Fixation-Free Assessment of the Hirschberg Ratio

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Abstract

Purpose: To describe a novel methodology to measure the Hirschberg Ratio (HR) in infants. The methodology does not require fixations on specific points and the measurement is done while infants look naturally at a display.

Methods: The HR is calculated automatically from measurements of the direction of the optical axis and 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, with 43 adults, by measuring the average difference and 95% limits of agreement with the standard Fixation-Based Procedure (FBP). The repeatability of the HR measurements was evaluated by assessing the 95% limits of agreement between two independent measurements. The performance of the FFP was also evaluated with 5 infants.

Results: Adults: The average HR is 12.89 ± 1.22 °/mm for FFP and 12.81 ± 1.22 °/mm for FBP. The measurements by FFP and FBP are highly correlated (r = 0.95, p < 0.001). The 95% limits of agreement between FFP and FBP are ±0.86 °/mm. The 95% limits of agreement of repeated measurements are ±0.66 °/mm for FFP and ±0.77 °/mm for FBP.

Infants: The 95% limits of agreement of repeated measurements by FFP are ±0.63 °/mm.

Conclusions: In adults, the FFP provides accurate measurements of HRs that are in excellent agreement with measurements by FBP. In infants, measurements of HRs by the FFP show the same repeatability and consistency as in adults.
Introduction

The Hirschberg test as an assessment of binocular motor alignment was introduced more than 120 years ago.\(^1\)\(^-\)\(^3\) By shining a penlight towards 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 that expresses the ratio between ocular rotation and reflex displacement is called the Hirschberg ratio.\(^4\)\(^,\)\(^5\) It can be expressed in either degrees per millimeter or prism diopters (\(\Delta\) per millimeter\(^2\)\(^,\)\(^6\) (\(\Delta = 100\times\tan(\text{degrees})\)).

Though, originally, the HR was believed to be around 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 inter-subject variability of more than ±20% of the mean value. To measure the HR, subjects are required to accurately fixate multiple targets (at least two) with known spatial coordinates. Since 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\textsuperscript{15}, it is important to develop more exact measurements of ocular misalignment for infants and young children.

This paper describes a novel Fixation-Free Procedure (FFP) for the estimation of the 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\textsuperscript{16} for the estimation of the position and orientation of the eye in space. The performance of the FFP for the estimation of the Hirschberg ratio is compared, in adults, with the performance of the standard Fixation-Based Procedure (FBP). The performance of the FFP is also evaluated in a study with 5 infants.

**Materials and Methods**

**Fixation Free Procedure**

![Figure 1](image-url). A pair of images of an eight-months-old baby 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 IR light sources) are identified and tracked automatically by the system (see Inset).

An advanced remote binocular eye-tracking system\textsuperscript{16} (VISION 2020-RB, El-Mar Inc., Toronto, Ontario, Canada) is used to determine the coordinates of the pupil-center and corneal reflexes in images from the system’s two video cameras (see Figure 1). Using
these coordinates, the direction of the optical axis of each eye is estimated without any user calibration procedure. The displacement of the central corneal reflex (CR) from the virtual image of the pupil center (P), in each eye, is calculated by back projecting the corresponding pupil-centers and corneal reflexes in each image (see Inset in Figure 1: pupil center is marked by a cross, corneal reflexes are enclosed by small boxes) to their 3-D 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)) vs. the horizontal component of the direction of the optical axis is created (see Figure 2). The absolute value of the slope of a line, which was fitted to the data points using a ‘robust-fit’ algorithm (to remove outliers), is an estimate of the HR (in units of °/mm).

**Figure 2.** A graph of the horizontal component of the direction of the optical axis (on the Y-axis) vs. the horizontal component of the displacement of the corneal reflex, CR, from the pupil center, P, (on the X-axis). Dots represent actual data points. Solid line is fitted to the data points. The absolute value of the slope of the line represents the Hirschberg ratio in °/mm.

During the 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 parent’s laps with their heads supported by their parent’s hands. Different images (animations, cartoons and images of the subject’s face from the
video camera) were displayed at the lower half of the screen. The horizontal position of
the center of the image changed randomly every 2-3 seconds to encourage larger range 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 (FBP)**

In the standard FBP to measure the HR, adult subjects looked at 5 points that were
presented in sequence on the computer monitor. The horizontal angular separation
between each 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, \((\text{CR}(x) – \text{P}(x))\), was calculated in the same manner that it was calculated
in the FFP. The HR was determined by the slope (absolute value) of a line that was fitted
to the data that describe the changes in the horizontal angular coordinates of the points on
the screen as a function of \((\text{CR}(x)-\text{P}(x))\). Each measurement of the HR was repeated
twice (to determine repeatability).

**Subjects**

Forty three adult subjects (mean age 27, range 18 to 57), from 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 test. The
mean spherical equivalent refractive error of the tested eyes was –2 diopters (range: -7.5
to +1 diopters). Five healthy babies (ages 5, 5, 6, 7 and 10 months old) were also tested.
Ophthalmological examination revealed no pathology 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**

The measurements of the HR by the FFP and the FBP were compared by using both correlation analysis and the difference versus mean analysis. 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 (α = 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**

The Hirschberg ratio was successfully measured in left and right eyes of 43 adult subjects with both procedures, providing 86 measurements for each procedure. The frequency distribution for the measurements of the HR for the FFP and the FBP are shown in Figure 3. Lilliefors test for normality shows that HRs measured by both procedures had normal distributions (α = 0.01). The mean value ± Standard Deviation (SD) of the HR is 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 both procedures is approximately 5.5 °/mm or 10 Δ/mm.
Figure 3. Histograms of the HRs measured by the FBP (A) and the FFP (B). Mean ± SD is 12.81 ± 1.22 °/mm in (A) and 12.89 ± 1.22 °/mm in (B).

HR estimates by the two procedures are highly correlated (r = 0.95, p<0.001; see Figure 4A) and the difference versus mean analysis\textsuperscript{18}, showed that the average difference between the procedures is -0.08 ± 0.44 °/mm and the 95% limits of agreement are ±0.86 °/mm (see Figure 4B). A paired t-test (α = 0.05) showed no statistically significant bias between the two procedures.

Figure 4. (A) HRs measured by the FFP vs. measurements by the FBP. Correlation coefficient r=0.95. The solid line (HR by FFP = HR by FBP) is shown for reference. (B) Difference vs. mean plot of the data in (A). Solid line indicates the mean of differences (bias = -0.08 °/mm); The 95% limits of agreement (±0.86 °/mm) are indicated by the dashed lines.
Figure 5. Difference vs. mean plot of two independent measurements of the HR by the FBP (A) and by the FFP (B). Solid line indicates the mean of differences (bias = 0.12 °/mm in (A) and -0.03 °/mm in (B)); The 95% limits of agreement (±0.77 °/mm in (A) and ±0.66 °/mm in (B)) are indicated by the dashed lines.

Figure 6. (A) HR of the left eye vs. 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 vs. mean plot of the same data as in (A). Solid line indicates the mean of differences (bias = 0.06 °/mm). The 95% limits of agreement (±0.82 °/mm) are indicated by the dashed lines.

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 (Figure 5A) and the FFP (Figure 5B). The average of the differences is 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 ($r = 0.95, p < 0.001$; see Figure 6A). The average difference between the right and left eyes is $0.06 \pm 0.42 \, ^\circ/\text{mm}$ and the 95% limits of agreement are $\pm 0.82 \, ^\circ/\text{mm}$.

For infants, the average difference between two measurements is $0.09 \pm 0.32 \, ^\circ/\text{mm}$ and the 95% limits of agreement for repeated measurements are $\pm 0.63 \, ^\circ/\text{mm}$ (see Figure 7A). The HRs of the left and right eyes shows good correlation ($r = 0.83$). The average difference between right and left eyes is $-0.02 \pm 0.36 \, ^\circ/\text{mm}$ and the 95% limits of agreement between the left and right eyes are $\pm 0.70 \, ^\circ/\text{mm}$ (see Figure 7B).

**Discussion**

The results of the study with adults show that HRs measured with the novel FFP are 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 ($\pm 0.86 \, ^\circ/\text{mm}$) are similar to the 95% limits of agreement between repeated measurements with the FBP.
The slightly better repeatability of the measurement of the HR by the FFP (95% limits of agreement of repeated measurements of ±0.66 ′/mm versus ±0.77 ′/mm with FBP) can be explained by the fact that the novel FFP is not affected by inaccurate fixation and/or fixation eye movements. The mean and standard deviation of the measurement of the HR by the FFP (12.89 ± 1.22 ′/mm) are similar to measurement of HR by FBP (12.3 ± 1.2 ′/mm, 12.93 ± 1.23 ′/mm and 12.81 ± 1.22 ′/mm in this study).

The accuracy of repeated measurements of the HR with the FFP is very similar for infants and adults (95% limits of agreement of repeated measurements in infants are ±0.63 ′/mm versus ±0.66 ′/mm in adults). Also, the agreement between the measurements of the HR in the left and right eyes of each subject is very similar for infants and adults (95% limits of agreement between the measurements in the right and left eyes are ±0.70 ′/mm for infants versus ±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 suggest that the FFP can be used to estimate accurately the HR in infants and young children.

Several studies suggested 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. Since 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 Hirschberg ratio to accurately estimate the angle of misalignment.
Since the HR exhibits high inter-individual differences (±20% of the mean value or 10 Δ/mm\(^9,12,13,22\) as well as the current 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 uses the standard average Hirschberg ratio for adults (22 Δ/mm\(^13,14\)) to calculate the eye misalignment for one of the infants in our study who has a HR of 17.5 Δ/mm, the error in the surgical dose for 40 Δ of eye misalignment will be 10.3 Δ. This error in surgical dose will 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 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 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 non-deviating 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/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.
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