Fixation-Free Assessment of the Hirschberg Ratio

Dmitri Model,[1] *Moshe Eizenman,*[1,2,3] *and Veit Sturm*[4]

Purpose. To describe a novel methodology by which to measure the Hirschberg ratio (HR) in infants. The methodology does not require fixation on specific points, and measurements are made while infants look naturally at a display.

Methods. The HR is calculated automatically from measurements of the direction of the optical axis, the position of the pupil center, and corneal reflexes in video images from an advanced two-camera eye-tracking system. The performance of the novel fixation-free procedure (FFP) was evaluated in 43 adults by measuring the average difference and the 95% limits of agreement with the standard fixation-based procedure (FBP). Repeatability of the HR measurements was evaluated by assessing the 95% limits of agreement between two independent measurements. Performance of the FFP was also evaluated in five infants.

Results. In adults, the average HR was 12.89 ± 1.22°/mm for FFP and 12.81 ± 1.22°/mm for FBP. FFP and FBP measurements were highly correlated ($r = 0.95$; $P < 0.001$). The 95% limits of agreement between FFP and FBP were ±0.86°/mm. The 95% limits of agreement of repeated measurements were ±0.66°/mm for FFP and ±0.77°/mm for FBP. In infants, the 95% limits of agreement of repeated measurements by FFP were ±0.63°/mm.

Conclusions. In adults, the FFP provides accurate measurements of the HR that are in excellent agreement with measurements by FBP. In infants, measurements of HR by FFP show the same repeatability and consistency. (*Invest Ophthalmol Vis Sci.* 2010;51:4035–4039) DOI:10.1167/iovs.09-5014

The Hirschberg test as an assessment of binocular motor alignment was introduced more than 120 years ago.[1–3] By shining a penlight toward the patient's eyes, the displacement of the light reflex (first Purkinje image) from the center of the pupil can be observed, allowing an estimate of the amount of ocular misalignment. Originally, this displacement was described in terms of proximity of the corneal reflex to ocular landmarks (pupil, iris, limbus).[1,3] More recently, the test has been interpreted in a more quantitative form, and ocular misalignment is expressed by the displacement of the light reflex multiplied by a simple proportionality constant. This proportionality constant, which expresses the ratio between ocular rotation and reflex displacement, is called the Hirschberg ratio (HR).[4,5] It can be expressed in either degrees per millimeter or prism diopters (Δ) per millimeter[2,6] [$\Delta = 100 \times \tan(°)$].

Although the HR was originally believed to be approximately 8°/mm,[2,7,8] several recent investigations using photographic[6,9–11] and videographic[12–14] techniques have measured a mean value of approximately 12.5°/mm (22 Δ/mm) and an intersubject variability of more than ±20% of the mean value. To measure HR, subjects are required to accurately fixate multiple (at least two) targets with known spatial coordinates. Given that it is impossible to reliably complete such a procedure with infants or young children, ocular misalignment in these groups is calculated by multiplying the average HR (22 Δ/mm) by the measured/estimated displacement between the corneal reflex and the center of the pupil for each subject. The use of the average HR introduces inherent uncertainty of ±20% to the estimate of ocular misalignment of each infant/young child. As surgeons attempt to perform corrective surgery for infantile esotropia at younger and younger ages,[15] it has become important to develop more exact measurements of ocular misalignment for infants and young children.

This article describes a novel fixation-free procedure (FFP) for the estimation of HR in infants and young children. The procedure does not require fixation on specific points, and it is based on the use of an advanced remote eye-tracking system[16] for estimation of the position and orientation of the eye in space. Performance of the FFP for estimation of the HR is compared, in adults, with the performance of the standard fixation-based procedure (FBP). Performance of the FFP is also evaluated in a study with five infants.

Materials and Methods

Fixation-Free Procedure

An advanced remote binocular eye-tracking system[16] (Vision 2020-RB; El-Mar Inc., Toronto, ON, Canada) was used to determine the coordinates of the pupil center and corneal reflexes in images from the system's two video cameras (Fig. 1). With these coordinates, the direction of the optical axis of each eye was estimated without any user calibration procedure.[16] Displacement of the central corneal reflex (CR) from the virtual image of the pupil center (P) in each eye was calculated by back-projecting the corresponding pupil center and corneal reflex in each image (Fig. 1, inset: pupil center is marked by a cross, corneal reflexes are enclosed by small boxes) to their three-dimensional positions inside the eye. As subjects look at video images on the computer monitor of the eye-tracking system, a graph showing the horizontal component of the displacement vector [$CR(x) - P(x)$] versus the horizontal component of the direction of the optical axis is created (Fig. 2). The absolute value of the slope of a line, which was fitted to the data points using a robust-fit algorithm[17] (to remove outliers), is an estimate of the HR (in degrees per millimeter).

During measurement of the HR, adult subjects sat at approximately 85 cm from the center of the computer monitor while leaning their heads against a forehead support. Infants were seated on their parents'

From the Departments of [1]Electrical and Computer Engineering and [2]Ophthalmology and Vision Sciences and the [3]Institute of Biomaterials and Biomedical Engineering, University of Toronto, Toronto, Ontario, Canada; and the [4]Department of Ophthalmology, University Hospital of Zurich, Zurich, Switzerland.

Supported by the Natural Sciences and Engineering Research Council of Canada (NSERC 130149); the Vision Science Research Program of the Toronto Western Research Institute, University Health Network, Toronto, Ontario, Canada; and the Nachwuchsforderungskredit Stieferl-Zangger-Stiftung of the University of Zurich, Zurich, Switzerland.

Submitted for publication December 2, 2009; revised January 25, 2010; accepted February 2, 2010.

Disclosure: **D. Model**, None; **M. Eizenman**, El-Mar Inc. (F, I); **V. Sturm**, None

Corresponding author: Moshe Eizenman, Institute of Biomaterials and Biomedical Engineering, 164 College Street, Room 415, University of Toronto, Toronto, ON, M5S 3G9, Canada; eizenm@ecf.utoronto.ca.

Figure 1. A pair of images of an 8-month-old infant from the two video cameras of the remote binocular gaze-tracking system. Pupil center and three corneal reflexes (virtual images of the system's three infrared light sources) are identified and tracked automatically by the system (*inset*).

laps with their heads supported by their parents' hands. Different images (animations, cartoons, and images of the subject's face from the video cameras) were displayed at the lower half of the screen. The horizontal position of the center of the image changed randomly every 2 to 3 seconds to encourage larger ranges of horizontal eye movements. For each measurement of the HR, subjects looked at the computer monitor for 10 seconds. Measurements were repeated twice (to determine repeatability).

Fixation-Based Procedure

In the standard FBP to measure the HR, adult subjects looked at five points that were presented in sequence on the computer monitor. The horizontal angular separation between every two points was 5°, and each point was presented for approximately 2 seconds. The horizontal displacement between the virtual image of the corneal reflex and the pupil center [$CR(x) - P(x)$] was calculated in the same manner as that used for the FFP. The HR was determined by the slope (absolute value) of a line that was fitted to the data that described the changes in the horizontal angular coordinates of the points on the screen as a function of [$CR(x) - P(x)$]. Each measurement of the HR was repeated twice (to determine repeatability).

Subjects

Forty-three adult subjects (mean age, 27 years; range, 18–57 years) from among the students and staff at the University of Toronto were tested. Best-corrected visual acuity was at least 20/20 in all participants. Subjects did not wear eyeglasses or contact lenses during the

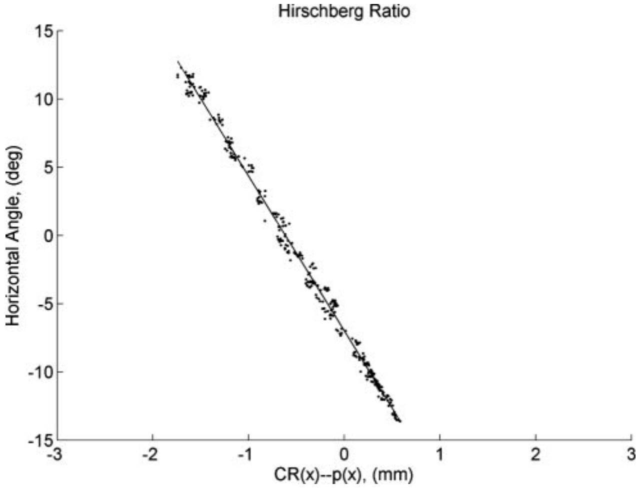

Figure 2. A graph of the horizontal component of the direction of the optical axis (on the *y*-axis) compared with the horizontal component of the displacement of the corneal reflex from the pupil center (on the *x*-axis). *Dots*: data points. *Solid line*: fitted to the data points. The absolute value of the slope of the line represents the HR in degrees per millimeter.

test. The mean spherical equivalent refractive error of the tested eyes was −2 diopters (range, −7.5 to +1 diopters). Five healthy infants (ages 5, 5, 6, 7, and 10 months) were also tested. Ophthalmologic examination revealed no abnormality in any of the subjects. All infants showed good monocular and binocular fixation and light following responses. Informed consent was provided by the subject or a legal guardian after an explanation of the study purpose and procedures. This study followed the tenets of the Declaration of Helsinki. The protocol was approved by the University of Toronto Research Ethics Board.

Statistical Analysis

Measurements of the HR by the FFP and the FBP were compared with the use of both correlation analysis and the difference versus mean analysis.[18] The correlation coefficient and the 95% confidence interval for the difference between the measurements were calculated for the first measurement of the HR by each procedure. A paired *t*-test ($\alpha = 0.05$) was used to test for bias between the measurements of the two procedures. The repeatability of each procedure was tested by calculating the average difference between two independent measurements and the 95% confidence interval for the difference.

Results

HR was successfully measured in left and right eyes of 43 adult subjects with both procedures, providing 86 measurements for each procedure. Frequency distributions for the measurements of the HR for the FFP and the FBP are shown in Figure 3. Lilliefors test for normality[19] shows that HRs measured by both procedures had normal distributions ($\alpha = 0.01$). Mean ± SD of the HR was 12.81 ± 1.22°/mm (22.74 ± 2.13 Δ/mm) with FBP and 12.89 ± 1.22°/mm (22.88 ± 2.13 Δ/mm) with FFP. The range of HRs in each procedure was approximately 5.5°/mm or 10 Δ/mm.

HR estimates by the two procedures were highly correlated ($r = 0.95$, $P < 0.001$; Fig. 4A). The difference versus mean analysis[18] showed that the average difference between procedures was −0.08 ± 0.44°/mm and that the 95% limits of agreement were ±0.86°/mm (Fig. 4B). Paired *t*-test ($\alpha = 0.05$) showed no statistically significant bias between the two procedures.

Figure 5 shows a plot of the differences between two independent measurements of the HR for each subject versus the mean value for the FBP (Fig. 5A) and the FFP (Fig. 5B). The average of the differences was 0.12 ± 0.39°/mm and −0.03 ± 0.34°/mm for FBP and FFP, respectively. The 95% limits of agreement for repeatability were ±0.77°/mm for FBP and ±0.66°/mm for FFP.

Measurements of the HR in the left and right eyes shows good correlation ($r = 0.95$, $P < 0.001$; Fig. 6A). The average difference between the right and left eyes was 0.06 ± 0.42°/mm, and the 95% limits of agreement were ±0.82°/mm.

For infants, the average difference between two measurements was 0.09 ± 0.32°/mm, and the 95% limits of agreement

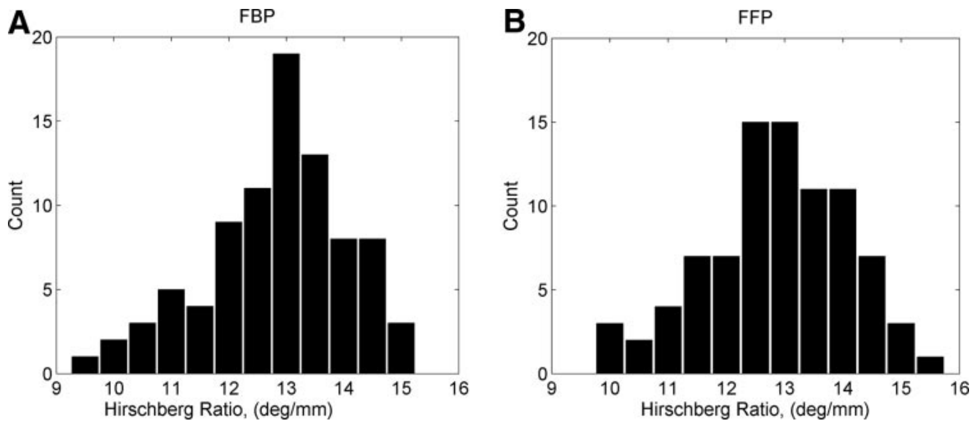

FIGURE 3. Histograms of the HRs measured by the FBP (**A**, 12.81 ± 1.22°/mm) and the FFP (**B**, 12.89 ± 1.22°/mm).

for repeated measurements were ±0.63°/mm (Fig. 7A). HRs of the left and right eyes showed good correlation ($r = 0.83$). The average difference between right and left eyes was −0.02 ± 0.36°/mm, and the 95% limit of agreement between the left and right eyes was ±0.70°/mm (Fig. 7B).

DISCUSSION

Results of the study with adults show that HRs measured with the novel FFP were in excellent agreement with the measurements of HRs by the standard FBP. The 95% limits of agreement between the measurements of the HR by the FFP and the FBP (±0.86°/mm) were similar to the 95% limits of agreement between repeated measurements with the FBP (±0.77°/mm). The slightly better repeatability of the measurement of the HR by the FFP (95% limits of agreement of repeated measurements of ±0.66°/mm vs. ±0.77°/mm with FBP) can be explained by the fact that the novel FFP was not affected by inaccurate fixation or fixation eye movements. The mean ± SD of the measurement of the HR by the FFP (12.89 ± 1.22°/mm) was similar to measurement of the HR by FBP (12.3 ± 1.2°/mm,[13] 12.93 ± 1.23°/mm,[14] and 12.81 ± 1.22°/mm in this study).

The accuracy of repeated measurements of the HR with the FFP was similar for infants and adults (95% limits of agreement of repeated measurements were ±0.63°/mm in infants and ±0.66°/mm in adults). In addition, agreement between the measurements of the HR between left and right eyes of each subject was similar for infants and adults (95% limits of agreement between the measurements in the right and left eyes are ±0.70°/mm for infants and ±0.82°/mm for adults). The excellent agreement between the measurements of the HR with the novel FFP and the standard FBP and the consistency of the measurements in adults and infants suggested that the FFP can be used to estimate accurately the HR in infants and young children.

Several studies suggest that corrective surgery for infantile esotropia, which relies on the measurement of the angle of ocular misalignment, should be performed in the first or second year of life.[15,20,21] Given that the standard test for the measurement of ocular misalignment, the alternate prism and cover test, cannot be used reliably in infants and very young children, the angle of deviation is often determined using the Hirschberg test, which relies on the HR to accurately estimate the angle of misalignment.

Because the HR exhibits high interindividual differences (±20% of the mean value or 10 Δ/mm found in several studies[9,12,13,22] and in the present study), it can introduce significant errors in the measurement of eye misalignment and, consequently, significant errors in determining the surgical dose. For example, if one used the standard average HR for adults (22 Δ/mm[13,14]) to calculate the eye misalignment of one of the infants in our study who had an HR of 17.5 Δ/mm, the error in the surgical dose for 40 Δ of eye misalignment would be 10.3 Δ. This error in surgical dose would compromise the ability to achieve a postoperative alignment within 8 Δ of orthotropia, which is considered to be a favorable outcome for infantile esotropia.[23–25]

For accurate estimation of the deviation from ocular alignment with the Hirschberg test, both the HR and the angle kappa (the angle between the optical and visual axes) should be estimated for each infant. Hasebe et al.[13] described an automated procedure that was successfully used to estimate angle kappa in infants and young children. In this procedure, infants and young children looked at a bright light in their

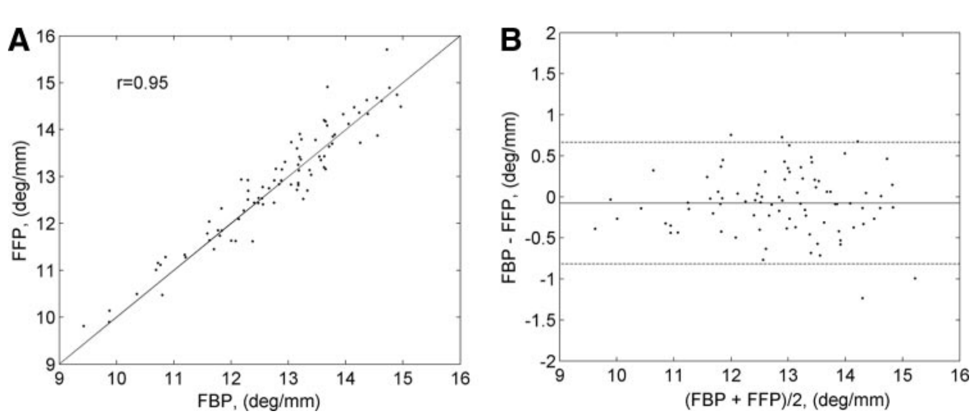

FIGURE 4. (**A**) HRs measured by the FFP compared with the FBP ($r = 0.95$). The *solid line* (HR measured by FFP = HR measured by FBP) is shown for reference. (**B**) Difference versus mean plot of the data in (**A**). *Solid line*: mean of differences (bias, −0.08°/mm); *dashed lines*: 95% limits of agreement (±0.86°/mm).

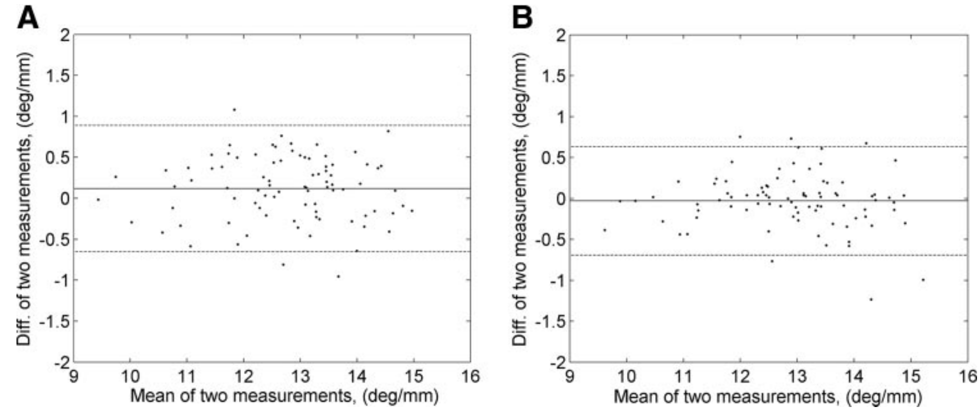

FIGURE 5. Difference versus mean plot of two independent measurements of HR: (**A**) by FBP, (**B**) by FFP. *Solid line*: mean of differences (bias, 0.12°/mm in (**A**) and −0.03°/mm in (**B**)); *dashed lines*: 95% limits of agreement (±0.77°/mm in (**A**) and ±0.66°/mm in (**B**)).

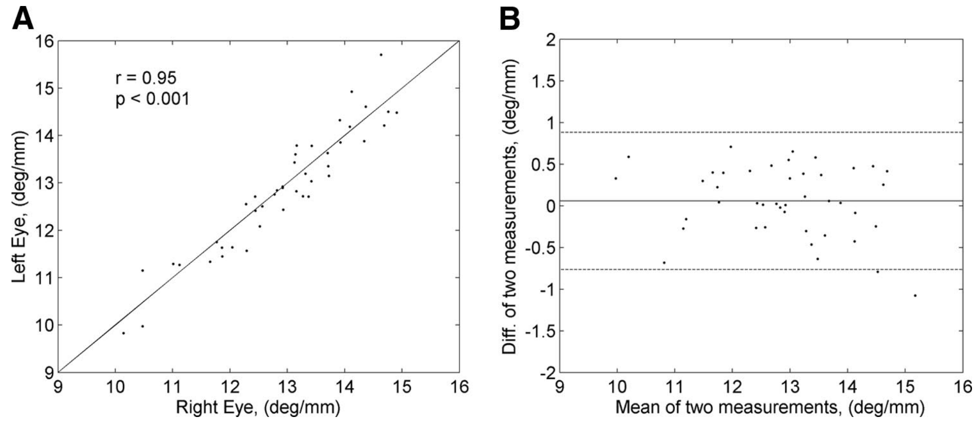

FIGURE 6. (**A**) HR of the left eye versus HR of the right eye for adult subjects using the FFP. The *solid line* (HR of the left eye = HR of the right eye) is shown for reference. (**B**) Difference versus mean plot of the same data as in (**A**). *Solid line*: mean of differences (bias, 0.06°/mm); *dashed lines*: 95% limits of agreement (±0.82°/mm).

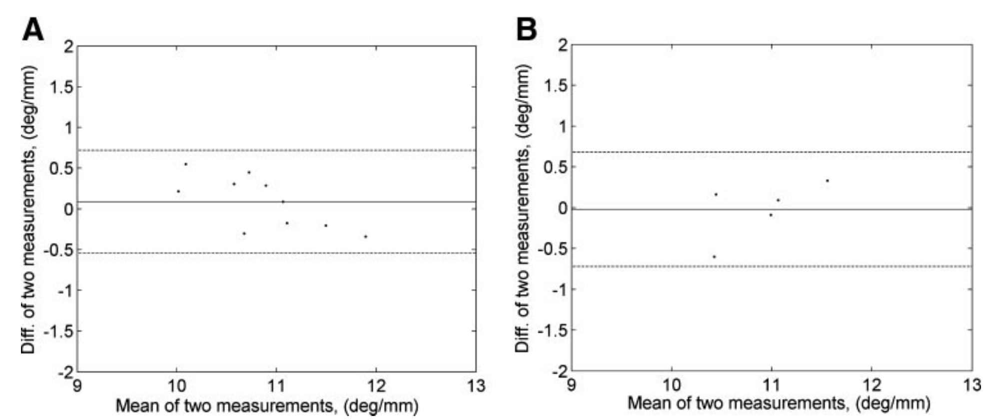

FIGURE 7. (**A**) Difference versus mean plot for two independent measurements of the HR in infants by the FFP. *Solid line*: mean of differences (bias, 0.09°/mm); *dashed lines*: 95% limits of agreement (±0.63°/mm). (**B**) HR of the left eye versus HR of the right eye. *Solid line*: mean of differences (bias, −0.02°/mm); *dashed lines*: 95% limits of agreements (±0.70°/mm).

central visual field, and the displacement of the corneal reflex of the light from the pupil center was measured in both eyes (the displacement in the nondeviating eye divided by the HR is angle kappa). By assuming mirror symmetry of angle kappa in the two eyes, the displacement of the corneal reflex from the pupil center in the deviating eye could be adjusted to account for angle kappa. This adjusted value multiplied by the personal HR of each infant or young child can improve significantly the accuracy of the Hirschberg test. A more accurate Hirschberg test should help in the planning of strabismus surgery or other interventions to correct eye misalignment in infants and young children.

Acknowledgments

The authors thank Agnes Wong and Stephen Kraft for their insightful comments.

References

1. Hirschberg J. Ueber Messung des Schielgrades und Dosirung der Schieloperation. *Zentralblatt für Praktische Augenheilkunde*. Leipzig: Verlag von Veit & Co.; 1885:325–327.
2. Hirschberg J. Beiträge zur Lehre vom Schielen und von der Schieloperation. *Zentralblatt für Praktische Augenheilkunde*. Leipzig: Verlag von Veit & Co.; 1886:5–9.
3. Du Bois-Reymond C. Ueber Schielmessun. *Zentralblatt für Praktische Augenheilkunde*. Leipzig: Verlag von Veit & Co.; 1886:1–5.
4. Jones R, Eskridge JB. The Hirschberg test: a reevaluation. *Am J Optom.* 1970;47:105–114.
5. Brodie SE. Corneal topography and the Hirschberg test. *Appl Opt.* 1992;31:3627–3631.
6. Brodie SE. Photographic calibration of the Hirschberg test. *Invest Ophthalmol Vis Sci.* 1987;28:736–742.
7. Wheeler MC. Objective strabismometry in young children. *Arch Ophthalmol.* 1943;29:720–714.
8. Krimsky E. *The Management of Binocular Imbalance*. Philadelphia: Lea & Febiger; 1948.
9. Carter AJ, Roth N. Axial length and the Hirschberg test. *Am J Optom Physiol Opt.* 1978;55:361–364.
10. Eskridge JB, Wick B, Perrigin D. The Hirschberg test: a double-masked clinical evaluation. *Am J Optom Physiol Opt.* 1988;65.
11. Riddell PM, Hainline L, Abramov I. Calibration of the Hirschberg test in human infants. *Invest Ophthalmol Vis Sci.* 1994;35:538–543.
12. Miller JM, Mellinger M, Greivenkemp J, Simons K. Videographic Hirschberg measurement of simulated strabismic deviations. *Invest Ophthalmol Vis Sci.* 1993;34:3220–3229.
13. Hasebe S, Ohtsuki H, Tadokoro Y, Okano M, Furuse T. The reliability of a video-enhanced Hirschberg test under clinical conditions. *Invest Ophthalmol Vis Sci.* 1995;36:2678–2685.
14. Schaeffel F. Kappa and Hirschberg ratio measured with an automated video gaze tracker. *Optom Vis Sci.* 2002;79:329–334.
15. Wong AM. Timing of surgery for infantile esotropia: sensory and motor outcomes. *Can J Ophthalmol.* 2008;43:643–651.
16. Guestrin ED, Eizenman M. Remote point-of-gaze estimation requiring a single-point calibration for applications with infants. *Proc Symp Eye Tracking Res Applications*. Savannah, GA: ACM; 2008: 267–274.
17. Holland PW, Welsch RE. Robust regression using iteratively reweighted least-squares. *Commun Stat Theory Methods.* 1977;A6: 813–827.
18. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *The Lancet.* 1986; 327:307–310.
19. Lilliefors HW. On Kolmogorov-Smirnov test for normality with mean and variance unknown. *J Am Stat Assn.* 1967;62:399–402.
20. Helveston EM, Ellis FD, Plager DA, Miller KK. Early surgery for essential infantile esotropia. *J Pediatr Ophthalmol Strabismus.* 1990;27:115–118, discussion 119.
21. Von Noorden GK. A reassessment of infantile esotropia: XLIV Edward Jackson Memorial Lecture. *Am J Ophthalmol.* 1988;105:1–10.
22. Eskridge JB, Perrigin DM, Leach NE. The Hirschberg test: correlation with corneal radius and axial length. *Optom Vis Sci.* 1990;67: 243–247.
23. Fu VLN, Stager DR, Birch EE. Progression of intermittent, small-angle, and variable esotropia in infancy. *Invest Ophthalmol Vis Sci.* 2007;48:661–664.
24. Birch E, Stager D, Wright K, Beck R. The natural history of infantile esotropia during the first six months of life. *J AAPOS.* 1998;2:325–328.
25. Parks MM. The monofixation syndrome. *Trans Am Ophthalmol Soc.* 1969;67:609–657.