to minimize the errors due to manual manipulation of the calipers. The AOD 500 was calculated as the distance from the corneal endothelium to the anterior iris surface perpendicular to a line drawn at 500 μm from the scleral spur. Trabecular-iris angle was measured as an angle with its apex at the deepest point of the iris recess and the arms of the angle passing through a point on the trabecular meshwork 500 μm from the scleral spur and the point on the iris perpendicularly opposite. The program requires the user to enter the location of the reference points (the scleral spur and the deepest point of the iris recess) and the calculations of AOD 500 and TIA then proceed automatically.

PROGRAMMING AND STATISTICS

All the software programs in this study were written in Matlab version 6.5. Statistical analysis was performed on computer (SPSS version 11.0; SPSS Inc, Chicago, Ill). The relationships between angle measurements calculated by the algorithm called ACADEMIA (anterior chamber angle detection with edge measurement and identification algorithm) and the AOD 500 and TIA were studied with linear regression analysis. Correlation was expressed as the Pearson coefficient of correlation and the Cox and Snell coefficient of determination.
RESULTS

DETECTION OF ANTERIOR CHAMBER ANGLE PROFILES

We analyzed 69 randomly selected UBM ocular images and assessed whether the algorithm could faithfully capture the changes in the anterior chamber angle. The algorithm failed to identify the edge points correctly in 8 images (11.6%) because of strong background noise, which renders the program inaccurate in delineating between signal and noise. Apart from the fact that there are individual variations in the magnitude of the anterior chamber angle, 3 basic types of angle configuration were identified: constant, increasing, and decreasing angle profiles, which corresponded to flat, bowed forward, and bowed backward iris contours, respectively. Because of the irregularity of the anterior iris surface, a few cases failed to show a definite trend, and these were classified as irregular (irregular iris) angle profiles. Typical examples of these basic types of angle configurations are shown in Figure 3. Among the 30 analyzed images, 13 had constant, 8 had increasing, 5 had decreasing, and 4 had irregular angle profiles. Although the characteristic profiles of the anterior chamber angle changes were captured by the algorithm, plotting the AOD against the distance from the scleral spur only revealed a similar rising trend and profile in each of the different types of angle configuration (Figure 3).

CORRELATIONS AND COMPARISON WITH AOD

To further characterize the anterior chamber angle measurements derived from this new approach, we measured the AOD 500 and TIA (as defined and described in the “Methods” section) and correlated these with the automatically derived angle in the 30 randomly selected images. Several different parameters could be derived from the analyzed anterior chamber angle profile. One could use the specific angle measurement at a fixed pixel distance from the detected apex. Alternatively, the median or the averaged angles could also be used as indicators of the angle depth. To identify the parameter that would be most associated with the established standards, AOD 500 and TIA, we calculated the coefficient of correlations between AOD 500 and TIA and each of the proposed measurements (Table). All the angle measurements demonstrated high correlations with AOD 500 and TIA. In particular, the median and the averaged angle derived from the angle profile provided the highest correlation with AOD 500 (both with r=0.90, P<.001). Defining narrow angle as the averaged ACADEMIA angle less than 20°, 14 angle pro-
files were classified as narrow based on the measurement in the UBM images.

There are some cases in which the AOD failed to represent the true angle depth. Figure 4 presents the scatterplots between the averaged angle derived from the algorithm and the AOD 500. Although it was evident that anterior chamber angle B appeared narrower than angle A in the UBM images, the AOD 500 were approximately the same, measuring 223 µm and 216 µm, respectively. Nevertheless, this difference in the angle dimensions was revealed both in the values and in the profiles of the derived anterior chamber angle measurements (Figure 5). A constant trend and an increasing trend were demonstrated in the angle profiles of A and B, respectively, corresponding to the angle configurations as imaged in UBM.

A number of parameters have been proposed by Pavlin et al in quantifying the relationships of anatomical structures in the anterior chamber in UBM images. Angle opening distance is a commonly used index to quantify the angle width. Trabecular-iris angle, on the other hand, requires manual determination of the positions of both the scleral spur and the deepest point of the iris recess and was considered to be imprecise and less reproducible. From the evaluation of angle dimensions in primary angle-closure glaucoma to the prospective analyses of changes in angle configurations after cataract extraction or laser iridotomy, AOD has been the established standard for angle quantification despite its poor accountability in generating reproducible measurements. Even if the errors secondary to scanning techniques, scanning positions, and physiological changes of the anatomical structures could be eliminated, it has been shown that the coefficient of variation of intraobserver measurements in reading single images could still be up to 16.97%. One of the major reasons for the low reproducibility stems from the poor identification and inconsistent localization of the scleral spur, which is the reference point for measuring AOD. The scleral spur in UBM images is identified based on the differential tissue density between the collagen fibers of the scleral spur and the longitudinal muscle of the ciliary body. The reflectivity signals in UBM may not always give a sharp contrast for an accurate delineation of the scleral spur, and the manual identification of scleral spur is prone to introducing errors in the measurements. In addition, because of the irregular iris surface, AOD is always not a reproducible descriptive index for angle. In this context, how close the peripheral iris is to the trabecular meshwork at a fixed distance is a problematic indicator. The measurement would be longer if the line falls on an iris hump whereas it would be shorter if the line falls on an iris bump. Although angle recess area had been proposed to overcome the problem of iris irregularity in angle measurement, the calculation of this parameter also requires manual input of the scleral spur location and therefore is subject to the same problem with interobserver and intraobserver variability as AOD. Therefore, the development of an automated approach to quantify the angle width is highly advantageous in providing accurate and reproducible angle readings.

In this study, we presented a novel algorithm to measure and document the anterior chamber angle dimension and profile based on UBM images. The algorithm takes special considerations to average out the variability of angle measurements secondary to iris irregularity by using the least absolute distance method. The measured angle, the ACADEMIA angle, represents the angle averaged to a defined distance. The high correlation found between AOD 500 and the median/average ACADEMIA angle ($r = 0.90/0.91$) indicates that the median/average ACADEMIA angle could provide a representative and comparable measurement for documenting angle dimensions with the merits of being less subject to the influence of irregularity in the anterior iris surface as compared with AOD. Our approach is fully automated and does not require manual identification of the scleral spur. As a consequence, the measurements are always reproducible with the same input image. In addition, the ACADEMIA angle could be a more useful parameter in detecting narrow angle configurations compared with AOD. In this study, it was found that the coefficient of determination describing the relationship between the AOD and the averaged ACADEMIA angle was 0.82 (Table), indicating that 18% of the variation could not be
explained in this relationship. One of these variations was exemplified in Figure 5 and Figure 6 demonstrating that the AOD falls short of reflecting the true angle dimension in certain cases. In contrast to calculating AOD, the proposed algorithm uses multiple points for edge fitting, thereby providing a more sensitive approach to discerning the iris profiles for angle measurements.

Another strength of the algorithm is that the irido-corneal configurations can be quantified and examined in the trend and pattern of the angle profiles. Through consecutive tracing and fitting of the detected edge points along the anterior iris surface, we found that the detected angle profiles (constant, increasing, and decreasing trends) corresponded well to the 3 basic patterns of the iridocorneal junction, described as flat, convex or bowed forward, and concave or bowed backward iris contours. These patterns, however, were not revealed from the plots of AOD against the distance from the scleral spur (Figure 3). To our knowledge, this is the first report to document the angle configuration (constant, increasing, and decreasing) quantitatively. Although the clinical relevance of each particular profile remains to be explored, quantitative analysis of the angle profile may provide additional information in classifying angle configurations and in understanding the pathophysiologic nature of the angle dynamics involved in different forms of angle-closure or open-angle glaucoma.

The merit of the ACADEMIA is that it provides a new approach for quantifying the angle dimension in a fully automated and reproducible manner without the subjective input of the location of the scleral spur, which the current standards for angle measurements (AOD, TIA or angle recess area) cannot achieve. And yet the independence of the identification of a local landmark also limits the potential of the ACADEMIA giving a precise measurement in appositional angle closure, which is 0. It is because the contact of the peripheral iris and the corneal-scleral surface could be falsely identified as the apex for angle measurement. However, from the clinical point of view, it would be less meaningful to subject an image to angle measurement if it is already evident that the angle is appositionally closed. Another limitation of the present approach is that good-quality UBM images with high signal-to-noise ratios are required for accurately determining the anterior chamber angle. Nevertheless, the success rate of correctly detecting and measuring the anterior chamber angle in the studied samples was close to 90%. Despite the fact that any intraobserver or interobserver variability can be totally eliminated in reading any single image with the ACADEMIA, other factors that could affect the measurement reproducibility cannot be avoided. These include the examiner’s technique, the position of the scanning probe, and the exact location of the scanning position on the eyeball.

In summary, the ACADEMIA was found to be an objective, standardized, and reproducible approach for an-
terior chamber angle measurement. This new algorithm enables us to quantify the dimensions and the configurations of the angle and may shed light on a better understanding of the different angle configurations and dynamics in normal and in glaucomatous individuals.

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REFERENCES