Videographic Hirschberg Measurement of Simulated Strabismic Deviations

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Purpose. To demonstrate the potential use of subpixel image processing methods to perform automated Hirschberg measurements of strabismic deviations using relatively inexpensive personal computer hardware; to determine if the method might allow screening for strabismus using full-face video images obtained from a distance of 1 meter.

Methods. Strabismic deviations (< 25 prism diopters) were simulated by means of induced asymmetric fixation. A ring of coaxial infrared light-emitting diodes (LED) were used to generate first Purkinje reflexes. Computerized image analysis with subpixel processing was used to measure the locations of the first Purkinje reflexes and pupil centers of video images of 10 normal subjects, following the technique of the clinical Hirschberg test. The apparent strabismic deviation was calculated from the relative asymmetry of the center of the corneal reflex ring to the pupil center in each eye.

Results. In 10 normal subjects, there was a statistically significant linear correlation of Hirschberg horizontal reflex deviation with asymmetric fixation pseudo-esotropia (0.85 ≥ r² ≥ 0.99, P < 0.05).

Conclusions. The Hirschberg test is used manually to detect strabismus in infants and children but requires a highly skilled examiner. The image processing method described here requires no operator interpretation and may make the test more applicable. The results suggest that this technology may be appropriate for a screening instrument. Invest Ophthalmol Vis Sci 1993;34:3220-3229.
the pupil. We define the pupillary axis as the line normal to the cornea, passing through the center of the entrance pupil. The pupillary axis also passes through the center of the radius of curvature of the anterior corneal surface. The line of sight is the line passing through the center of the entrance pupil to the fixation point. As both lines pass through the center of the pupil, an angle is formed. This angle (between the pupillary axis and the line of sight) is known as the angle lambda. Angle lambda can be measured separately for each eye by imaging each eye under monocular viewing conditions. Bifixating eyes viewed along the line of sight will display displacement of the first Purkinje reflexes from the pupillary axes that are attributable to angle lambda.

In normal individuals, angle lambda is similar in each eye and the eyes bifixate. As a result, when the eyes bifixate on a light source and the eyes are observed along the line of sight, symmetrical displacements of the Purkinje reflexes from the centers of the pupils are observed. If equal angle lambdas are assumed and a strabismic deviation is present, unequal nasal displacements of the reflexes from the centers of the pupils will be seen when viewed along the line of sight of the fixing eye (Fig. 1). A screening strategy would be to assume equal angle lambdas. If unequal displacements are observed, asymmetric fixation is suspected and the eyes are presumed to be heterotropic.

The difference in image displacement is proportional to the magnitude of the deviation. The proportionality constant, or Hirschberg Constant, has a generally accepted value of about 21 PD/mm of displacement.

Measurement of strabismic deviation then depends upon accurate measurement of four loci in the face image: the two centers of the pupil images and the two centers of the first Purkinje images. The accuracy of these measurements will affect the resolution with which strabismic deviations can be detected.

Using manual analysis of face photographs, an excellent correlation (r = 0.97) of corneal reflex displacement with prism and alternate cover test measurement of strabismic deviation has been reported. However, these measurements were derived from a large range of esotropias and exotropias, and the sensitivity of the method in detecting small magnitude deviations cannot be ascertained from this report.

Subjective interpretation of full-face photographs taken under ideal conditions by experienced observers has also been studied. Photographs were taken of five subjects displaying either orthotropia or a small induced strabismus (5 PD esotropia). These photographs were presented to a group of 66 second-year optometry students and nine faculty members. Sensitivity, the presence of strabismus correctly identified, was approximately 80%. Specificity, the absence of strabismus correctly identified, was approximately 40%.

We wanted to determine the feasibility of using image processing methods to improve strabismus detection and compare them with observer-based analysis. Because cost is always an important consideration in screening, we placed cost-related constraints on this determination: Standard resolution (RS-170) television camera imaging would be used, and a single camera would be used for the whole face rather than one camera per eye. Furthermore, a standard microcomputer (IBM PC Compatible) hardware would be used for the image analysis, rather than workstation or mainframe machines.

To detect small strabismic deviations from a full-face (15-cm field) video using standard hardware (640 X 480 pixel array), subpixel resolution is required. Using this hardware, the pixel resolution of the face image is 4 pixels/mm. Without subpixel resolution, the theoretical detection limit under noiseless conditions for this image resolution and a Hirschberg constant of 20 PD/mm is 5 PD. Using subpixel imaging methods, this limit may be reduced to a continuous variable. Assuming a factor of four improvement in resolution through subpixel resolution imaging methods, one can conservatively expect an improvement to 1 PD resolution.

In addition, we wanted to enhance the Hirschberg test by incorporating a keratometer into the device to provide a measurement of corneal radius of curvature. Brodie has identified the sinusoidal relationship between corneal light reflex displacement and angular rotation for a spherical cornea. For small deviations, a nearly linear relationship exists between corneal light
reflex displacement and angular rotation. For larger deviations (greater than approximately 40 PD), there is a predicted diminution in the incremental corneal light reflex displacement for incremental turning. Clinically, this diminution—presumably an artefact of peripheral corneal flattening—is not observed. We wanted to employ the theoretical model of Brodie by determining the corneal radius of curvature.

Instead of a single on-axis light source, a ring of infrared light-emitting diodes (IRLED) (880 nm) was used as the Purkinje reflex-generating light source. This system provides data that can be used to estimate the corneal radius of curvature and detection of corneal astigmatism. The centroid of the Purkinje reflex group was assumed to be the vertex of the cornea. A spherical cornea would give this result. Although most corneas have elliptical boundaries at the limbus when viewed from the front, in the central optical zone they are spherical. For a highly aspheric cornea or for large magnitude strabismic deviations, this would not be true. For this experiment, this assumption did not result in a quantifiable error.

METHODS

Subjects

Ten adult subjects were recruited. A protocol approved by the University Human Subjects Committee was followed, as were the tenets of the Declaration of Helsinki. No subject had a detectable manifest ocular deviation, and all had stereo acuity without correction of at least 60 arc seconds, as determined with Randot Circles stereo testing. All were able to fixate on objects from a distance of 20 cm to 1 m without the assistance of eyeglasses.

Test Apparatus

The test apparatus consists of an illumination system to generate the Purkinje images, a video system to obtain a full-face image, a fixed-position fixation target, and a movable fixation target to induce esotropia. Each subject's face was positioned in a headrest located 1 m from the pupil of the video camera objective. The headrest had been centered in the video image. The optical system is shown in Figure 2.

Two concentric rings of IRLED (880 nm), centered about the optical axis of the video system, were used to illuminate the subject at a distance of 78 cm. The inner ring of IRLED (ring diameter, 200 mm) provided facial illumination while maintaining a dark pupil. A second ring of IRLED (ring diameter, 750 mm) created a set of eight Purkinje images that could be distinctly resolved. Because all IRLED were located off the visual axis, a dark pupil was observed.

The video system used an f/1.2 standard 35-mm camera lens, with a 50-mm focal length (Nikon, Tokyo, Japan), connected to a high-sensitivity monochrome CCD video camera (DageMTI Model CCD-72, Michigan City, IN) with a c-mount adapter. The relatively "fast" optics resulted in a narrow depth of field that was verified to be approximately 3 cm. The horizontal field of view was approximately 14 cm, which produces the maximum magnification of each eye compatible with maintaining an image of both eyes in the same frame. Images were acquired with a 640 X 480 pixel resolution frame grabber (Dipix P360, Ottawa, Quebec, Canada). The pixel resolution of the face image is approximately 4.5 pixels/mm.

A 5-inch diagonal video monitor was used to generate a single-pixel, illuminated fixation target. A mirror and a beam splitting "cold mirror" were used to create a fixation target that is optically coincident with the center of the pupil of the video camera objective. The cold mirror transmits the infrared light from the facial scene to the video system. The fixation target is coincident with the video camera pupil and 1 m from the plane is defined by the subject's corneas.

Esotropia was experimentally induced in the subjects by means of a movable target that was located on the line defined by the pupil of the video camera objective and the subject's left eye pupil (Fig. 3). To accomplish this, an optical rail was mounted so that it
rotated about a point directly under the camera pupil. The optical rail was then aligned to the subject's left eye by having the subject fix on the video target. The movable fixation target (a small accommodative target mounted on the optical rail) was positioned midway between the subject and the distant target. The rail was then rotated so the movable fixation target was aligned with the distant, single-pixel, illuminated fixation target on the video monitor when viewed with the subject's left eye.

Using this apparatus, the left eye should not have moved as the target was advanced. The right eye increasingly turned in as the target advanced, producing a small apparent esotropia (Fig. 4). The room lights were then dimmed to stimulate maximum pupil dilation. A small, green, light-emitting diode illuminated the movable fixation target. As the movable fixation target was advanced, the subject verified that at each distance the targets aligned with the left eye, and then fixated at the near target with both eyes.

Images were acquired from each subject while the subject was fixing on the distant, single-pixel illuminated fixation video target and while fixing the movable target at distances of 60, 50, 40, 30, and 20 cm from the subject's left eye. Three image pairs were acquired from each subject at each position. Image acquisition preceded image analysis, so the operator was masked to the results.

An IBM-compatible personal computer (Intel, [Sunnyvale, CA] 486/33 MHz processor) was used to acquire and process images. Image analysis was performed using programs written in the C language.

**Image Analysis Protocol**

Two images were acquired in rapid succession, with and without the outer ring of IRLED illuminated (Fig. 5). The first image, with the outer ring of IRLED on, was split vertically, and each half was scanned for the large, bright corneal reflex arising from the inner ring of IRLED. A 100 × 100 pixel image of each eye was then extracted from both facial images. The two-eye image sets were analyzed to determine the centers of the pupils and the centers of the eight-point sources comprising the outer ring of IRLED.

![Diagram of experimental setup](attachment:diagram.png)
FIGURE 5. Images were acquired in rapid succession, with (a) and without (b) the outer ring of IRLED illuminated.

The pupil center for each eye was determined by finding the centroid of a binary image of the pupil. A brightness histogram was determined for the eye image (Fig. 6), and the local minimum above the cluster of dark pupil pixels was used to determine a threshold. Pixels darker than the threshold were assigned to the pupil, and pixels brighter than the threshold were excluded. Bright pixels within the central cluster (as from the inner ring of IRLED) were filled. The result was an image of the pupil for which the binary pupil centroid (balance point) could be determined (Fig. 7).

Digital subtraction was then performed for each 100 X 100 pixel image pair. The image with the outer ring of IRLED off (Figs. 5b, 8b) was digitally subtracted from the image with the outer ring of IRLED on (Figs. 5a, 8a). This difference image (Fig. 8c) contains the Purkinje images. In the case of a constricted pupil, strabismic deviation, or both, some of the Purkinje images from the IRLED are located outside the pupil (Fig. 8a). The difference image (Fig. 8c) does not contain the underlying iris features. This technique minimizes the interference from the underlying iris features.

The outer ring IRLED first Purkinje image centroids were localized in the digital subtraction image by scanning a template across an area containing the expected locations of the outer ring of IRLED. At each central pixel of the eight first Purkinje image locations, a 5 X 5 pixel window was marked on the image (Fig. 9). Subpixel resolution of the location of the first Purkinje image centroids was achieved by computing the centroid of these 5 X 5 pixel window regions. With each of the eight IRLED first Purkinje locations found, the outer ring centroid was determined by averaging the eight distinct positions. For a spherical cornea, this average location is equivalent to the location of the first Purkinje position of a single point source located at the aperture of the camera.

For each eye, the horizontal distance in pixels from the outer ring centroid to the pupil centroid was computed. If the pupil centroid was temporal to the outer ring centroid, it was assigned a positive sign in keeping with the convention of a normally positive angle lambda.

The distance in pixels between the outer ring centroid of the two eyes was measured. This distance was then converted to millimeters, giving the interpupillary distance.

The horizontal reflex asymmetry was found by subtracting the right nasal reflex displacement from the left. Data were then stored for subsequent statistical analysis.

RESULTS

Our cost-driven design constraints resulted in a standard television image capture format that has much
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FIGURE 8. A constricted pupil or large strabismic deviation (25 PD shown), or both, lead to Purkinje images located outside the pupil. Digitally subtracting image 8b from 8a yields a difference image, 8c, containing the Purkinje images with minimal interference from the underlying iris features.

lower image resolution than film used in previous photographic-based Hirschberg measurements. However, the video image can be analyzed both immediately and quantitatively in a way that even a Polaroid photograph-based analysis cannot achieve. The prototype instrument requires approximately 1 minute to acquire and analyze an image pair. Because the instrument (rather than the operator) determines if the image pair is acceptable, little operator training is required. No supplies are consumed and no expenses are incurred if the first image is not acceptable. This is particularly important in testing children, because it allows determination of whether adequate image capture and measurement have been made while the screening subject is still available. Multiple captures can be easily and quickly made on a relatively uncooperative child until an adequate reading is obtained. In the present study, three images were obtained at each condition of asymmetric fixation, and the results were averaged to improve the signal-to-noise ratio. Figure 10 shows the scatterplot of the averaged data for all subjects.

FIGURE 9. Each Purkinje image centroid is localized in the digital subtraction image using a 5 X 5 pixel window for subpixel image processing. Note how the centroid does not lie at the center of the innermost pixel.

FIGURE 10. Raw data from the 10 subjects are pooled. The regression coefficient r² was 0.84 (P = 0.000).
For each subject, a linear correlation of the horizontal reflex asymmetry and the amount of calculated esotropia induced by asymmetric fixation were computed. Figure 11 shows the regression lines for each subject. Regression values ranged from $r^2 = 0.85$ to 0.99 ($P < 0.05$ all cases) for each of the individuals.

Table 1 lists by subject the $r$ value indicating the relative strength of the linear association and the coefficients of the regression equation, as well as the regression offsets.

For a given subject, errors in centration of the face in the camera-image plane (Fig. 12a) and errors in

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**TABLE 1. Summary of Linear Regression Data for 10 Subjects at Esotropic Angles Induced by Asymmetric Fixation From 0 to 25 Prism Diopters**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Hirschberg Coefficient, Prism Diopters/mm</th>
<th>Regression Offset Error, Prism Diopters</th>
<th>$r^2$, Corrected Model (P &lt; 0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.8</td>
<td>-0.74</td>
<td>0.98</td>
</tr>
<tr>
<td>2</td>
<td>23.7</td>
<td>-8.69</td>
<td>0.97</td>
</tr>
<tr>
<td>3</td>
<td>17.7</td>
<td>0.50</td>
<td>0.99</td>
</tr>
<tr>
<td>4</td>
<td>18.3</td>
<td>2.19</td>
<td>0.85</td>
</tr>
<tr>
<td>5</td>
<td>18.0</td>
<td>0.89</td>
<td>0.98</td>
</tr>
<tr>
<td>6</td>
<td>18.9</td>
<td>-0.20</td>
<td>0.99</td>
</tr>
<tr>
<td>7</td>
<td>14.4</td>
<td>-2.13</td>
<td>0.98</td>
</tr>
<tr>
<td>8</td>
<td>17.5</td>
<td>2.02</td>
<td>0.99</td>
</tr>
<tr>
<td>9</td>
<td>22.0</td>
<td>-3.40</td>
<td>0.99</td>
</tr>
<tr>
<td>10</td>
<td>16.7</td>
<td>-5.16</td>
<td>0.98</td>
</tr>
<tr>
<td>Mean</td>
<td>19.0</td>
<td>-1.47</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Data were averaged before regression. The model employed was Esotropia (Prism Diopters) = Hirschberg Coefficient (Prism Diopters/mm) * Reflex Position Asymmetry (mm) + Regression Offset Error (Prism Diopters). The corrected model eliminated the regression offset error by subtracting the x-intercept from each observation.

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**FIGURE 11.** The raw data regression lines are shown for each subject. Regression values ranged from $r^2 = 0.85$ to 0.99 ($P < 0.025$ all cases) for each of the individuals.

**FIGURE 12.** (a) Systematic error is introduced when the subject is not centered on the optical axis. (b) Systematic error is introduced when the optical bench is not aligned with the subject's left pupil.
alignment of the optical bench (Fig. 12b) introduce systematic errors. Centration errors primarily introduce an apparent asymmetry in angle lambda with the addition of an offset in the regression. Bench alignment errors primarily result in a change in slope of the regression because of an inaccurate derivation of the amount of apparent esotropia induced by asymmetric fixation. These systematic errors were simulated, and the results are shown in Figure 13. These errors could have been minimized by interactively acquiring data, analyzing the images, and adjusting the alignment. However, we were concerned that such a method would bias the results and instead relied upon the subject to monitor the alignment. As a result, small amounts of misalignment are present and result in systematic errors of both slope and offset.

We observed evidence of all three systematic errors in the creation of apparent esotropia: decentration of the image plane with respect to the midpoint between the eyes (observed in all subjects); misalignment of the optical bench (evidenced by motion of the left eye, which should not move, as the target was advanced along the line of sight of the left eye); and translation of the left eye (a result of the subject attempting to keep the left eye properly positioned along the bench).

The only readily identifiable and correctable systematic error is the offset in each subject's regression line from the origin. Therefore, for each subject the constant offset was subtracted from the predicted esotropia to force the linear regression line to pass through the origin (Fig. 14). An offset from the origin, as from an asymmetric angle lambda, must be assumed to be equal to 0 in a clinical situation, unless monocular viewing conditions are analyzed.

For the pooled observations in the present study, when corrected for intrasubject offset, the regression coefficient $r^2$ was 0.98 ($P = 0.000$) and the value of the Hirschberg Constant was 18.7 PD/mm of horizontal reflex deviation. The scatter plot of these observations is shown in Figure 15.

When paired comparisons of the measurements at the orthotropic position and the minimal induced deviation (mean 4.1 PD, range 3.7 to 4.2 PD) are made...
DISCUSSION

There has been a recent resurgence of interest in the objective measurement of strabismic deviations. Several recent studies have investigated the origins of the Hirschberg coefficient using geometric models. Brodie’s figure of 21 PD/mm horizontal displacement of the corneal reflex has been confirmed over a wide range of clinical data.

The present study has demonstrated that small magnitude strabismic deviations of less than 5 PD can be detected by automated analysis of a face image derived from a single video camera at standard (RS-170) resolution following the Hirschberg method. This is made possible by subpixel image processing methods, which allow measurement of both the location of the pupil center and corneal light reflections using standard video images.

One noteworthy difference between the present and previous reports is the observed pooled Hirschberg Constant of 18.7 PD/mm of displacement, as opposed to the 21 PD/mm predicted from the geometric model of Brodie. The origin of this difference may arise from systematic errors in the model used to simulate esotropia, from change in the center of the pupil as the pupil constricts, or from the expected decrease in accurately measuring pupil center as the pupil constricts and fewer pixels define its location.

Subject 7, with a Hirschberg Constant of 14.4 PD/mm, is best indicative of the limits of our model. Subject 7 had a pronounced pupillary constriction as the fixation target was advanced, and variations in pupil size demonstrated changes in accuracy. In subject 7, we cannot rule out change in pupil center with pupillary constriction because no limbal reference points were used in this analysis. A better method of analysis may be to include limbal landmarks in the estimation of the pupillary axis.

A second source of variation of the observed Hirschberg Constant from that predicted by the geometric model may lie in the curvature of the cornea. The cornea is known to be increasingly aspheric as the limbus is approached. This peripheral flattening may compensate for a nonlinear relationship between ocular rotation and reflex displacement. The present study examines primarily small deviations, but we wish to refine the method further to allow accurate measurement of large deviations. Direct measurement of corneal curvature will allow an improved model within each subject. Work is underway using our device to measure corneal curvature in the principle meridians and incorporating this information in refinement of image analysis. We also anticipate incorporation of limbal landmarks in the measurement of large deviations.

Although this study demonstrates that our automated analysis can detect small amounts of ocular rotation from video face images, the data were obtained under laboratory conditions using cooperative adult subjects. We are now testing the instrument with children and infants in actual screening settings. In view of the challenges in getting children to sit still to be photographed, it seems likely that in some cases multiple image captures may be needed to obtain usable data. Making multiple captures in a short period of time is not difficult on a system such as described here. We hope to determine instrument sensitivity and specificity as a function of the number of images captured and analyzed to determine the optimum tradeoff between predictive power and test duration.

We foresee a system in which multiple measurements will be made as the child views a cartoon on the video monitor. Many images could be acquired and analyzed while the child is viewing the cartoon. The cartoon or animation sequence will direct attention to the center of the monitor. Because the video monitor is large for a fixation target (7° field), measurement of central tendency will be used to determine central fixation. Such a system, operating at a distance of 1 meter, is readily achievable with the demonstrated technology and holds the promise of nonthreatening, rapid, and accurate screening for strabismus.

Key Words: strabismus, Hirschberg, pediatric, image analysis

References


