SURVEY OF OPHTHALMOLOGY VOLUME 53 • NUMBER 3 • MAY–JUNE 2008

ELSEVIER

DIAGNOSTIC AND SURGICAL TECHNIQUES

MARCO ZARBIN AND DAVID CHU, EDITORS

Anterior Chamber Angle Assessment Techniques

David S. Friedman, MD, MPH, PhD,[1] and Mingguang He, MD, MPH, PhD[2]

[1]*Wilmer Eye Institute and Johns Hopkins Bloomberg School of Public Health, Baltimore, Maryland, USA; and*
[2]*State Key Laboratory of Ophthalmology, Zhongshan Ophthalmic Center, Sun Yat-sen University, Guangzhou, China*

Abstract. Angle-closure glaucoma is a leading cause of irreversible blindness. Diagnosis and treatment are intricately related to angle assessment techniques. This article reviews the literature on angle assessment and provides recommendations about optimal techniques based on the published evidence. Specifically, we review gonioscopy, ultrasound biomicroscopy, and anterior segment optical coherence tomography, all of which can be used to assess the anterior chamber angle directly. In addition, we discuss surrogate approaches to measuring the angle configuration, including limbal anterior chamber depth measurement, scanning peripheral anterior chamber depth measurement, and Scheimpflug photography. (**Surv Ophthalmol 53**:250–273, 2008. © 2008 Elsevier Inc. All rights reserved.)

Key words. angle closure • glaucoma • gonioscopy • ocular anatomy

Introduction

Primary angle-closure glaucoma (PACG) is a leading cause of blindness throughout the world.[23,69,73] Although acute forms of angle closure are preventable through prophylactic treatment of the eye with laser peripheral iridotomy (LPI),[62,90] it remains uncertain whether or not more chronic forms of PACG can be prevented in the same way. A major challenge to developing a systematic approach to screening for angle closure and adopting universal approaches to prophylaxis remains the assessment of the anterior chamber angle (ACA). The current reference standard is gonioscopy, a technique that has substantial inter-observer variability and relies on subjective assessment of ACA findings in real time. Verifying gonioscopic findings reported in the clinical and research setting remains problematic due to the difficulty of obtaining good images of the ACA photographically.

Other approaches have been developed to aid in the assessment of the ACA. Ultrasound biomicroscopy (UBM), Scheimpflug photography, and optical coherence tomography of the anterior segment (AS-OCT) all provide some insight into the configuration of the ACA and techniques like these promise to provide more objective measures of the ACA, which may allow for more accurate determination of risk related to angle findings.

This is a review of techniques for assessment of the ACA. Each technique will be discussed along with currently used grading schemes. An assessment of the strengths and limitations of each approach will also be provided. Finally, comparisons of findings using the various techniques will be detailed.

0039-6257/08/$–see front matter
doi:10.1016/j.survophthal.2007.10.012

Gonioscopy

The current reference standard for evaluation of the ACA remains gonioscopy, a technique that was developed in the late 1800s by Trantas.[16] Trantas physically indented the sclera in order to see angle structures using a direct ophthalmoscope, an ingenuous approach, but one which certainly distorted the structures he was viewing.[95] Indentation was necessary because angle structures are not visible using direct observation of the anterior segment of the eye due to the lower refractive index of air compared with the tear film. According to Snell's law, this interface leads to total internal reflection of light because light going from a more to a less dense medium is refracted away from the normal. When a critical angle is reached (in the eye this is approximately 50°), the light is reflected internally, and the object is not visible without the use of techniques to overcome the bending of light at the tear air interface (such as using indentation or a lens). Salzmann introduced the use of the contact lens for indirect viewing of the ACA, and documented in a series of color paintings angle recession and peripheral anterior synechiae (PAS) for the first time.[76] Direct visualization of the ACA with a contact lens was developed by Koeppe who used a lens he designed in conjunction with a slit-lamp for visualization.[8,49–51] Troncoso subsequently published the first book on gonioscopy in 1947.[96] A major breakthrough was the technological innovation of Otto Barkan, who used higher magnification and better illumination to clarify further the distinctions between angle-closure and open-angle glaucoma.[7,8]

Overcoming total internal reflection of light emanating from the angle can be done with lenses that allow for direct viewing of the angle structures (e.g., Koeppe and Barkan lenses) or with mirrored lenses that give an indirect view. Although many of the early observations of the angle were performed using direct gonioscopy, in the current era—with the exception of operating room gonioscopy—the standard clinical approach is to use mirrored lenses to perform indirect gonioscopy. Shaffer and Tour reviewed at length the advantages and disadvantages of direct and indirect gonioscopy.[84] At the time of their dissertation (1955), slit-lamp illumination did not always provide stereo vision, and illumination sources were not as predictable or easy to use as in current machines. Shaffer found the direct method of performing gonioscopy more comfortable for the patient (the patient was lying down and the lenses are designed to fit comfortably on the eye), and argued that in his hands it was the preferred approach. However, he recognized that performing direct gonioscopy required a microscope distinct from the one on the slit-lamp and that such a microscope required its own mounting so that it could be maneuvered around the patient as the physician walks around the patient's head to view the entire angle (also necessitating a larger room). Such mounting can be portable or attached to the ceiling of the examination room. A further hindrance to widespread clinical use of direct gonioscopy is the requirement for a separate illumination source. Finally, a large nose can block visualization of the superior temporal angle, and the lenses used cause some astigmatic distortion.

Indirect gonioscopy (which relies on mirrors or prisms to reflect light from the angle to the viewer) has several advantages over direct gonioscopy. The patient can be examined at the slit lamp, reducing the size of the office needed and removing the requirement for extra equipment solely designed for imaging the angle. With modern slit lamps a stereoscopic view is available, and magnification can be varied as needed. Furthermore, because all light leaves the indirect gonioscopy lens normal to the face of the lens, there is no astigmatic distortion.

In an era where illumination systems for direct gonioscopy are uncommon, some have suggested approaches to indirect gonioscopic evaluation of patients who cannot position themselves in the slit-lamp. One technique is to use a streak retinoscope in combination with magnifying loupes to image the angle in a seated or supine position.[67] An alternative is to use a direct ophthalmoscope as a viewing and magnification device.[83] Table 1 outlines the

TABLE 1

Advantages and Disadvantages of Direct and Indirect Gonioscopy

Direct Gonioscopy		Indirect Gonioscopy	
Advantages	Disadvantages	Advantages	Disadvantages
Patient comfort	Second microscope and illumination	Uses the slit lamp	Bubbles can block the view
Possibly better view	Space needed	Variable magnification	Plastic can scratch
	Nose can block temporal angle	No astigmatic aberrations	Need rotating head on slit lamp to get slit view nasally and temporally
	Astigmatic distortion		

advantages and disadvantages of direct and indirect approaches.

The base curvature is a major feature that distinguishes the various indirect gonioscopy lenses. Smaller lenses that sit directly on the cornea are able to compress the cornea centrally, which allows for greater dynamic assessment of angle structures. Those with base curves extending to the sclera are somewhat less likely to inadvertently distort the angle. Nevertheless, the angle can be artifactually narrowed or widened using larger base-curve (Goldmann-style) lenses.[38,79] The lens most commonly associated with compression gonioscopy (which is no longer commercially available) is one originally produced by Zeiss (Zeiss 4-mirror lens), although many variations of this lens exist (Fig. 1). This style lens has a 9-mm diameter corneal surface (radius of curvature 7.72 mm). One reason for the popularity of this type of lens is the ease of use—there is no need to apply a coupling agent before placing it on the cornea. This not only simplifies the process of performing gonioscopy, it also leaves the anterior segment clear for later viewing of the posterior pole. However, this type of lens can more easily compress the cornea, and it is possible to unwittingly widen the ACA appearance with light pressure exerted on the cornea. Use of this style lens also requires greater expertise and training than using the coupled, steeper base curve lenses.

Goldmann-style goniolenses have larger base diameters (corneal surface has a 12-mm diameter and a radius of curvature of 7.38 mm) and therefore are less able to compress the cornea (Fig. 1). The Goldmann lenses use a mirror to reflect the light emanating from the angle, whereas Allen/O-Brien and Allen-Thorpe lenses rely on prism. These types of lenses require a coupling agent (thick artificial tears or hydroxypropyl methylcellulose are frequently used). Manipulation of the view (with some degree of indentation) can be performed with Goldmann-style lenses as well, and the angle can be opened using this technique in most cases.[21,22,25,35,36] By having the patient look in the direction of the mirror and pressing down over the mirror, one can indent the central cornea and open the angle since the cornea is under the rim of the lens when the patient looks towards it. A major advantage of this style lens is the fact that it can be held squarely on the eye without distorting the cornea, resulting in a clear view of angle structures. Recent modifications to the lens (increasing magnification in some designs, e.g., the Magnaview lens) allow for even better assessment of angle details.

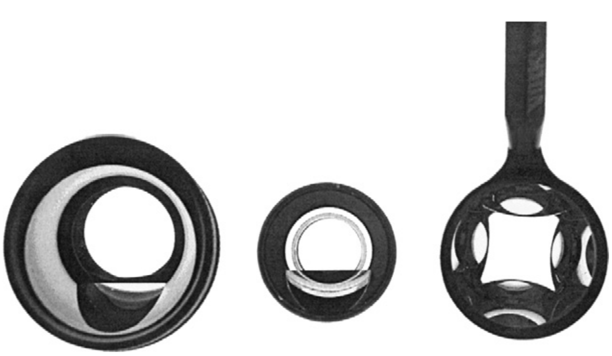

Fig. 1. Magnaview (*left*), Goldmann one mirror (*middle*), and Zeiss-style (*right*) lenses.

VIEWING THE ANGLE

Early reports on angle assessment tended to emphasize manipulations that would allow the observer to view more deeply into the angle in order to demonstrate that an angle that appeared closed was actually, if viewed in just the right way, open. At that time the only option other than pilocarpine for treating a narrow angle was surgical iridectomy, so ophthalmologists set a high standard for calling an angle “occludable.”[11,88] This mindset that the angle is “open” if an observer can see angle structures in any position or with any degree of illumination has resulted in unclear thinking about ACA anatomy and the risk of angle closure. Many angles that appear closed in primary gaze are in fact open when a patient looks in the direction of the lens (Fig. 2), or when tilting the lens slightly (looking “over the hill” of the iris).[9,21,25,33,38]

More recently, researchers and clinicians have emphasized the fact that if no angle structures are visible in the primary position of gaze (i.e., there is

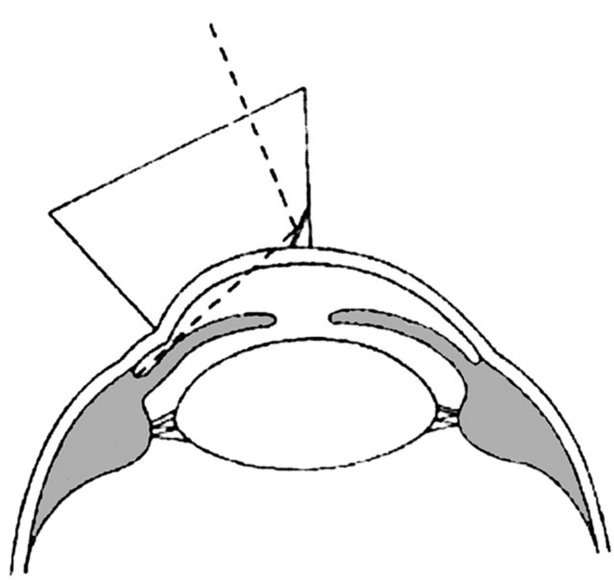

Fig. 2. Compression technique described by Hoskins (1972) for opening the angle with the Goldmann style goniolens (Reprinted from Hoskins[38] with permission of *Investigative Ophthalmology and Visual Science*.)

apparent appositional closure of the angle), then such an individual is at risk of angle-closure glaucoma.[99] We and others have clearly demonstrated that illumination conditions dramatically alter the angle configuration,[27,29] and one would expect that degree of dilation would also alter the amount of angle closure seen.[70] Certainly if an angle is closed on gonioscopy in the darkest possible conditions, but opens with increased illumination, that angle is closed on and off throughout the day. One exception may be when viewing an angle with a steep approach. Such angles can often appear much more open with only a minor tilt of the lens. How to classify such angles (ones where looking over the hill of the iris one can see all structures) remains a source of debate. Therefore our approach to angle assessment is to view the angle in primary gaze allowing for minor adjustments of the lens to improve the view. In research settings limiting the amount of manipulation of the lens may allow for a more reproducible assessment of angle findings. Clinically, it is unknown whether or not angles that have a steep iris profile but are open with changes in gaze or tilting of the lens, are at greater risk of angle-closure glaucoma.

ARTIFACTS WHEN PERFORMING GONIOSCOPY

There are multiple artifacts that can be created during indirect gonioscopy. Pressure on the larger base lenses can lead to compression over Schwalbe's area and result in narrowing underneath the area of compression and widening of the opposite angle.[79] This can result in misclassification of angles. Alternatively, the angle can be artifactitiously widened when the lens is not centered on the cornea. Localized corneal compression can cause fluid displacement and subsequent widening of the angle.[38] Similarly, with smaller base, Zeiss-style lenses the cornea can be inadvertently compressed leading to image distortion (limiting angle interpretation), or angle widening or narrowing depending on how the compression is placed.[18]

INDENTATION AND MANIPULATIVE GONIOSCOPY

Once an angle is viewed with the patient looking straight ahead in dim illumination and it is determined that there is iridotrabecular contact, additional efforts are needed to determine if the angle is appositionally closed or if there are permanent PAS. Initial approaches to visualization of the ACA to distinguish synechial closure from appositional closure included the use of saline injected into the anterior chamber at the time of surgery (this allowed the surgeon to decide whether or not to perform an iridotomy or a filtration procedure),[11] the use of osmotics such as mannitol to decrease vitreous volume, and ultimately, the use of compression gonioscopy as described by Max Forbes (Fig. 3).[18]

Indentational and manipulative maneuvers to view angle structures that are not readily visible are intended to demonstrate iris processes and PAS. Although PAS are frequently discussed in research and clinically are an important clue to the likelihood that angle closure is pathologic in a given patient, no standard approach to defining PAS exists in the literature, and many articles reporting on PAS do not clearly state the definition used. Foster has attempted to distinguish between PAS and iris processes and notes that PAS typically are broader at the base than at the apex, more elevated than iris processes, and have a more saw-toothed pattern.[55] However, this definition still leaves much room for subjective interpretation of angle findings, and iris processes can appear confluent, making them difficult to distinguish from PAS in some persons. PAS are abnormal adhesions of iris tissue to the corneo-scleral wall, and typically are not felt to be clinically significant if they form at the level of

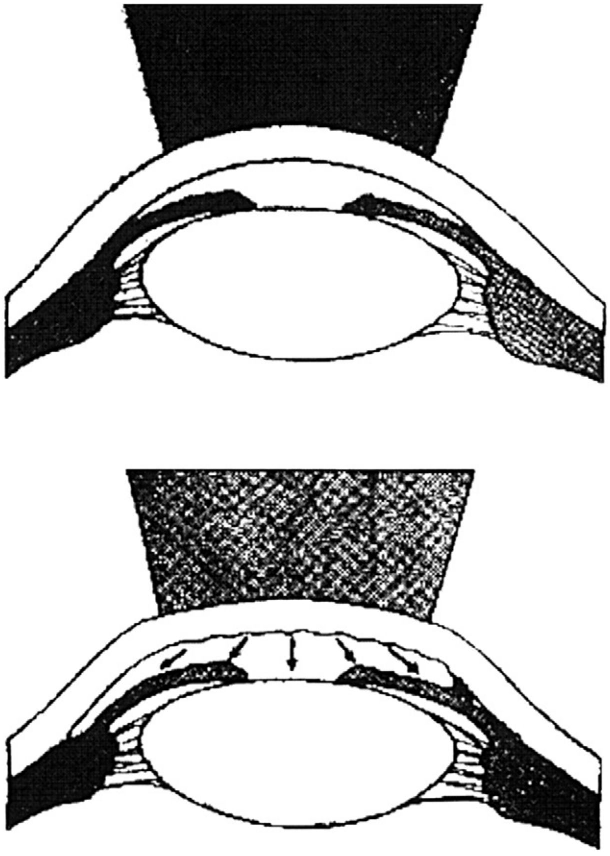

Fig. 3. Compression gonioscopy using a four-mirror Zeiss-style lens as described by Forbes. (Reprinted from Forbes[18] with permission of *Archives of Ophthalmology.*)

scleral spur or below. How wide they have to be to be called "present" is unclear, and distinguishing PAS from iris processes may be problematic. In one of the only publications to assess iris processes in detail, Lichter reported on 340 eyes of 175 subjects (nearly all below the age of 30 years, presenting for refraction).[6] He defined iris processes as "tissue connecting the iris to the angle wall, either bridging or wrapping around the angle recess." It is not clear from the publication how PAS were excluded using this definition. Based on a Zeiss lens evaluation, and using a grading scheme that he devised (which was not validated), he reported that fewer than 10% of this relatively young population had many iris processes (grades 3 or 4), and nearly half had no iris processes. Iris processes were not associated with IOP in this population, and he concluded that iris processes were not pathologic.

One of the earliest reports on PAS referred to them as "pigment bands," which were only clearly seen after iridectomy. These bands were felt to contribute to the failure of some persons to have normalized IOP after iridectomy.[5] Barkan also reported that PAS were associated with narrow angles even when an acute attack did not occur. The presence of PAS was recently found to be associated with angle width.[20] Foster and colleagues reported on the prevalence of PAS (defined as ≥ 1 clock hour at or above the level of the scleral spur) in Mongolian and Singapore Chinese subjects (none of whom had prior surgery).[35] PAS were more prevalent in persons with narrow angles, but even some with mean angle width over 30° had PAS. There was a monotonic relationship between angle width and the presence of PAS with the narrowest angles having the highest likelihood of PAS. Similar findings were reported by He and colleagues in a population based study in southern China.[35] Subjects with Shaffer iridotrabecular angle (ITA) of 3 or 4 virtually never had PAS in this population, whereas 1.9% with ITA of 2, 12.6% with ITA of 1, and 27.5% with ITA of 0 had PAS as defined in that study. In a study of patients from 7 Asian countries enrolled in a trial of PACG in which all subjects had an IOP > 21 and PAS (defined as abnormal adhesions of the iris to the angle that are at least half of 1 clock hour in width and are present to the level of the anterior trabecular meshwork or higher), the mean number of clock hours of PAS was 4.8, and there was weak correlation between the number of clock hours and the gonioscopic angle width ($R^2 = 0.20$).[24] The number of clock hours of PAS was also correlated with IOP.

The development of PAS is clearly pathologic. Two studies have documented that higher IOP is associated with the presence and amount of PAS,[3,24] and there is preliminary evidence that appositional closure may damage the trabecular meshwork prior to the formation of PAS.[86] Understanding why some persons with narrow angles develop PAS and others do not is a key missing component in our knowledge of the pathogenesis of PACG. Furthermore, a greater understanding of the impact of appositional adherence of the iris to the trabecular meshwork will help clinicians determine who needs a laser iridotomy and who can be monitored.

GRADING SCHEMES

Gonioscopy is performed for several reasons: 1) to determine the mechanism of glaucoma (i.e., open or closed angle, pigment dispersion, plateau iris, etc.); 2) to identify persons at risk of developing angle closure glaucoma; and 3) to monitor changes in the ACA over time as part of clinical care or research. A highly reproducible approach and grading scheme are essential for appropriate classification of persons as having open, at-risk, or closed angles.

The ACA anatomy is complex. The observer sees the apparent and true level of iris insertion, the angle of opening, the contour of the iris, and the pigmentation of the ACA structures. Because natural history data are lacking, it is unclear which angle findings predict clinical outcomes, and which persons are at high risk of suffering harm due to narrow or closed angles. Several grading schemes have been proposed for documenting angle findings seen on gonioscopy, most notably those by Shaffer, Scheie, and Spaeth. Two key considerations often not addressed in the original papers on how to use these grading schemes are: 1) should the angle be assessed in primary gaze or should the patient be allowed to look around to allow for the most open view to be obtained; and 2) what should the level of illumination be when doing gonioscopy. As stated previously, these two factors can dramatically alter the angle findings, and yet, most research reporting on gonioscopy does not clarify the conditions under which gonioscopy was performed. A recent consensus document published by the Association for International Glaucoma Societies proposed that the ACA should be viewed in a dark room using a 1-mm beam with adequate illumination to visualize angle structures clearly with the patient looking straight ahead.[99] This approach allows one to see the corneal wedge, it minimizes the angle-opening effect of illumination, and it avoids artifactitiously widening the angle by manipulating the lens.

SCHEIE SYSTEM

This system, published in 1957, attempted to categorize risk of angle closure based on gonioscopy, although no prospective studies were performed for validation purposes.[78] The ability to see ACA structures is the key element in this grading system (Fig. 4). The system labels the degree of angle closure such that a Scheie grade zero is a wide open angle. Grade 1 is "slightly narrow," grade 2 means that the ciliary body root is not visible, and grade 3 means that the posterior (pigmented) trabecular meshwork is not visible. Grade 4 is closed, meaning that no structures are visible. Scheie believed that persons with grade 3 and grade 4 angles were at greatest risk of angle-closure glaucoma. In addition to grading the structures seen, Scheie also recommended recording the degree of pigmentation and was one of the first to divide the trabecular meshwork into pigmented and non-pigmented regions. As stated previously, there was no clear discussion of the conditions under which the angle should be viewed, and whether or not manipulation of the view (e.g., having the patient look into the lens) was permissible using this scheme. No studies have been published documenting the reproducibility of using this grading scheme either within an observer or between observers.

SHAFFER SYSTEM

The Shaffer system uses the opposite approach of the Scheie system, grading from closed (grade 0) to wide open (grade 4).[83] The use of opposite grading schemes can cause confusion, and it is important to be clear as to which scheme is in place (Shaffer grading seems to be dominant at this time).

The angle width is based on two lines, one drawn from the angle depth to Schwalbe's line, and the second drawn through the iris starting from the base of the angle. A later modification of this by Spaeth recommended that the line through the iris be drawn as a tangent to the peripheral third of the iris.[88] Angles between 35° and 45° are grade 4, those 20°–35° are grade 3, those 10°– 20° are grade 2, and those ≤ 10° are grade 1, with a closed angle (zero degrees) is grade 0. Shaffer also reported the structures that should be seen for each of these grades, stating that grades 2–4 allow visualization of the CB, whereas grade 1 allows visualization of the posterior pigmented trabecular meshwork.[81] This is confusing, as there are angles that may not fulfill both criteria and it is not clear from the original papers how the system should be employed when width and structures seen place an angle into different categories. Current practice appears to be to use angle width when describing the angle using the Shaffer system and to use structures when describing the ACA using the Scheie system.

The Shaffer grading scheme has been widely adopted clinically and in research, although the reliability of this approach has not been tested. No intraobserver reproducibility studies have been published. Those reporting inter-observer reproducibility on convenience samples of patients (which likely underestimate the proportion of difficult cases since open angles are relatively easy to categorize), have found weighted kappa values in the range of 0.6 using a Goldmann lens.[3,21,25] No reports using Zeiss-type lenses have been published, but it is likely that reproducibility would be lower using this approach, given the greater skill level required.

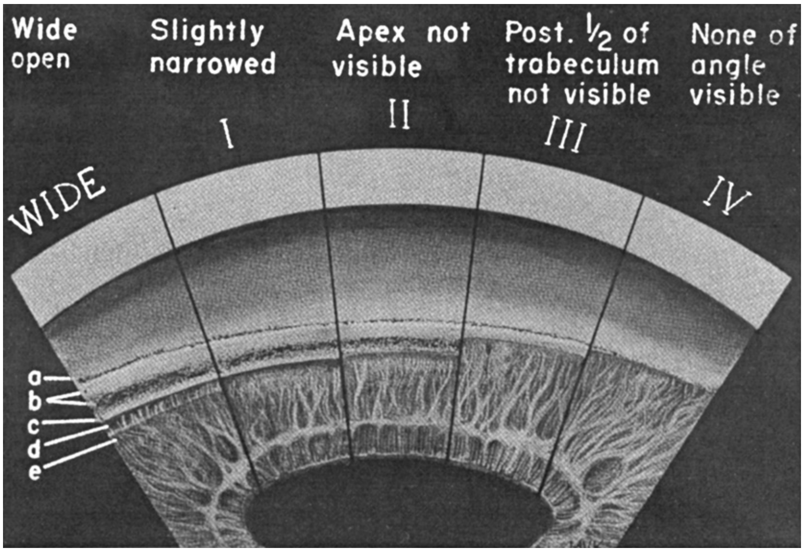

Fig. 4. The original Scheie classification scheme as published in *Archives of Ophthalmology.* (Reprinted from Scheie[78] with permission of *Archives of Ophthalmology.*)

SPAETH SYSTEM

The Spaeth system was designed to give a more comprehensive and readily communicated approach to angle assessment (Fig. 5).[88] The emphasis is on describing what is seen in the angle, which is divided into three findings: 1) the angle of insertion (described by estimating a tangent to the endothelial surface of the cornea, but the exact location along the curve or the cornea is not stated) and a tangent to the anterior surface of the iris, measured at the point of Schwalbe's line; 2) the configuration of the iris; and 3) the level of iris insertion. The level of iris insertion is reported from most anterior to most posterior: A = anterior to Schwalbe's line, B = behind Schwalbe's line, but anterior to scleral spur, C = posterior to scleral spur (i.e., scleral spur visible, but not ciliary body), D = ciliary body visible, and E = large amount of ciliary body visible.

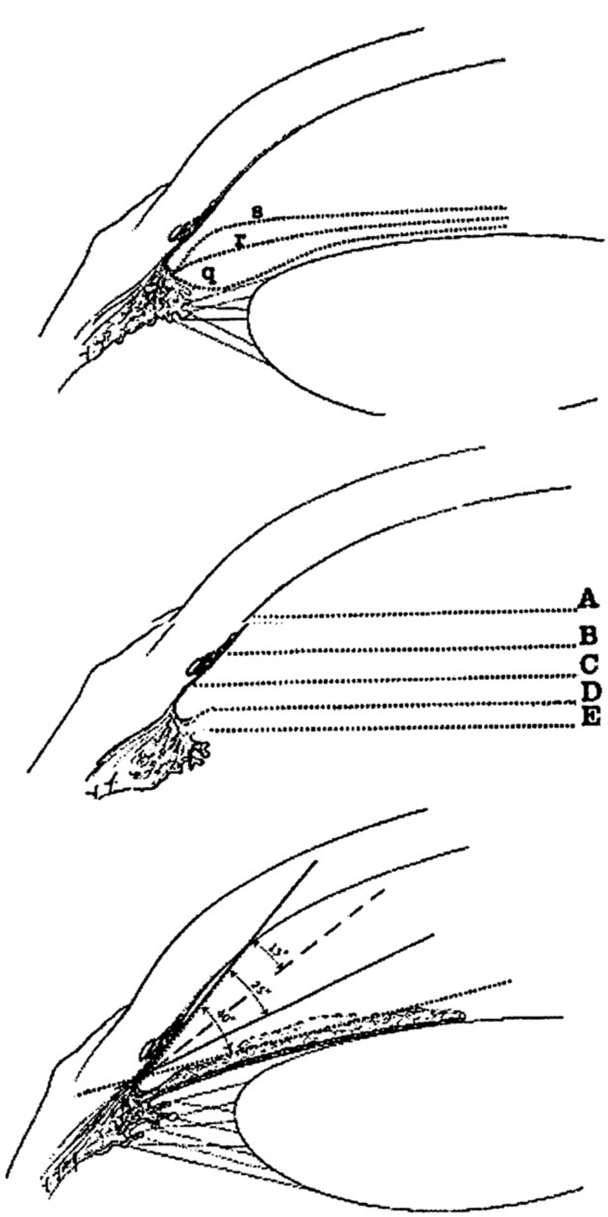

Fig. 5. Spaeth classification scheme for gonioscopy. (Reprinted from Greenridge[34] with permission of *International Ophthalmology Clinics.*)

In addition, the Spaeth system reports both the apparent insertion point of the iris as well as the true location of iris insertion (after manipulation or compression). Finally, the Spaeth grading scheme also rates the amount of pigmentation in the angle (as graded in the 12 o'clock position) and the presence or absence of PAS. Pigmentation is graded as none, just visible (grade 1), more visible, but mild (grade 2), moderately dense (grade 3), and dense (grade 4). The definition of PAS is not clearly described.

The iris configuration is reported as "r" (regular), "s" (steep), or "q" (queer, or backward, bowing).

One limitation of this approach is that it does not separate the steep, smoothly bowing iris from one that is steep in the angle and more flat centrally (a "plateau" configuration). A suggested modification of this approach adding a "p" configuration has been proposed and used in recent research.[3,21] This appears to be an important addition to the grading scheme as it may point to different mechanisms of angle closure (and perhaps different clinical outcomes) based on iris morphology. Furthermore, as the figure used to describe this condition shows, Spaeth's classification scheme did not implicate the ciliary body as the cause of the plateau iris configuration.

The Spaeth system has been studied for its reproducibility and comparability to UBM in 22 patients in whom the anterior chamber angle was felt to be easily visualized (non-consecutive patients).[90] Five of the 22 subjects were excluded because the two observers did not agree on the gonioscopy findings. The correlation between UBM angle grade (it is not clear which angle was compared) and Spaeth grade in the remaining 17 subjects was extremely high. Based on the tendency for UBM to identify angles as somewhat shallower than was seen on gonioscopy, Spaeth recommended that the angle width determined gonioscopically be rounded down instead of up when it is in between grades.

QUANTITATIVE GONIOSCOPY

As early as 1940 Sugar suggested the use of a graticule attached to the ocular of a magnifying lens to help improve the reproducibility of measurements of the angle width, but did not present data on the use of this technique.[91] More recently two researchers have proposed quantitative assessment of angle grading to improve statistical analysis of gonioscopy findings. Cockburn reported a linear angle grading scheme in order to increase the reproducibility of gonioscopy findings (Fig. 6).[13] His approach was to use the combined width of the trabecular meshwork and the scleral spur (using the corneal wedge to mark the start of trabecular meshwork) as a unit and to grade the angle width using these units. The approach was to allow the lens to be manipulated to allow the maximum visible angle without distorting the view through the cornea.

This approach was tested in the superior angle only on 50 patients who were examined 3–7 days apart. The mean angle width of this population was 1.2 units, and the R^2 value for repeated measurements was 0.56 for a single observer. The major limitation of this approach is the use of the trabecular meshwork in the standardization process, as the trabecular meshwork width can vary substantially, and identifying the anterior most portion of the trabecular meshwork may be problematic (especially if the corneal wedge cannot be visualized). Also, allowing manipulation of the lens and the patient viewing angle is likely to introduce variability into this measure, and will tend to call angles as more open than they may truly be.

Congdon and colleagues attempted to improve on this quantitative approach to gonioscopy, and added a graticule to the slit-lamp ocular to allow standardized measurement of the length of the angle recess (Fig. 7).[15] A reticule was mounted on the slit-lamp ×10 ocular segmented in 0.1-mm increments. The investigators allowed patients to look into the lens, and used bright illumination, attempting to grade the maximum width of the angle from the angle depth to Schwalbe's line. They reported on 21 subjects selected specifically to include a range of findings (10 angle-closure patients, 4 pigment dispersion patients, 5 with POAG, and 2 with pseudoexfoliation). The mean of all four quadrants was calculated based on the findings using both a Zeiss-type and a Goldmann-type lens (although which lens findings were used is

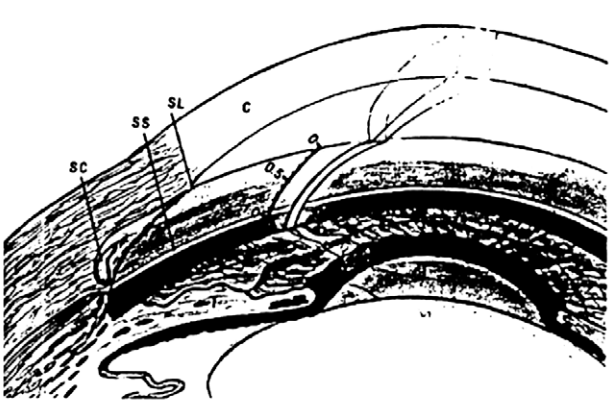

Fig. 6. Cockburn method for measuring extent of angle opening. (Reprinted from Cockburn[13] with permission of *American Journal of Optometry and Physiological Optics.*)

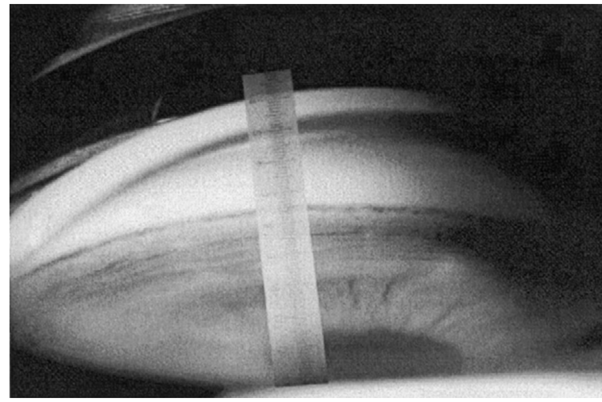

Fig. 7. Congdon biometric gonioscopy technique. (Reprinted from Congdon et al[15] with permission of *Ophthalmology.*)

not clear). The same subjects were imaged with the Scheimpflug camera and underwent gonioscopy with Spaeth grading by a separate observer. The mean biometric grades were reported for groupings based on Spaeth angle width and iris insertion (showing an increase in biometric gonioscopy with increasing width and lower insertion), but the means were likely based on three to five persons per group (confidence intervals were not reported). The authors also studied the ability of a naïve observer to learn and perform biometric gonioscopy and reported good agreement with an expert observer (intraclass correlation coefficient = 0.97 versus intraclass correlation coefficient = 0.84 for Spaeth grade of iris insertion).

Although biometric gonioscopy under bright illumination appears relatively reproducible, and was validated against a second ACA imaging device (Scheimpflug photography), the units reported give no detail about the structures seen, and therefore the technique offers only limited insight into the angle configuration. Some have questioned the impact that this illumination has on the appearance of the angle. Neither of the two linear estimates of angle opening have been widely adopted.

GONIOSCOPY FINDINGS: ANGLE VARIATION, SEX DIFFERENCES, AND CHANGES WITH AGE

Few authors have documented variations in angle findings by quadrant. A recent study from southern China reported on the gonioscopic findings in 1,330 eyes of 1,405 participants in a population-based study.[3] The superior angle was most frequently documented as having a grade A or B insertion (using Spaeth criteria, 27%), and the nasal angle was most frequently grade C or higher (92%). Angle width was only recorded in the superior and inferior angles, and was found to be wider inferiorly. This finding largely supports a non-quantitative assessment by Otto Barkan published in 1935.[8] Two additional publications agree with this conclusion,[82,87] although few studies have looked directly at this issue.

Population-based studies have frequently documented higher rates of "occludable angles" among women and older persons.[2,3,19,21,30,76] Similar findings have been reported in studies of the incidence of acute angle closure attacks.[80,101] The most likely explanations for a higher prevalence of PACG among older persons is the increase in lens thickness that occurs with age.[1,12,56] This leads to crowding of the anterior segment. In addition, it is postulated that the zonule becomes more lax with age, allowing anterior movement of the lens/iris diaphragm. Although it is clear that PACG prevalence increases with age, few studies have assessed the distribution of angle findings across a wide age range, and none to date have assessed a population prospectively to see how the angle configuration changes.

Women tend to have shallower anterior chambers, which may predispose them to angle closure.[20] Spaeth assessed the impact of sex and age on angle configuration.[88] He enrolled 759 white subjects 5 to 79 years of age. Subjects were selected from three locations: a U.S. government agency, a kindergarten through ninth grade private school, and private homes for the aged. Spaeth found that the angle width decreased with increasing age, and that pigment in the angle increased with age, but there were no differences in angle configuration comparing men and women. Only 10 cases were identified as having closed angles. In a clinic-based study of 291 subjects without pre-existing ocular disease, Oh and colleagues reported an average angle width of 33° for men and 31° for women ($p < 0.5$), but did not perform a multivariate analysis.[62] Older age was also associated with narrower angles in that paper. Congdon and colleagues used biometric gonioscopy to compare the anterior chamber angle on Chinese, African American, and white subjects.[14] Chinese subjects were enrolled from a population-based study in Singapore, whereas the African American and white subjects were living in the United States and were identified in medical emergency rooms and vision screening programs. Comparing the mean biometric gonioscopy grades for all four quadrants showed no differences by race. However, angle width decreased with increasing age, and decreased more rapidly among Chinese subjects than among the other two groups. No differences in angle findings were noted between men and women, but many of the lowest measurements were seen among older Chinese women. A similar finding with no difference in biometric gonioscopy between sexes but a decline in angle width with age was seen among Alaskan Eskimos.[100] A recent population-based study of eye disease from Guangzhou, China, reported that angle width was narrower in women and in older persons using both a Spaeth and Shaffer grading scheme.[3]

In summary, the angle appears to narrow with age, and this is largely due to increasing lens thickness. Studies consistently find that older persons have narrower angles. PACG is more common among women, but only one population-based study has concluded that women had narrower angles than men when using gonioscopy. Although there may in fact be no differences in angle configuration between men and women, it is highly likely that the failure of some studies to detect a difference is due to intra and inter-observer variability in gonioscopy results in these studies.

GONIOSCOPY CONCLUSIONS

Gonioscopy is the current reference standard for assessing ACA structures and configuration. It requires a subjective assessment by an observer placing a contact lens on the eye of the patient. Definitions of angle findings vary across grading schemes, and no single scheme is used, although the Shaffer angle width appears to be commonly reported in research. Gonioscopy is prone to potential measurement errors including artificially opening the angle or closing the angle due to how the lens is placed on the eye. Reproducibility of gonioscopy has only rarely been studied in small samples of patients, with moderate agreement reported. This variability (even when conditions are standardized) is a cause for concern when assessing reports on angle closure because gonioscopy findings often define the condition.

Angle assessment is essential for determining treatment—in particular, for deciding whether or not to perform laser iridotomy. This article does not attempt to address the issues underlying this clinical decision. However, based on accumulating evidence in the literature that appositional closure may be harmful to trabecular function, and associations now found between degree of angle opening and the prevalence of PAS and elevated IOP, there appears to be an increasing belief that the term "occludable" should apply to angles with 180° of appositional closure as opposed to the previous definition of 270°.[99] Some have argued that any appositional closure is pathologic, but this remains controversial.

Anterior Chamber Angle Assessment by Ultrasound Biomicroscopy

An alternative approach for viewing the ACA is UBM, a technique that was developed in the early

1990s (Fig. 8). The use of a higher frequency transducer allows for a more detailed assessment of the anterior ocular structures than was available using traditional B-scan ultrasound.[62,66] It also decreases penetration (to only 5 mm), but increases the resolution of the imaged structures. Lateral and axial resolutions are estimated to be 40 and 20 microns, respectively.

The initial report of this device used a 100-MHz probe on cadaver eyes and compared the findings to histological sections.[67] The first case series reported on 14 patients with various ocular abnormalities using a 50-MHz probe.[65] The prototype device had poorer resolution than later devices and relied on a rudimentary water bath made by suspending a surgical drape from a metal hoop. This report was the first to suggest the use of angle opening distance (AOD) at 250 mm (AOD 250) from the scleral spur as a potentially reproducible means of assessing the ACA. This location was selected on the assumption that the trabecular meshwork is in this region (Sugar reported on pathologic specimens that the distance from scleral spur to pigmented trabecular meshwork was in this range[91]), and therefore if the iris was in apposition here, there would be no flow of fluid through the meshwork. The AOD 250 (and the AOD at any other distance) is calculated by drawing a line from the scleral spur to the point on the corneal endothelial surface 250 microns away, and then drawing a perpendicular to the corneal endothelium down to the iris surface (Fig. 9). The AOD 250 and all other measurements

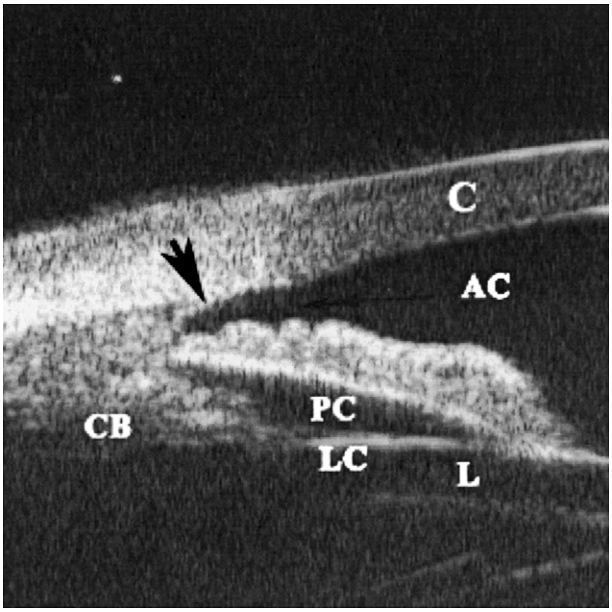

Fig. 8. Ultrasound biomicroscopy of the anterior chamber angle: Arrow points to the scleral spur. C = cornea; AC = anterior chamber; PC = posterior chamber; CB = ciliary body; L = lens; LC = lens capsule.

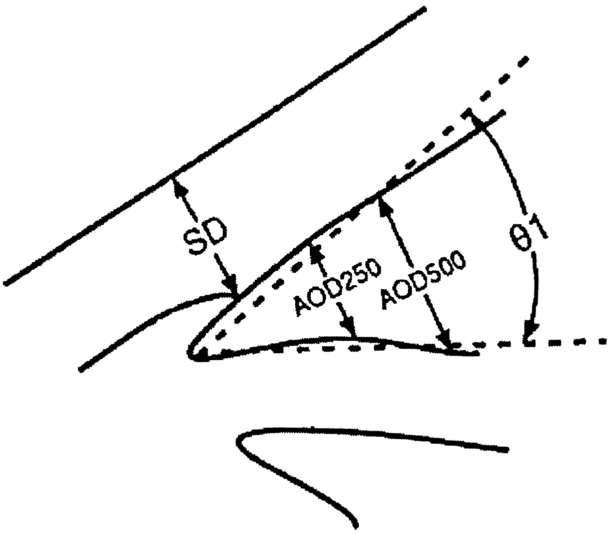

Fig. 9. Quantitative anterior segment analysis as proposed by Pavlin. AOD 250 and AOD 500 = angle opening distance at 250 microns and 500 microns, respectively. (Reprinted from Pavlin et al[64] with permission of *American Journal of Ophthalmology*.)

of AOD are therefore somewhat influenced by the variability in the anterior iris surface since a relatively high point along the iris will yield a smaller AOD, and a relatively lower point will yield a larger AOD. The AOD 250 is rarely used at present due to the high variability in iris configuration at this location. Authors have tended to rely on the AOD at 500 microns as the best estimate of angle opening. No prospective studies have assessed the importance of the AOD findings in the development of angle closure.

Pavlin and colleagues also attempted to define the angle in degrees, once again encountering the problem of the where to put the apex of the angle (at the level of the scleral spur or at the level of the greatest angle depth), and how to draw the lines emanating from this point. They proposed the superior line be drawn through the trabecular meshwork (i.e., 250 microns from the scleral spur), and the inferior one along the iris (although how this "through the iris" line was to be drawn was not clearly specified). Further development of UBM technology included the addition of an eyecup to simplify the creation of a water bath (however, the eyecup may exert a compressive force on the sclera and artificially narrow the angle) and the development of an articulated arm to allow more precise control over the ultrasound tip. The updated device scanned five frames per second and assumed the speed of sound in the ocular tissue to be 1,540 meters/second, although additional research was planned to determine more precisely what value should be used (however, no further mention is made of whether or not this assumption was altered in later models of the device).

The authors published a series of "normal" patients (no details are given on how these patients were selected) and documented a wide range of findings in temporal angle measurements.[64] They reported that the AOD 250 mean was 347 microns, with an SD of 158 microns. Iris thickness also varied to a similar extent. Interestingly, the most myopic subject studied (−5.00 diopters) had an AOD 250 of 125 microns, one of the narrowest measurements recorded in this small sample. The authors also reported on the AOD at 500 microns from the scleral spur, arguing that this would fall on the anterior trabecular meshwork and therefore might also be clinically significant. In this publication the authors recognized that defining the angle in degrees is somewhat subjective due to variation in iris configuration, and proposed a uniform approach by drawing a line from the deepest recess of the angle through the point along the corneal endothelial surface 500 microns from the scleral spur to create the superior line, and then drawing the inferior line through the point on the iris where a line perpendicular to the point at 500 microns from the scleral spur was drawn. Although this approach may lend uniformity to how the angle is drawn, it is a relatively simplistic representation of angle width because it ignores changes in iris configuration near the scleral wall (it would not identify plateau iris, for example). Others have described the angle width placing the apex at the scleral spur. Pavlin and colleagues also described other parameters that could be used to describe the angle structures including the trabecular-ciliary process distance (TCPD) which offers insight into the width of the space of the angle recess that must accommodate the iris, the iris-ciliary process distance which estimates the size of the posterior chamber, and the iris thickness (or distance, ID) at three different locations, also in an effort to describe the relative congestion of the angle (Fig. 10).

UBM measurement of angle structures can be influenced by variation in image acquisition, image analysis and physiological variability. Inconsistencies in alignment and failure to control accommodation and room illumination can alter the findings when using UBM. Direction of gaze can be standardized by placing five markers on the ceiling to optimize orientation of the eye when measuring different quadrants.[97] Other sources of variability are more difficult to control and there is an element of subjectivity inherent in angle imaging with this technique.

An important initial limitation of UBM technology is the difficulty in image analysis when observers

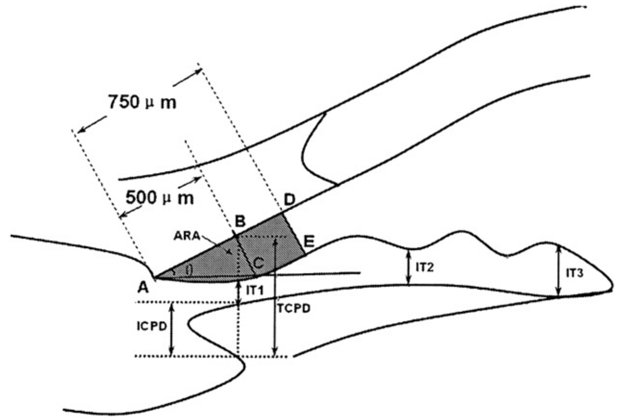

Fig. 10. Parameters used to describe anterior chamber angle structures using ultrasound biomicroscopy. ARA = angle recess area at 750 microns anterior to the scleral spur; IT1-3 = Iris thickness at various location to the scleral spur; TCPD = trabecular ciliary process distance; ICPD = iris ciliary process distance.

are required to manually place calipers on the areas of interest in order to derive values from each image. Using this approach, authors reported relatively high reproducibility when analyzing a single image. However, no authors to date have documented the reproducibility of re-examining the same patient starting the process over (i.e., having the patient get up and re-examining the same quadrant with a completely separate analysis of the image), which would almost certainly increase the variability of UBM measurements. Nevertheless, the reported reproducibility of analyses on single UBM images range widely. Spaeth used a grading scheme similar to his gonioscopy grading approach in which two observers determined the location of iris insertion, the anterior chamber angle (using a hand-held protractor), and the curvature of the iris on 41 eyes of 22 consecutive patients imaged with UBM. He reported kappa values of 0.8 or greater between observers analyzing a single UBM image of each eye.[89] Urbak and colleagues reported that three different observers analyzing the same image had coefficients of variation (COV) of 10.5%, 17.0%, and 16.5% for AOD 500, whereas other measurements such as the iris ciliary process distance (ICPD) had much higher COV (18%, 47%, and 53%).[65] The authors do not report how many subjects were imaged, and, as previously stated, the study was based purely on image analysis, not on the overall variability in obtaining multiple images from a single individual. Tello and colleagues reported on a non-automated analysis technique in which multiple parameters were measured by three observers on five separate occasions.[93] Intraobserver variability was low (COV < 10% for virtually all parameters), but interobserver variability was high for several parameters including iris thickness and corneal thickness. The relatively small number of subjects studied, almost all of whom had open angles, is a limitation of this study. Similarly, Kobayashi, reporting on the impact of pilocarpine on angle structures, reported COV < 10% for a single observer making multiple measurements.[48] Marchiani reported high reproducibility in a paper comparing UBM parameters in angle closure patients (range of COV 1.4–16%).[57] Even better reproducibility was reported by Gohdo when measuring the ciliary body thickness (CBT) at one and two millimeters posterior to the scleral spur (COV < 2.5%).[31]

Image analysis using calipers to mark each structure takes a large amount of time due to the need to place a cursor at each point for any given measurement. Furthermore, the data are not stored in an exportable format and need to be transcribed from the screen into a database. To overcome these issues, Ishikawa and colleagues created a semi-automated program (UBM Pro2000) that calculates several important parameters once the scleral spur is identified (Fig. 11).[41] Furthermore, the software program includes a training set to allow for relatively consistent identification of the location of the scleral spur. No articles regarding the reproducibility of this software package have been published, but Ishikawa comments in a review of the UBM technology that the COV is 2.5–7.3% for various parameters.[42] Using this software one can obtain the AOD 250, AOD 500, and angle recess area (ARA) out to 750 microns from the scleral spur with the placement of a single mark identifying the scleral spur.

In addition, the software provides a linear regression of the AOD out to 750 microns, which is referred to as the "acceleration", and provides information about the shape of the iris. If the acceleration is negative, this indicates that the iris and cornea are in closer contact further from the scleral spur than when one is next to the scleral spur, indicating a closed or narrow entrance to the angle with a sinus posterior to this entrance (Fig. 12).

A second parameter that can be derived from this regression is the *y*-intercept, which when negative indicates that the angle recess is shallow or absent and widens centrally (as in plateau iris, Fig. 13).

Potash and colleagues also published a system for describing the iris configuration (convex, concave, or flat) by drawing a line from the root of the iris to the central most aspect and measuring the gap that is formed.[68] This approach provides further detail about the anterior segment status, and may offer some insight into the relative force of pupil block (presumably more anteriorly bowed irides are under greater pressure from behind), but no studies to date have evaluated this parameter.

One of the unique benefits of UBM is the ability to visualize the ciliary body, a structure that clearly plays a role in the configuration of the ACA. Researchers have studied the trabecular-ciliary process distance, the iris–ciliary process distance, and the CBT at various distances posterior to the scleral spur. No standard exists for the best location to measure CBT, but it has been reported at 1, 1.5, 2, and 2.5 mm by different investigators.[31,57] Gohdo

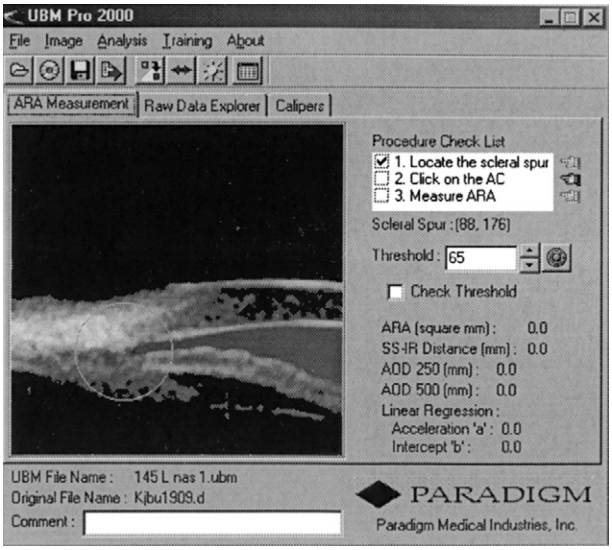

Fig. 11. Screen shot of the analysis software from the Paradigm UBM.

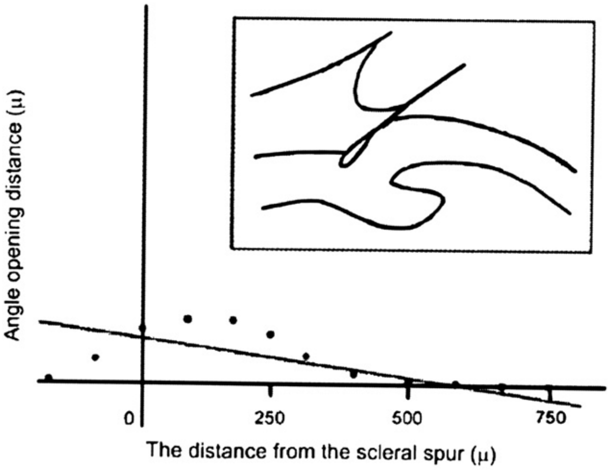

Fig. 12. Example of a negative acceleration of the angle opening distance indicating that the iris is in closer contact to the cornea anterior to the scleral spur than next to the scleral spur. (Reprinted with permission from *Ophthalmology Clinics of North America*, vol 17, 2004, pp 7–20.)

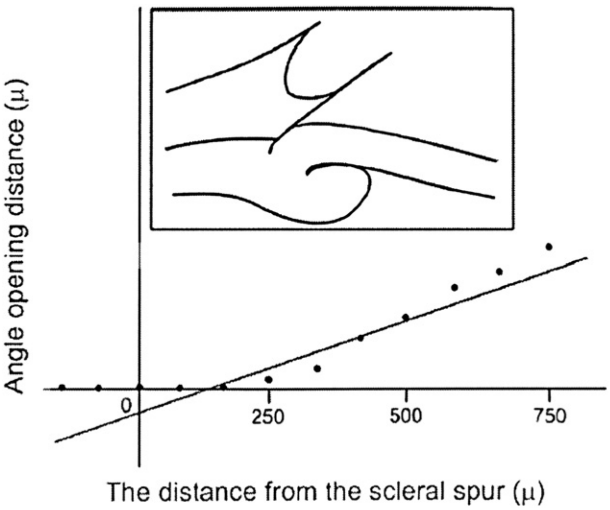

Fig. 13. Regression of the angle opening distance demonstrating a negative *y*-intercept, which indicates that the angle recess is narrow and widens centrally. (Reprinted with permission from *Ophthalmology Clinics of North America*, vol 17, 2004, pp 7–20.)

and colleagues found that persons with angle closure had thinner CBT at both 1- and 2-mm posterior to the scleral spur than age and sex-matched controls.[31] Another quantitative approach to assessing the ciliary body position was proposed by Marchini and colleagues.[57] The authors dropped a perpendicular line from the scleral spur and determined if the ciliary body was anterior or posterior to this line and by how much. Persons with angle closure were much more likely to have an anterior CB position using this technique. A similar approach was used by Sakata and colleagues on a Brazilian population, but in this case the line passed through a point 750 microns anterior to the scleral spur.[75] The authors documented in this study that nearly 60% of gonioscopically closed angles had this appearance on UBM whereas about half as many with apparently open angles also had this UBM appearance.

Qualitative assessment of ciliary body anatomy, in which the apex of the ciliary body position is documented as either lying parallel to the iris plane (rotated forward) or not, has also been reported. He and colleagues reported that among 72 subjects with PAC (S) who were identified in a population-based study in Guangzhou, China, over 50% had anterior position of the ciliary body in at least one quadrant.[36] This configuration is frequently referred to as "plateau" iris. However, in that study, over 80% who had anterior ciliary body rotation appeared "open" on gonioscopy after laser iridotomy, indicating that pupil block plays a role in closing angles even when the ciliary body is anteriorly positioned. Fig. 14 shows an example of

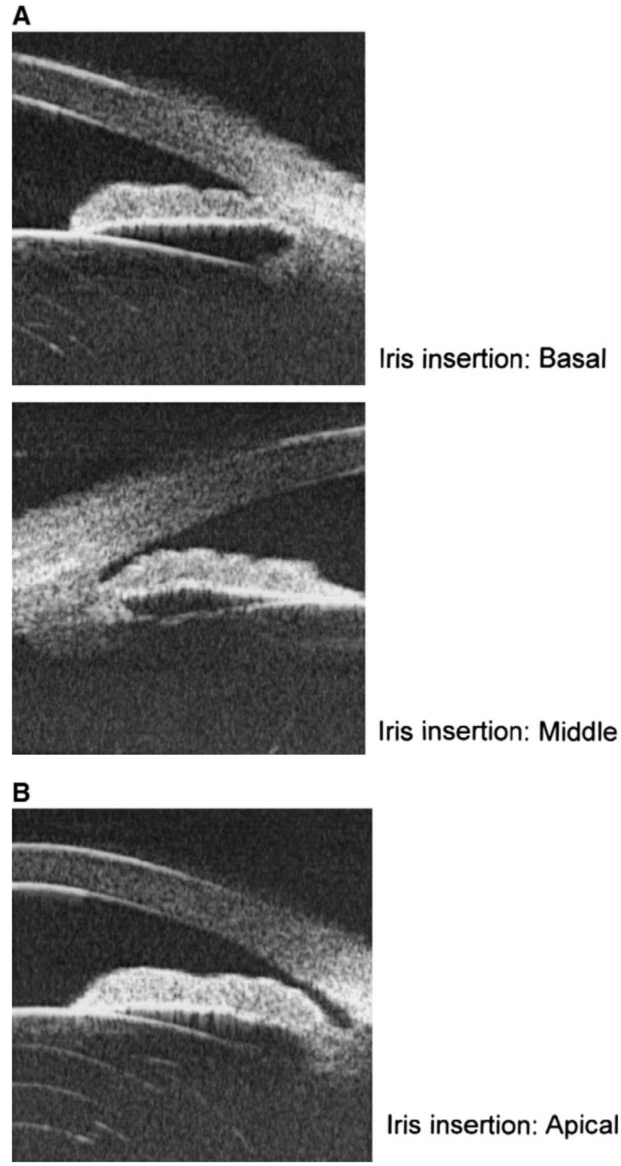

Fig. 14. Variability in iris insertion from UBM images taken in Chinese eyes. (Reprinted with permission from *Ophthalmology Clinics of North America*, vol 17, 2004, pp 7–20.)

variability in iris insertion location as demonstrated by UBM.

In summary, UBM offers tremendous insight into the anterior chamber angle configuration and allows for detailed imaging of the ciliary body and the posterior chamber. UBM has dramatically influenced how ophthalmologists think of angle closure mechanisms, and images demonstrate large variation in ocular structures between individuals. As one example of this, Fig. 14 shows the various locations where the ciliary body can insert on the iris. Although these findings have been incredibly helpful in understanding angle closure mechanisms, UBM remains mostly a research tool due to the cost of the machinery, the need for a water bath to image the eye, and the inconvenience of the examination.

Anterior Segment Optical Coherence Tomography (AS-OCT)

AS-OCT is an evolving alternative approach to imaging the anterior chamber angle. AS-OCT is analogous to ultrasound, but uses light instead of sound to determine tissue depth. The time required for the reflected light to return to the transducer is determined using a Michelson interferometer (which relies on the principle that two waves of light in phase will amplify eachother while two waves of light out of phase will cancel eachother out), and was first proposed for the assessment of ocular tissue in the early 1990s.[39] The initial use of OCT was to image the posterior segment structures and used an 0.8-micron superluminescent diode (SLD) as the light emitting source. This device was then used to image anterior segment structures, but the 0.8-micron SLD source fails to penetrate the sclera, so detailed angle imaging was not possible. Changing to a 1.3-micron SLD produced clear images, and the devices in use today for imaging the anterior segment use this approach. The spatial resolution of the OCT devices using this light source is about 10 to 20 microns.

The initial report to draw attention to the potential for OCT to evaluate angle structures was published in 2002,[72] and used a prototype, hand-held device. Although previous investigators had published anterior segment OCT findings, the image acquisition with those prototypes was too slow to obtain clear images. The improved device had a rapid acquisition time (4–16 frames/second with real-time imaging). The authors noted that angle structures could be imaged non-invasively without contacting the eye using this device, but that the device could not fully image the ciliary body due to degradation of the light by the sclera.

Subsequent development of the OCT has resulted in a slit-lamp mounted device that can image the anterior segment at a rapid rate. The images have to be processed by a computer ("dewarped") to account for bending of light by the cornea. Images are similar to those seen with UBM, although one can image the entire anterior segment at one time (which is not possible with a 50-MHz UBM probe, but is possible with a 35 MHz version, Fig. 15). The device allows for image analysis identical to that performed on UBM images including AOD, ARA, and anterior chamber angle measurement. Measurements involving the ciliary body are not possible.

Using a prototype device, Goldsmith and colleagues were able to scan the angle width in 20 healthy volunteers with a scanning rate of 4,000

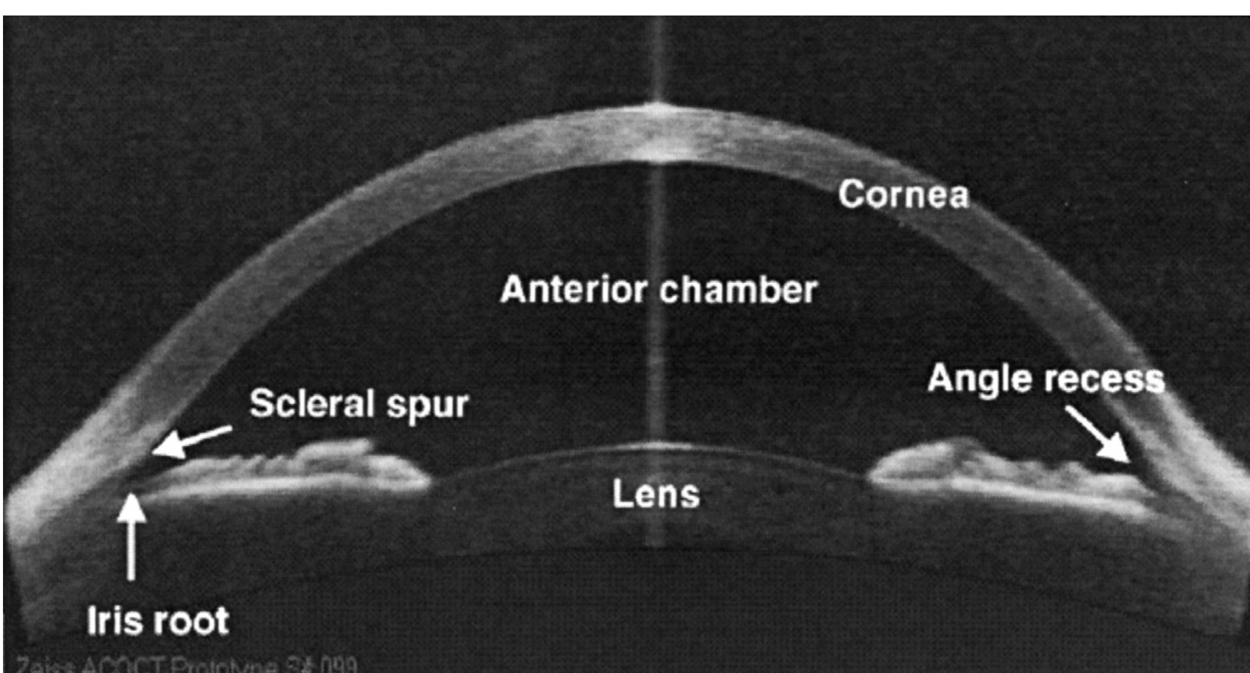

Fig. 15. AS-OCT images from prototype device demonstrating angle to angle measurement and location of angle structures. (Reprinted from Radhakrishnan et al[71] with permission of *Archives of Ophthalmology*.)

axial images/second.[32] This high scan rate allowed the investigators to obtain clear images of the entire anterior segment in 0.125 seconds, which allowed for real-time video display of the images at 8 frames/second (each frame consists of 500 axial scans). Lateral resolution is 15 microns and axial resolution is 8 microns. Although this study focused on the potential to use AS-OCT for determining the width of the anterior segment (to assist in placing phakic intraocular lenses), it also provided high-resolution images of angle structures. Following on this work, researchers in the same group using the same prototype device studied the comparability of AS-OCT findings to those seen with UBM.[71] They imaged 17 normal subjects and 7 subjects with narrow angles on gonioscopy (total 31 eyes, so both eyes of some patients were included) using both UBM and AS-OCT (still a prototype device, not the one currently in commercialization). Gonioscopy, UBM, and AS-OCT were all performed under similar room illumination. AS-OCT images were 3.8-mm wide and 4-mm deep, and UBM images were 5-mm wide and 5-mm deep. Three images each of the temporal and nasal angles were obtained with AS-OCT and UBM (these angles can be visualized using AS-OCT without touching the patient, whereas superior and inferior imaging can require the observer to move the lids out of the way). Both AS-OCT and UBM images were assessed using the same customized software. The authors reported on the AOD at 500 microns, the ARA at both 750 and 500 microns, the trabecular iris space area (TISA) which removes from the ARA the area posterior to the scleral spur (Fig. 16), and the trabecular-iris contact length (TICL). Repeatability (defined as the pooled standard deviation of the repeated images—each image was obtained three times) was similar between UBM and AS-OCT, as were the values for most of the parameters measured (Fig. 17). AS-OCT tended to have larger values than UBM, however.

The same authors attempted to define the sensitivity and specificity of the UBM and AS-OCT at identifying narrow angles using a cutoff of Shaffer grade of 1 or less in 31 subjects (8 of whom had Shaffer grade $\leq$ 1) and found that for most parameters sensitivity and specificity were high in this study population (area under the receiver-operator curve $>$ 0.95 for all parameters).[71]

Nolan and colleagues reported on 304 eyes of 200 subjects examined by a masked observer who were subsequently imaged with the Zeiss prototype AS-OCT device in Singapore.[61] Subjects had primary angle closure, PACG, POAG, ocular hypertension, or cataract, and the OCT (when performed in the dark and graded subjectively as closed if the iris was seen to be against the scleral spur) identified 98% of

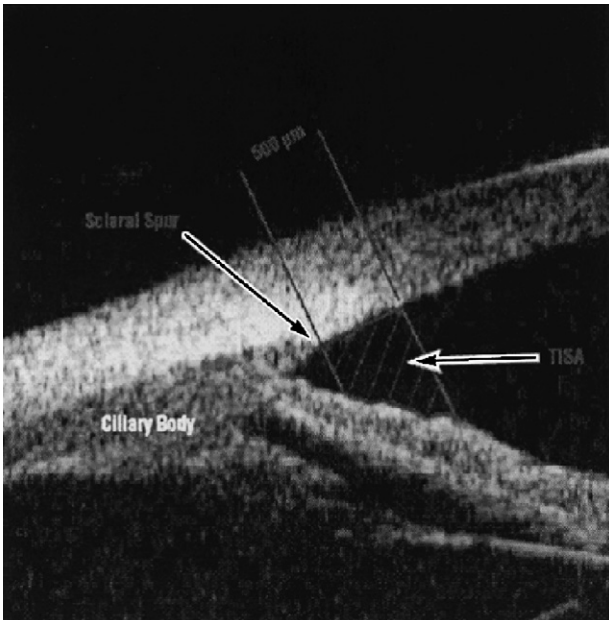

Fig. 16. Trabecular iris space area, a modification of the angle recess. (Reprinted from Radhakrishnan et al[71] with permission of *Archives of Ophthalmology*.)

the 130 subjects with angle closure on gonioscopy. However, specificity was 55%, indicating that far more subjects appeared closed on OCT than on gonioscopy. No quantitative algorithms were used in this study. The authors offer several possible explanations for this finding, including lower illumination when using the OCT than when using gonioscopy, possible distortion of the anterior segment by gonioscopy resulting in wider appearing angles, and use of different landmarks to define angle closure using the two methods. The high sensitivity demonstrated here, if reproduced in other studies, could support the use of AS-OCT as an initial screen in clinical practice.

Only one report has been published looking at reproducibility of anterior segment OCT (using the 4Optics AS-OCT device).[43] The authors reported that intraobserver variability had a coefficient of variation of 6% for anterior chamber angle and 4% for AOD500. Interobserver variability was 11% for ACA and 8% for AOD500.

In summary, AS-OCT can rapidly image the angle structures without contacting the eye. Preliminary studies indicate that the device identifies most persons with angle closure, but also characterizes many who are gonioscopically open as closed. Whether this non-contact assessment that does not require illumination is more or less accurate than gonioscopy remains to be seen. At the least, if follow-up studies confirm the high sensitivity of AS-OCT for detecting angle closure, AS-OCT could be used as a screening device to reduce the need to perform

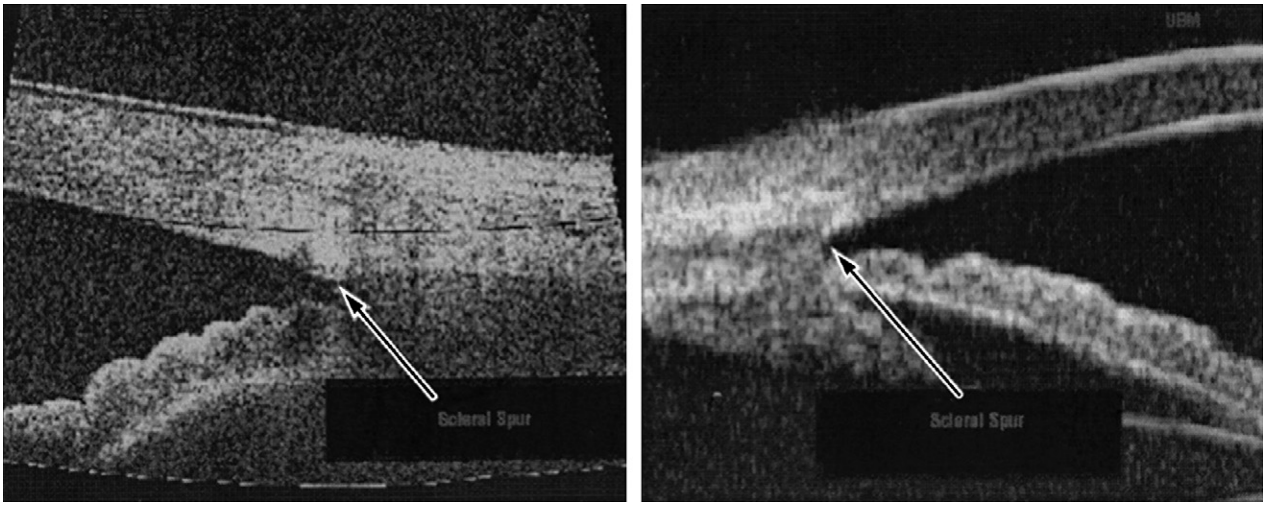

Fig. 17. Side-by-side comparison of optical coherence tomography image of the angle (*left*) and ultrasound biomicroscopy image (*right*). (Reprinted from Radhakrishnan et al[71] with permission of *Archives of Ophthalmology*.)

gonioscopy on all subjects. Further research is warranted.

Viewing the ACA configuration directly requires either gonioscopy or the use of imaging devices such as UBM and AS-OCT described herein. Three techniques that will be described subsequently have been developed which allow an observer to estimate angle opening using only visible light; limbal anterior chamber depth (LACD), Scheimpflug photography of the anterior segment, and a new device, the scanning peripheral anterior chamber depth (SPAC) analyzer.

Scheimpflug Photography

While multiple photographic slit-lamps have been developed using the Scheimpflug principle, the Topcon SL45 and the Nidek EAS-1000 are the two most widely used in study of ACA anatomy and anterior chamber depth assessment. The Scheimpflug principle (named after Theodor Scheimpflug, an Austrian army captain), describes the change in the focal plane that occurs when the lens is tilted. Instead of having the focal plane, the lens plane and the film plane aligned so that they are exactly parallel (as occurs in standard cameras), the film plane is tilted, which shifts the plane of sharp focus to the intersection point of the film and lens planes (see Fig. 18). This approach has been used to allow investigators to obtain slit images of the anterior segment of the eye that retain depth. In addition to studying anterior segment biometry, the Scheimpflug cameras have been adapted for measuring cataract density and following cataract progression.[28,59]

The potential use of this device for anterior segment biometry was first proposed by Drews in the late 1950s,[17] leading to the later development of instruments based on the Scheimpflug principle. Richards reported the initial work aimed at standardizing data processing of Scheimpflug images using the Topcon SL-45.[74] He determined that multiple corrections needed to be made to account for digitization of film (a standard at the time), and image rotation and magnification factors due to the refractive properties of the cornea. He studied a small number of patients using software he developed and demonstrated high reproducibility of images.

The major commercial Scheimpflug camera is the Nidek EAS-1000. Other devices take similar images, including the Pentacam camera, which collects 12 to 50 images in about two seconds using a rotating camera for a complete assessment of the anterior chamber. Images are reconstructed unto a three-dimensional image, and semi-automated analysis of the angle width is performed.

Measuring angle width with the EAS-1000 requires the user to place up to ten marks on the cornea endothelium to determine the plane of curvature,[85] and to place a line along the iris to identify the angle at which it is directed. This is somewhat subjective, but nevertheless, two investigators have reported high reproducibility of angle width measurements using this approach.[4,53] Reproducibility of angle width measurements using the Nidek EAS-1000 measured in one quadrant by three observers photographing the eye on three different occasions was extremely high (interobserver correlation for angle measurement was 0.91, 95% CI 0.81–0.95, and for ACD was 0.98, with

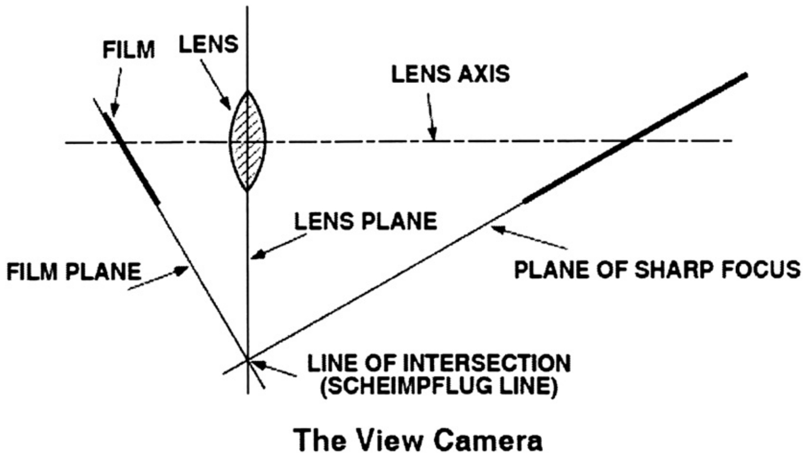

Fig. 18. Demonstration of the Scheimpflug principle from www.trenholm.org/hmmerk/SHBG05.pdf

higher intraobserver correlations).[4] Lam reported on 25 healthy subjects with open angles (average angle width by Scheimpflug was 35° in all quadrants) and found that the 95% limit of agreement on repeat measurements of angle width was 5°, and interobserver agreement was 6.[53] None of the studied subjects had narrow angles. The 95% limit of agreement for ACD was 0.1 mm, indicating high reproducibility for this measure. Lee documented that imaging using the visual or optical axis led to only small differences in measured anterior chamber angle width.[54]

While Scheimpflug photographic techniques can be performed in a reproducible fashion in open angles, the ability to reliably image populations with a variety of angle configurations has not been documented. Furthermore, the validity of Scheimpflug findings has been called into question.[10,27] Scheimpflug requires light to penetrate to the structure of interest (as in routine photography), which means that at best no more than the angle approach can be visualized with this technique. Scheimpflug photography cannot fully visualize the entire angle. Furthermore, details of the ciliary body or iris ciliary body relationship cannot be obtained with this technique. Boker and colleagues documented these limitations in a study of 20 healthy volunteers who underwent both Scheimpflug photography with the Topcon SL-45 and UBM.[10] The correlation of angle width using the two approaches was 0.64, which is moderate. The author noted that the Scheimpflug images were less detailed than those from the UBM, and that the subjective grading of angle width relied on the observer having to draw a straight line to describe a curved object (the iris). Friedman reported that Scheimpflug angle measures were less sensitive to changes in the angle than UBM in response to pilocarpine and to changes in illumination.[27]

In summary, although Scheimpflug cameras offer a non-contact approach to angle assessment (which is highly appealing for screening purposes), they do not allow detailed visualization of angle structures and have relatively low correlation with gonioscopy (the current reference standard). Furthermore, while angle width and anterior chamber depth measures have been highly reproducible in persons with open angles, more research is needed to determine the reproducibility in populations with more angle variation (i.e., the populations of greatest interest for using such a device).

Limbal Anterior Chamber Depth Measurement (van Herick Technique)

Slit-lamp estimation of the limbal anterior chamber depth (LACD) by the van Herick technique was developed as a non-contact approach for estimating angle width. To perform this evaluation, the illumination column of the slit lamp is offset from the central axis of the microscope by 60° to the temporal side. A bright, narrow beam of light is directed perpendicular to the ocular surface at the limbus. LACD measurement is performed by comparing the depth of the peripheral anterior chamber depth to the thickness of the cornea. The original description outlined a four-point grading scheme of LACD—with LACD graded as ≤ 25%, 25%, >25% to 50%, or >100%.[98] Curiously, this original scheme did not include a grade for the category 50–100%. However, gonioscopic angle closure is seen rarely in persons with van Herick >50%, so for the purposes of defining risk of angle closure, the original, flawed scheme allows fairly reasonable indirect assessment of angle closure risk. One study comparing this test to gonioscopic angle closure (defined as 270° of angle in which the pigmented trabecular meshwork is not visible in primary gaze allowing minor tilting of the lens) reported the sensitivity and specificity of the test to be 61.9% and 89.3%, respectively.[22] Foster proposed a modified scheme with increased precision of LACD measurement. The original grade 1 was sub-divided into 0%, 5%, and 15% corneal thickness, and a grade of 75% CT was added to compensate for the gap between the original grades 3 and 4. The description of this augmented scheme identified the cutoff of 15% as producing the highest area under the receiver operating curve, but sensitivity was lower using this cutoff than using the traditional cutoff of 25% (Fig. 19). The grade ≤15% CT gave sensitivity and specificity at 84% and 86% for detection of narrow angles (less than 90° of posterior trabecular meshwork visible in primary position). Using a cutoff of ≤25% specificity decreased to 65%, but sensitivity increased to 99%.

Studies show the inter-observer reproducibility for the van Herick test may be high.[22,94] However, there is a tendency for wider angles if the LACD is measured at the nasal limbus, and it is now standard to use the temporal limbus for this test. An important limitation of the test is that it can only be performed if the limbus is clear, so eyes with pterygium or scarred temporal corneas cannot be graded.

In summary, LACD is a quick, easy test that can identify the vast majority or persons with gonioscopically closed anterior chamber angles. The test requires a slit-lamp and a trained observer. The screening performance of LACD in identifying closed angles is about as good as that seen for any other approach used to date and it certainly continues to have a role in both clinical and research settings.

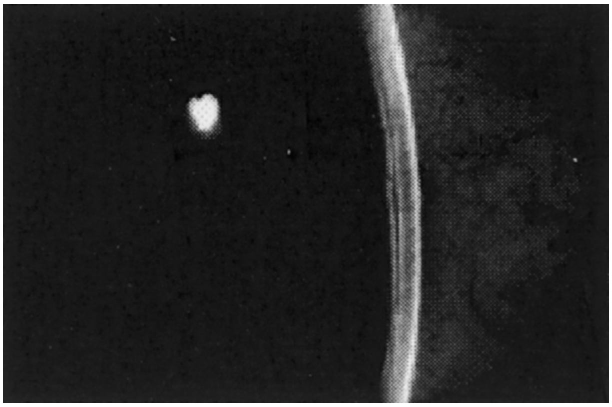

Fig. 19. Limbal anterior chamber depth of 15%. (Reprinted from Foster et al[22] with permission of *British Journal of Ophthalmology*.)

Scanning Peripheral Anterior Chamber Depth Analysis

A final technology worth discussing in the assessment of angle configuration is the scanning peripheral anterior chamber depth analysis system (SPAC). The SPAC does not image the angle directly, and therefore does not give detailed information on angle anatomy. Instead, it obtains up to 21 measurements of anterior chamber depth using a slit-lamp based photographic technique. The images are obtained using a 60° offset starting at the optical axis and scanning towards the periphery. Images are then captured on a small charge-coupled device camera and automatically analyzed by computer. The SPAC also calculates the corneal thickness and the radius of corneal curvature in order to derive a more accurate assessment of the anterior chamber depth at various points. The entire scan takes 0.67 seconds to capture, with images captured at 0.4-mm intervals.

SPAC findings were first reported using a model eye, and the authors demonstrated that the measured anterior chamber depth (ACD) was similar to the expected ACD at each of the 21 points assessed (difference of not more than 1.8% from expected).[45] A pilot study on 10 eyes of five subjects reported that the estimated radius of corneal curvature and corneal thickness were similar to values obtained with an automated keratometer and a pachymeter, respectively.[45]

The authors also demonstrated that varying the corneal thickness and curvature had only a small effect on the SPAC-measured ACD, with an increase in ACD with thicker corneas and with decreased radius of curvature. Finally, they demonstrated that the measurements were reproducible both between and within observers (technicians) with a coefficient of variation under 8% for both.

The authors used the SPAC device to assess whether or not the SPAC could detect changes in the anterior segment of individuals with different forms of angle-closure after laser peripheral iridotomy (LPI).[44] They compared the findings from SPAC, UBM, and A-scan ultrasound before and after LPI. The authors were able to detect a widening in peripheral ACD after LPI. An increase in angle depth was seen when using the UBM in this population, supporting the SPAC findings. The central ACD and axial length did not change when using A-scan ultrasound, as has been reported previously.

More recently the authors published data on 10 patients with PACG (how this was defined is not completely clear) and 10 with POAG and the device identified one POAG patient as suspect for PACG, and 9 of 10 PACG patients were correctly identified as PACG suspects.[46] A second paper by the same authors assessed the SPAC in 40 subjects, 10 each with Shaffer grades of 1, 2, 3, and 4 in the temporal angle.[47] The authors excluded subjects when obtaining SPAC measurements was difficult, so the findings are not generalizable to larger unselected populations. The SPAC results were strongly correlated with Shaffer (and van Herrick) grades. The authors also demonstrated that the SPAC grades were correlated with UBM measurement of the angle opening distance at 500 microns (R^2 of about 0.7).

These studies indicate that the SPAC findings correlate with angle findings to some extent, but it is unclear if the degree of correlation is high enough for the device to be used effectively for screening for angle closure. More research will be needed to clarify the role that SPAC will play in angle assessment.

Responses of the ACA to External Stimuli (Light-Dark Changes, Corneal Indentation, and Pilocarpine)

LIGHT–DARK CHANGES

Angle appearance can change dramatically depending on the amount of illumination that strikes the eye. When light shines on the eye the iris sphincter contracts and the peripheral iris moves centrally away from the angle. The result is in many cases a more open angle appearance (Fig. 20).

Pavlin first described a dark-room provocative test using UBM in eight patients who developed angle closure and appositional closure in response to decreased illumination.[63] Woo (with Pavlin as a co-author) followed up on this finding in 24 patients with gonioscopically narrow angles who demonstrated a convex posterior iris curvature on UBM testing.[102] The mean dark measurements of AOD500 were about half as wide as those taken in the light. In a similar study, Ishikawa reported on mostly white patients with gonioscopically narrow angles (Shaffer grade 1 or 2) who underwent dark room UBM of the inferior angle.[41] All 178 eyes had open angles under light conditions, and 55.6% were closed when re-imaged in the dark. For those who were subjectively closed in the dark, the ARA decreased from 0.11 mm^2 to 0.03 mm^2. A high likelihood of appositional closure in the dark was also reported in a population of Japanese subjects with either suspect PAC, PAC, PACG, or fellow eyes of persons undergoing an acute attack of angle closure.[77] 92% of non-fellow eyes and 82% of fellow eyes developed appositional angle closure in the dark on UBM in this study. Gazzard has published a video demonstrating rapid angle closure in a fellow eye revealing how variable angle findings can be in the light and the dark.[101] Friedman reported that the fellow eyes of persons with unilateral acute attacks have more substantial angle narrowing in the dark than normal controls, indicating that the dynamic response to external stimuli may play a role in the pathologic process.[27] In a recent study of 80 consecutive Japanese patients with LACD ≤25%, Kunimatsu and colleagues reported that 57.5% were appositionally closed in at least one quadrant in light conditions and 85% were appositionally closed in the dark.[52] For the quadrants where appositional

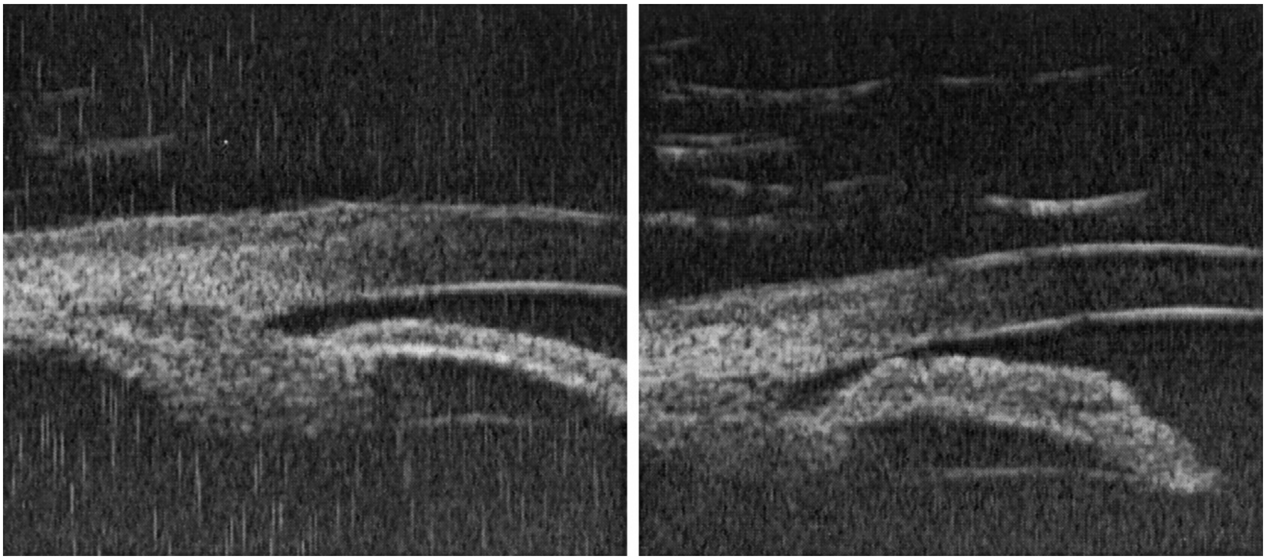

Fig. 20. UBM images of the same patient with the lights on (*left*) and the lights off (*right* image) showing marked angle narrowing in the dark. (Reprinted from Radhakrishnan et al[71] with permission of *Archives of Ophthalmology*.)

closure was not present, the trabecular iris angle was also narrower in the dark than in the light in all but the superior quadrant when measured by UBM.

Sugimoto and colleagues in Japan have recently published an example of gonioscopy captured using infrared light.[92] These authors showed substantial angle narrowing compared to standard gonioscopy with brighter illumination.

CHANGES WITH CORNEAL INDENTATION

One study assessed the UBM changes in the ACA when indenting the central cornea.[58] Matsunaga and colleagues enrolled 73 eyes of 52 Japanese patients in a study comparing UBM findings using a standard eyecup and a modified eyecup that places pressure on the central cornea. Twenty-six eyes with narrow angles, 21 with PAS in the angle, and 26 with a plateau configuration were enrolled. All three groups demonstrated widening of the ACA with indentation, with both the AOD 500 and the ARA increasing in all subgroups. However, the increases in ARA and AOD 500 was nearly three times as large in the group with narrow angles only when compared to the other two groups, demonstrating that not only do PAS limit the ability of compression to open the angle, but also, an anteriorly rotated ciliary body continues to push the peripheral iris forward in these eyes.

PILOCARPINE EFFECTS ON ACA CONFIGURATION

The effect of pilocarpine on ACA configuration remains unclear, with some persons appearing to have shallower ACA after pilocarpine and others having greater angle opening. Hitchings demonstrated that when persons had a shallowing of the central anterior chamber depth in response to 4% pilocarpine, the peripheral anterior chamber also shallowed, whereas if the central ACD did not shallow, the peripheral ACD widened.[37] In a small study of 10 eyes of five patients (only two with angle closure), Nemeth reported and increase in angle width with narrower angles and a decrease in angle width in wider angles.[60] Hung assessed 29 "normal" Chinese subjects using Scheimpflug photography and reported that after 2% pilocarpine, the ACA narrowed significantly.[40] The same group also looked at an additional 18 "normal individuals" (mean Scheimpflug angle width of 33°) and found that the ACA width narrowed by an average of about three degrees after the instillation of one drop of 4% pilocarpine.[103] Kobayashi compared the UBM response to 2% pilocarpine of 30 eyes of 30 Japanese patients with UBM trabecular iris angle width of 25° or less to 30 sex- and age-matched controls.[50] For all 30 subjects with narrow angles the AOD 250 and AOD 500 increased in response to pilocarpine. Twenty-three of the 30 subjects with open angles had a decrease in angle width by UBM after administration of pilocarpine, suggesting that the angle opens when closed in response to pilocarpine and narrows when open. Friedman and colleagues reported different findings in Chinese persons.[27] The ACA as measured by UBM increased in angle width after the administration of 4% pilocarpine in both fellow eyes of persons with acute angle closure and normal controls. However, the angle width increased in normal controls when assessed by Scheimpflug photography, but decreased in contralateral eyes ($p < 0.05$). Given the variable angle responses reported to date, it is not clear if the effect of pilocarpine on ACA configuration varies by race, or if differences in study methodology caused the differences seen.

Summary and Conclusions

With proper detection and prophylaxis, angle closure glaucoma appears to be a potentially preventable disease. Identifying persons at risk for acute angle closure attacks, as well as those prone to develop more chronic forms of angle closure remains a challenge. Nearly 15% of the Chinese population over 50 years of age has "occludable" angles. This translates into nearly 200 million people, and with the aging of the populations of Asia, this number will increase in the coming decades. Deciding which eyes need laser iridotomy, which need even more treatment (such as laser iridoplasty), and which are better left alone remains unclear.[26]

A key element in this decision-making process is the assessment of the anterior chamber angle. The current reference standard is gonioscopy, which offers a detailed view of angle structures. Gonioscopy is subjective and difficult to learn. Furthermore, skill is needed to perform gonioscopy properly, particularly in older individuals who are frequently less able to sit comfortably at the slit lamp. Studies generally report moderate reproducibility, but these studies employ trained persons with extensive gonioscopy experience. The real-world situation is likely not as good. It is the our belief that gonioscopy with Zeiss-style mirrors is likely even less reproducible, but studies on the differences in findings and reproducibility between Goldmann-style lenses and Zeiss-style lenses have not been published.

Ultrasound biomicroscopy has allowed a much deeper understanding of anterior chamber dynamics and the role of the ciliary body in angle closure.

It provides high quality images of anterior segment structures, but is cumbersome to perform, requires a trained technician, and involves placing an eyecup on the eye, all of which limit its usefulness in the clinical setting. Questions still remain about reproducibility with UBM, although most reports of analyses on a single image indicate that images analysis is highly reproducible. UBM remains a tool that is largely used only at academic centers.

There is a need for alternative approaches to imaging the angle or near enough to the angle to provide useful information about the angle configuration. Four approaches to assessing the angle that do not require contact with the eye are assessment of LACD at the slit lamp, Scheimpflug photography, SPAC photography, and AS-OCT. LACD is a simple approach that in the published literature appears to be highly sensitive at identifying angles that are gonioscopically closed. If gonioscopy remains the reference standard for angle assessment, then strategies for screening for angle closure that employ LACD assessment may prove effective.

The Scheimpflug camera requires light to enter the angle, and therefore only gives an approximation of angle configuration. Whether it, too, could be used as a screening device for gonioscopically closed angles is unclear from the literature. The correlation with gonioscopy appears good, but image analysis requires a trained observer and substantial manipulation of the obtained image. SPAC imaging of the anterior segment also does not directly assess ACA configuration, but appears to segregate out reasonably well those with closed angles (on gonioscopy) from those with open angles. Further research will be needed to confirm these findings.

AS-OCT appears to be a promising technology for angle assessment. However, more data are needed to determine if AS-OCT can reproducibly image the angle and provide information that is clinically useful. The devices currently available allow for non-contact imaging of the ACA, and are fairly easy to operate. Furthermore, semi-automated image analyses can be performed (as with UBM). These devices cannot image the ciliary body, however, and this may be an important limitation since insight into angle closure mechanisms may require this. Prognosis for angle closure suspects may vary by ciliary body anatomy. However, even with these limitations, the AS-OCT appears to be an important improvement over current approaches to imaging the angle, and its place in clinical ophthalmology will become more clear as research studies are published in the coming years.

In summary, ACA assessment is challenging, but it is a key clinical activity that alters how patients with glaucoma or suspect glaucoma are treated. Gonioscopy remains the reference standard, but it is suboptimal. Newer technologies may improve our ability to assess and monitor the ACA.

Method of Literature Search

Searches were performed in PubMed which includes Medline as well as additional citations (such as Old Medline manuscripts that have not been fully formatted and in press articles) for articles dating from 1950 through September 2006. PubMed automatically identifies MESH terms associated with the search and uses an “OR” strategy unless a specific “AND” command is provided. For this article we used the following search terms: *anterior chamber angle assessment, gonioscopy techniques, ultrasound biomicroscopy, pilocarpine and anterior chamber, Scheimpflug and anterior chamber, and anterior and optical coherence tomography.* In addition, once these searches were complete, for relevant manuscripts we used the “related articles” button in PubMed to identify any important articles that had been missed by the search. Finally, we reviewed the bibliographies of older articles to identify manuscripts published before the mid 1950s (which are not identifiable in PubMed). Only articles written in English were reviewed. The articles were included if they focused on anterior chamber angle assessment techniques or if they reported specific findings in the anterior chamber angle with regards to dynamic responses or to angle findings in specific groups of individuals.

References

1. Alsbirk PH: Primary angle-closure glaucoma. Oculometry, epidemiology, and genetics in a high risk population. Acta Ophthalmol 127(Suppl). 5–3, 1976
2. Arkell SM, Lightman DA, Sommer A, et al: The prevalence of glaucoma among Eskimos of northwest Alaska. Arch Ophthalmol 105:482–5, 1987
3. Aung T, Lim MC, Chan YH, et al: Configuration of the drainage angle, intraocular pressure, and optic disc cupping in subjects with chronic angle-closure glaucoma. Ophthalmology 112:28–32, 2005
4. Baez KA, Orengo S, Gandham S, et al: Intraobserver and interobserver reproducibility of the Nidek EAS-1000 Anterior Eye Segment Analysis System. Ophthalmic Surg 23:426–8, 1992
5. Barkan O: Pigment changes in the anterior segment in primary glaucoma. Trans Am Ophthalmol Soc 55:395–413, 1957
6. Barkan O: Iridectomy in narrow angle glaucoma. Am J Ophthalmol 37:504–19, 1954
7. Barkan O: A new focal illuminator. Am J Ophthalmol 24: 439, 1941
8. Barkan O, Boyle SF, Maisler S: On the genesis of glaucoma: an improved method based on slitlamp microscopy of the angle of the anterior chamber. Am J. Ophthalmol 19:209–15, 1936

9. Becker SC: Unrecognized errors induced by present-day gonioprisms and a proposal for their elimination. Arch Ophthalmol 82:160–8, 1969
10. Böker T, Sheqem J, Rauwolf M, et al: Anterior chamber angle biometry: a comparison of Scheimpflug photography and ultrasound biomicroscopy. Ophthalmic Res 27(Suppl 1):104–9, 1995
11. Campbell DG: A comparison of diagnostic techniques in angle-closure glaucoma. Am J Ophthalmol 88:197–204, 1979
12. Clemmesen V, Luntz MH: Lens thickness and anglo-closure glaucoma. A comparative oculometric study in South African Negroes and Danes. Acta Ophthalmol (Copenh) 54:193–7, 1976
13. Cockburn DM: A new method for gonioscopic grading of the anterior chamber angle. Am J Optom Physiol Opt 57: 258–61, 1980
14. Congdon NG, Foster PJ, Wamsley S, et al: Biometric gonioscopy and the effects of age, race, and sex on the anterior chamber angle. Br J Ophthalmol 86:18–22, 2002
15. Congdon NG, Spaeth GL, Augsburger J, et al: A proposed simple method for measurement in the anterior chamber angle: biometric gonioscopy. Ophthalmology 106:2161–7, 1999
16. Dellaporta A: Historical notes on gonioscopy. Surv Ophthalmol 20:137–49, 1975
17. Drews RC: Fundus photography by electronic flash III. A new fundus-anterior segment camera. Am J Ophthalmol 44:522–5, 1957
18. Forbes M: Gonioscopy with corneal indentation: A method for distinguishing between appositional closure and synechial closure. Arch Ophthalmol 76:488–97, 1966
19. Foster PJ, Alsbirk PH, Baasanhu J, et al: Anterior chamber depth in Mongolians: variation with age, sex, and method of measurement. Am J Ophthalmol 124:53–60, 1997
20. Foster PJ, Aung T, Nolan WP, et al: Defining "occludable" angles in population surveys: drainage angle width, peripheral anterior synechiae, and glaucomatous optic neuropathy in east Asian people. Br J Ophthalmol 88:486–90, 2004
21. Foster PJ, Baasanhu J, Alsbirk PH, et al: Glaucoma in Mongolia. A population-based survey in Hövsgöl province, northern Mongolia. Arch Ophthalmol 114:1235–41, 1996
22. Foster PJ, Devereux JG, Alsbirk PH, et al: Detection of gonioscopically occludable angles and primary angle closure glaucoma by estimation of limbal chamber depth in Asians: modified grading scheme. Br J Ophthalmol 84: 186–92, 2000
23. Foster PJ, Johnson GJ: Glaucoma in China: how big is the problem? Br J Ophthalmol 85:1277–82, 2001
24. Foster PJ, Machin D, Wong TY, et al: Determinants of intraocular pressure and its association with glaucomatous optic neuropathy in Chinese Singaporeans: the Tanjong Pagar Study. Invest Ophthalmol Vis Sci 44:3885–91, 2003
25. Foster PJ, Oen FT, Machin D, et al: The prevalence of glaucoma in Chinese residents of Singapore: a cross-sectional population survey of the Tanjong Pagar district. Arch Ophthalmol 118:1105–11, 2000
26. Friedman DS: Who needs an iridotomy? Br J Ophthalmol 85:1019–21, 2001
27. Friedman DS, Gazzard G, Foster P, et al: Ultrasonographic biomicroscopy, Scheimpflug photography, and novel provocative tests in contralateral eyes of Chinese patients initially seen with acute angle closure. Arch Ophthalmol 121:633–42, 2003
28. Fujisawa K, Sasaki K: Changes in light scattering intensity of the transparent lenses of subjects selected from population-based surveys depending on age: analysis through Scheimpflug images. Ophthalmic Res 27:89–101, 1995
29. Gazzard G, Foster PJ, Friedman DS, Khaw PT, Seah SK: Light to dark physiological variation in irido-trabecular angle width. Br J Ophthalmol Video Supplement, 2004
30. George R, Paul PG, Baskaran M, et al: Ocular biometry in occludable angles and angle closure glaucoma: a population based survey. Br J Ophthalmol 87:399–402, 2003
31. Gohdo T, Tsumura T, Iijima H, et al: Ultrasound biomicroscopic study of ciliary body thickness in eyes with narrow angles. Am J Ophthalmol 129:342–6, 2000
32. Goldsmith JA, Li Y, Chalita MR, et al: Anterior chamber width measurement by high-speed optical coherence tomography. Ophthalmology 112:238–544, 2005
33. Gorin G: Re-evaluation of gonioscopic findings in angle-closure glaucoma. Static versus manipulative gonioscopy. Am J Ophthalmol 71:894–7, 1971
34. Greenidge KC: Angle-closure glaucoma. Int Ophthalmol Clin 30:177–86, 1990
35. He M, Foster PJ, Ge J, et al: Gonioscopy in adult Chinese: the Liwan Eye Study. Invest Ophthalmol Vis Sci 47:4772–9, 2006
36. He M, Friedman DS, Ge J, et al: Laser peripheral iridotomy in primary angle-closure suspects: biometric and gonioscopic outcomes: the Liwan Eye Study. Ophthalmology 114: 494–500, 2007
37. Hitchings RA, Powell DJ: Pilocarpine and narrow-angle glaucoma. Trans Ophthalmol Soc UK 101:214–7, 1981
38. Hoskins HD: Interpretive gonioscopy in glaucoma. Invest Ophthalmol 11:97–102, 1972
39. Huang D, Swanson EA, Lin CP, et al: Optical coherence tomography. Science 254:1178–81, 1991
40. Hung L, Yang CH, Chen MS: Effect of pilocarpine on anterior chamber angles. J Ocul Pharmacol Ther 11:221–6, 1995
41. Ishikawa H, Esaki K, Liebmann JM, et al: Ultrasound biomicroscopy dark room provocative testing: a quantitative method for estimating anterior chamber angle width. Jpn J Ophthalmol 43:526–34, 1999
42. Ishikawa H, Liebmann JM, Ritch R: Quantitative assessment of the anterior segment using ultrasound biomicroscopy. Curr Opin Ophthalmol 11:133–9, 2000
43. Karandish A, Wirbelauer C, Häberle H, et al: [Reproducibility of goniometry with slitlamp-adapted optical coherence tomography]. Ophthalmologe 101:608–13, 2004
44. Kashiwagi K, Abe K, Tsukahara S: Quantitative evaluation of changes in anterior segment biometry by peripheral laser iridotomy using newly developed scanning peripheral anterior chamber depth analyser. Br J Ophthalmol 88: 1036–41, 2004
45. Kashiwagi K, Kashiwagi F, Toda Y, et al: A newly developed peripheral anterior chamber depth analysis system: principle, accuracy, and reproducibility. Br J Ophthalmol 88: 1030–5, 2004
46. Kashiwagi K, Shinbayashi E, Tsukahara S: Development of a fully automated peripheral anterior chamber depth analyzer and evaluation of its accuracy. J Glaucoma 15: 388–93, 2006
47. Kashiwagi K, Tsumura T, Tsukahara S: Comparison between newly developed scanning peripheral anterior chamber depth analyzer and conventional methods of evaluating anterior chamber configuration. J Glaucoma 15: 380–7, 2006
48. Kobayashi H, Kobayashi K, Kiryu J, et al: Ultrasound biomicroscopic analysis of the effect of pilocarpine on the anterior chamber angle. Graefes Arch Clin Exp Ophthalmol 235:245–430, 1997
49. Koeppe L: Die Mikroskopie des lebenden Kammerwinkels I'm fokalen Lichte der Gullstrandschen Nerstlampe. Albrecht von Graefe's Arch Ophthalmol 101:48, 1919
50. Koeppe L: Das stereoskopische Bild des lebenden Kammerwinkels an der Gullstrandschen Spaltlampe beim Glaucom. Deutsche Ophthalmol Gesell;87, 1920
51. Koeppe L: Die Mikroskopie des lebenden Auges. Berlin, J Springer, 1920, p. 303
52. Kunimatsu S, Tomidokoro A, Mishima K, et al: Prevalence of appositional angle closure determined by ultrasonic biomicroscopy in eyes with shallow anterior chambers. Ophthalmology 112:407–12, 2005

53. Lam AK, Chan R, Woo GC, et al: Intra-observer and inter-observer repeatability of anterior eye segment analysis system (EAS-1000) in anterior chamber configuration. Ophthalmic Physiol Opt 22:552–9, 2002
54. Lee TT, Lam AK, Chan BL: Anterior chamber angle measurement with Anterior Eye Segment analysis system Nidek EAS-1000: improving the repeatability. Ophthalmic Physiol Opt 23:423–8, 2003
55. Lichter PR: Iris processes in 340 eyes. Am J Ophthalmol 68: 872–8, 1969
56. Lowe RF: Causes of shallow anterior chamber in primary angle-closure glaucoma. Ultrasonic biometry of normal and angle-closure glaucoma eyes. Am J Ophthalmol 67:87–93, 1976
57. Marchini G, Pagliarusco A, Toscano A, et al: Ultrasound biomicroscopic and conventional ultrasonographic study of ocular dimensions in primary angle-closure glaucoma. Ophthalmology 105:2091–8, 1998
58. Matsunaga K, Ito K, Esaki K, et al: Evaluation and comparison of indentation ultrasound biomicroscopy gonioscopy in relative pupillary block, peripheral anterior synechia, and plateau iris configuration. J Glaucoma 13: 516–9, 2004
59. McNeil JJ, Robman L, Tikellis G, et al: Vitamin E supplementation and cataract: randomized controlled trial. Ophthalmology 111:75–84, 2004
60. Németh J, Csákány B, Pregun T: Ultrasound biomicroscopic morphometry of the anterior eye segment before and after one drop of pilocarpine. Int Ophthalmol 20:39–42, 1996/1997
61. Nolan WP, See JL, Chew PT, et al: Detection of primary angle closure using anterior segment optical coherence tomography in Asian eyes. Ophthalmology 114:33–9, 2006
62. Oh YG, Minelli S, Spaeth GL, et al: The anterior chamber angle is different in different racial groups: a gonioscopic study. Eye 8:104–8, 1994
63. Pavlin CJ, Harasiewicz K, Foster FS: An ultrasound biomicroscopic dark-room provocative test. Ophthalmic Surg 26:253–5, 1995
64. Pavlin CJ, Harasiewicz K, Foster FS: Ultrasound biomicroscopy of anterior segment structures in normal and glaucomatous eyes. Am J Ophthalmol 113:381–9, 1992
65. Pavlin CJ, Harasiewicz K, Sherar MD, et al: Clinical use of ultrasound biomicroscopy. Ophthalmology 98:287–95, 1991
66. Pavlin CJ, Sherar MD, Foster FS: Subsurface ultrasound microscopic imaging of the intact eye. Ophthalmology 97: 244–50, 1990
67. Perlstein SH, Galst JM, et al: A new technique for portable gonioscopy. Am J Ophthalmol 91:263–4, 1987
68. Potash SD, Tello C, Liebmann J, et al: Ultrasound biomicroscopy in pigment dispersion syndrome. Ophthalmology 101:332–9, 1994
69. Quigley HA, Broman AT: The number of persons with glaucoma worldwide in 2010 and 2020. Br J Ophthalmol 90:262–7, 2006
70. Quigley HA, Friedman DS, Congdon NG: Possible mechanisms of primary angle-closure and malignant glaucoma. J Glaucoma 12:167–80, 2003
71. Radhakrishnan S, Goldsmith J, Huang D, et al: Comparison of optical coherence tomography and ultrasound biomicroscopy for detection of narrow anterior chamber angles. Arch Ophthalmol 123:1053–9, 2005
72. Radhakrishnan S, Rollins AM, Roth JE, et al: Real-time optical coherence tomography of the anterior segment at 1310 nm. Arch Ophthalmol 119:1179–85, 2001
73. Resnikoff S, Pascolini D, Etya'ale D, et al: Global data on visual impairment in the year 2002. Bull World Health Organ 82:844–51, 2004
74. Richards DW, Russell SR, Anderson DR: A method for improved biometry of the anterior chamber with a Scheimpflug technique. Invest Ophthalmol Vis Sci 29: 1826–35, 1988
75. Sakata LM, Sakata K, Susanna R, et al: Long ciliary processes with no ciliary sulcus and appositional angle closure assessed by ultrasound biomicroscopy. J Glaucoma 15:371–9, 2006
76. Salzmann M: Die Ophthalmoskopie der Kammerbucht. Z Augenheilk 31:1, 1914
77. Sawada A, Sakuma T, Yamamoto T, et al: Appositional angle closure in eyes with narrow angles: comparison between the fellow eyes of acute angle-closure glaucoma and normotensive cases. J Glaucoma 6:288–92, 1997
78. Scheie HG: Width and pigmentation of the angle of the anterior chamber: a system of grading by gonioscopy. Arch Ophthalmol 58:510–2, 1957
79. Schirmer KE: Gonioscopy and artefacts. Br J Ophthalmol 51:50–3, 1967
80. Seah SK, Foster PJ, Chew PT, et al: Incidence of acute primary angle-closure glaucoma in Singapore. An island-wide survey. Arch Ophthalmol 115:1436–40, 1997
81. Shaffer RN: Primary glaucomas. Gonioscopy, ophthalmoscopy and perimetry. Trans Am Acad Ophthalmol Otolaryngol 64:112–27, 1960
82. Shaffer RN: Operating room gonioscopy in angle-closure glaucoma surgery. Arch Ophthalmol 59:532–5, 1958
83. Shaffer RN: Stereoscopic Manual of Gonioscopy. St Louis, Mosby, 1962
84. Shaffer RN, Tour RL: A comparative study of gonioscopic methods. Trans Am Ophthalmol Soc 53:189–204, 1955
85. Shibata T, Sasaki K, Sakamoto Y, et al: Quantitative chamber angle measurement utilizing image-processing techniques. Ophthalmic Res 22(Suppl 1):81–4, 1990
86. Sihota R, Lakshmaiah NC, Walia KB, et al: The trabecular meshwork in acute and chronic angle closure glaucoma. Indian J Ophthalmol 49:255–9, 2001
87. Spaeth GL: Gonioscopy: uses old and new. The inheritance of occludable angles. Ophthalmology 85:222–32, 1978
88. Spaeth GL: The normal development of the human anterior chamber angle: A new system of descriptive grading. Trans Ophthalmol Soc UK 91:710–39, 1971
89. Spaeth GL, Aruajo S, Azuara A: Comparison of the configuration of the human anterior chamber angle, as determined by the Spaeth gonioscopic grading system and ultrasound biomicroscopy. Trans Am Ophthalmol Soc 93: 337–47, discussion 347–51, 1995
90. Spaeth GL, Aruajo S, Azuara A: Comparison of the configuration of the human anterior chamber angle, as determined by the Spaeth gonioscopic grading system and ultrasound biomicroscopy. Trans Am Ophthalmol Soc 93: 337–47, discussion 347–51, 1995
91. Sugar S: Concerning the chamber angle I Gonioscopy. Am J Ophthalmol 23:853–66, 1940
92. Sugimoto K, Ito K, Matsunaga K, et al: New Gonioscopy system using only infrared light. J Glaucoma 14:264–6, 2006
93. Tello C, Liebmann J, Potash SD, et al: Measurement of ultrasound biomicroscopy images: intraobserver and interobserver reliability. Invest Ophthalmol Vis Sci 35: 3549–52, 1994
94. Thomas R, George T, Braganza A, et al: The flashlight test and van Herick's test are poor predictors for occludable angles. Aust NZ J Ophthalmol 24:251–6, 1996
95. Trantas A: Moyens d'explorer par l'ophtalmoscope—et par translucidite—La partie anterieure du fond oculaire, le cercle ciliaire y compris. Arch Opthalmol Paris 20:314, 1900
96. Troncoso M: Treatise on Gonioscopy. Philadelphia, F A Davis, 1947
97. Urbak SF, Pedersen JK, Thorsen TT: Ultrasound biomicroscopy. II. Intraobserver and interobserver reproducibility of measurements. Acta Ophthalmol Scand 76:546–9, 1998
98. Van Herick W, Shaffer RN, Schwartz A: Estimation of width of angle of anterior chamber. Incidence and significance of the narrow angle. Am J Ophthalmol 68: 626–9, 1969

99. Weinreb NR, Friedman DS (eds): Angle Closure and Angle Closure Glaucoma. The Hague, The Netherlands, Kugler Publications, 2006
100. Wojciechowski R, Congdon N, Anninger W, et al: Age, gender, biometry, refractive error, and the anterior chamber angle among Alaskan Eskimos. Ophthalmology 110:365–75, 2003
101. Wong TY, Foster PJ, Seah SK, et al: Rates of hospital admissions for primary angle closure glaucoma among Chinese, Malays, and Indians in Singapore. Br J Ophthalmol 84:990–2, 2000
102. Woo EK, Pavlin CJ, Slomovic A, et al: Ultrasound biomicroscopic quantitative analysis of light-dark changes associated with pupillary block. Am J Ophthalmol 127:43–7, 1999
103. Yang CC, Chou SC, Hung PT, et al: Anterior chamber angles shallowing and intraocular pressure after topical pilocarpine. J Ocul Pharmacol Ther 13: 219–24, 1997

Dr. Friedman has consulted for Carl Zeiss Meditec, Inc., Dublin, CA, but has no active relationship with the company. Dr. Mingguang He reported no financial or other conflicts of interest concerning this study.

Reprint address: David S. Friedman, MD, 600 North Wolfe Street, Wilmer 120, Johns Hopkins Hospital, Baltimore, MD 21287.