Measurement of Ocular Alignment With Photographic Purkinje I and IV Reflection Pattern Evaluation

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Purpose. To provide reference data for the measurement of ocular alignment and of angles of strabismus with a new stationary photographic apparatus at near and at distance fixation; to verify quantitative relations between the data by comparing experimental data with theoretical predictions.

Methods. Use of Purkinje I and IV Reflection Pattern Evaluation in conjunction with a new stationary photographic apparatus; application of previously derived equations; simulation of angles of strabismus of 5° and 10° in the primary position.

Results. Data from 62 subjects with orthotropia show good linearity of measured angles in different directions of gaze; a 95% confidence interval for errors up to 18.6% in the simulated angles of strabismus; no need for individual calibration of the apparatus; no bias due to wearing of spherical corrections, and a detection threshold for microstrabismus of ±0.35°.


Photographic Reflection Pattern Evaluation is a recently introduced technique for the objective assessment of ocular alignment under natural viewing conditions. A chief advantage of this technique is its applicability in infants because little cooperation is required for a measurement of manifest angles of strabismus. In infants, measurement is made by fixing at near with a handheld apparatus. If the infant has microstrabismus, the method may be used as a screening tool. Small and large angles of strabismus are not only detected, they are measured accurately. Larger manifest angles of strabismus may be measured accurately before surgery in noncooperative children.

The same measuring principle may be used for the measurement of small and large angles of strabismus at near and with distance fixation in primary, secondary, and tertiary positions of gaze with a stationary setup in cooperative patients. To verify the accuracy of this new application of Purkinje I and IV Reflection Pattern Evaluation, ocular alignment data at near and distance fixation were measured in subjects with orthotropia and were analyzed according to the computational principles developed in an accompanying article.

MATERIALS AND METHODS

Purkinje Reflection Pattern Evaluation measures the horizontal and vertical angles between the optical axis of an eye and the direction of a reference light in an array of light sources. The light sources’ positions are chosen to create Purkinje images in the subject’s pupil that will function as scales for the measurement of vertical and horizontal rotations of each eye. From these data, the ocular alignment may be calculated, for instance, to measure vertical and horizontal angles of strabismus accurately. Also, the angle α, the angle between an eye’s optical axis and the visual axis, can be measured when the subject fixates in the primary position. The basic equations have been deduced in detail elsewhere. The computational principles of
Purkinje I and IV Reflection Pattern Evaluation used in the evaluation of this study’s experimental data are presented in an accompanying article.\textsuperscript{7}

In this article, degrees are used as units for angles. They may be converted to prism diopters by using the following formula: angle (prism diopter) = 100 cm·tan (angle [degrees]). For angles up to 15°, this relation may be simplified: angle (prism diopter) = 1.74·angle [degrees].

Stationary Apparatus for Measurement of Ocular Alignment

In contrast to the previously used handheld apparatus,\textsuperscript{1} the stationary photographic apparatus used for the first time in this study consists of a reflex camera (Pentax ME, operated with an MX motor winder, and a 100 mm Vivitar macro-tele lens) mounted into a modified slit lamp stand with a head and chin rest. Figure 1 shows the setup schematically. A special frame attached to the stand is used to hold the camera that points to the subject’s face from underneath so that both eyes are photographed simultaneously while the subject fixes on a fixation target above the camera, or at a distance of 4 m. A photograph of the setup is shown in Figure 2.

Fixation at Near

For measurements at near, the patient fixes on one of five near fixation lights (red light-emitting diodes, diameter 5 mm, marked with a small, black, central circle as accommodative stimulus), positioned on a rail above the camera at a distance, d = 35 cm, from the eyes’ pupillary plane. The horizontal positions of the fixation targets correspond to horizontal fixation angles ε of 0° (primary position), 5°, and 10° to the right and to the left of the primary position.

Three small photoflash units (Tumax A 16, guide number 16), mounted with distances, D = 8.2 cm, between the three photoflash units at about H = 10 cm below the camera lenses center, are used for the generation of the reflection patterns (Figs. 3A, 3B). Slide film (Ektachrome ASA 64) was used at an f-stop of 11 in the pictures taken fixing at near.

With the near fixation setup, the reflection patterns consisted of a lower row of three bright anterior corneal reflections and an upper row of dimmer posterior crystalline lens reflections, as shown in Figure 4. In this photograph, taken with the subject wearing glasses, two additional rows of reflections can be seen that stem from the spectacle’s front and back surfaces.

For vertical fixation angles, the levered support of the camera can be rotated around an horizontal axis that can be adjusted to go through the subject’s eyes (Fig. 1) upward or downward, together with the hori-
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Distance Fixation

To achieve measurements with distance fixation, additional equipment—the flash unit and fixation screen—was constructed. Nine zoom reflector photoflash units (Soligor 42 AT, maximal guide number 42) and an array of fixation targets were integrated into a specially designed white tangent screen positioned vertically 4 m from the subject’s eyes. This flash unit and fixation screen are shown schematically and as a photograph in Figures 5A and 5B.

For measurements at different vertical fixation angles, an upper row, a middle row, and a lower row of three horizontally aligned photoflash units each are built into the screen. Each row can be operated separately, depending on the chosen vertical fixation angle. The horizontal distance between the three photoflash units in each row is $D = 70.5$ cm, and the horizontal distance between the vertically positioned flash unit and fixation screen and the pupillary plane is $d = 4$ m. The photoflash units’ vertical positions (170 cm above, 60 cm above, and 45 cm below the primary position fixation targets) were chosen so that a vertical angle of 5° to 15° resulted between the visual axis and the incident lights’ direction in different positions of gaze (Fig. 5B). This ensures good separation of all the Purkinje images I and IV in the subject’s pupils. With this setup, the three corneal reflections form the upper row and the three posterior crystalline lens reflections form the lower row of the reflection patterns, provided the visual axes are directed below the corresponding row of photoflashes.

The camera support is adjusted vertically so that the subject may fixate on one of the fixation lights in the chosen vertical direction and the camera lens axis comes as close as possible to the eyes’ optical axes without impairing the subject’s fixation or visual field.

The subject’s field of view, either with fixation at near or with distance fixation, was left undisturbed except for the lower portions of the visual field, and the subject may fixate at near and with distance fixation under various horizontal and vertical fixation angles without hindrance from the camera body or adjacent structures.

In this study, however, only the middle row of photoflash units in the flash unit and fixation screen shown in the Figures 5A and 5B was used because only gaze directions with vertical fixation angles $\epsilon = 0^\circ$...
FIGURE 5. (A) Custom-built flash unit and fixation screen. The photograph shows three horizontal rows of photoflash units and a number of fixation targets surrounded by black stars. Both the flash units and the fixation targets (light-emitting diodes) are operated by remote control. (B) Schematic representation of the distance fixation screen showing only the middle three photoflash units and the five fixation targets used for the assessment of ocular alignment with horizontal fixation angles as reported in this study. The characteristic distances between the photoflash units that serve as light sources are $D = 70.5$ cm. At the distance $d = 4$ m from the subject's pupillary plane, they lead to a reference angle $r_0 = 10^\circ$ calculated with the equation $r_0 = \arctan(D/d)$. The central fixation target, or primary position fixation target, is the reference point from which the measured angles in Reflection Pattern Evaluation are taken. Four additional fixation targets are positioned at distances $l = 35.25$ cm and $l = 70.5$ cm to the right and to the left of the primary position fixation target. This leads to horizontal fixation angles $\epsilon = 5^\circ$ and $10^\circ$ calculated with the equation $\epsilon = \arctan(l/d)$.

were examined. Five red light-emitting diodes with a horizontal separation $l = 35.25$ cm, corresponding to horizontal fixation angles $\epsilon = 0^\circ$ (primary position), $5^\circ$ and $10^\circ$ to the right and to the left, were mounted at 110 cm from the ground to provide fixation targets with a vertical fixation angle, $\epsilon = 0^\circ$. Each fixation target (a red light-emitting diode with a diameter of 5 mm) is set in the middle of a black star of 7 cm width to give an adequate fusion stimulus. The examination stand and the flash unit and fixation screen were perpendicularly aligned and centered relatively. For measurements at a distance of 4 m, an f-stop of 4 was used to compensate for the reduced light intensity.

Reflection Pattern Evaluation Procedure

To evaluate the reflection patterns, the slides were magnified with a microfiche reader (Agfa Scopix, Leverkusen, Germany). A video signal was generated with
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From reflection patterns recorded in monocular fixation, where \( \Delta \varepsilon = \varepsilon_{\text{RE}} - \varepsilon_{\text{LE}} \) is the difference between the horizontal fixation angles \( \varepsilon \), and where \( \sigma(\varepsilon) \) is the horizontal binocular angle of strabismus. Except for the sign, this quantity corresponds to the manifest horizontal angle of strabismus under binocular viewing conditions.

Another equation holds for the sum of the angles \( \tau_{\text{RE}} \) and \( \tau_{\text{LE}} \) in binocular fixation \( \Sigma \tau(\varepsilon) \):

\[
\Sigma \tau(\varepsilon) = \alpha_{\text{RE}} + \alpha_{\text{LE}} + \sigma(\varepsilon) \tag{3}
\]

A result equivalent to the simultaneous prism-and-cover test is obtained if one considers the difference \( \sigma_{\text{CT}} \), the manifest, objective angle of strabismus, in each eye separately:

\[
\sigma_{\text{CT}} = \tau_{\text{bin}} - \tau_{\text{mon}} \tag{4}
\]

where \( \tau_{\text{bin}} \) = angle \( \tau \) of one eye measured under binocular conditions, \( \tau_{\text{mon}} \) = angle \( \tau \) of the same eye measured under monocular fixation conditions with the \( \tau \) values recorded under the same fixation angles and with the same fixation targets.

For any subject, the individual angular ratios \( r_{\text{ang}} \) that represent the slope of the linear \( \tau \) versus \( \varepsilon \) plot may be computed from data in the primary and secondary positions, when a subject fixates under different fixation angles \( \varepsilon \) from the primary position successively. The following equation is used to calculate the angular ratio in the right eye \( r_{\text{ang RE}}(\varepsilon) \) and in the left eye \( r_{\text{ang LE}}(\varepsilon) \) from the angles \( \tau(\varepsilon) \), \( \alpha \) and \( \varepsilon \) in each eye, respectively:

\[
r_{\text{ang}}(\varepsilon) = (\tau(\varepsilon) - \alpha)/\varepsilon \tag{5}
\]

The vertical deviation, \( \text{VD} \), that corresponds to the manifest vertical angle of strabismus in binocular fixation was calculated with equation (6):

\[
\text{VD} = \tau_{\text{v}} \left( \frac{h_{\text{RE}}}{a_{\text{RE}} + A_{\text{RE}}} + \frac{h_{\text{LE}}}{a_{\text{LE}} + A_{\text{LE}}} \right) \tag{6}
\]

where \( h_{\text{RE}} \) and \( h_{\text{LE}} \) are the vertical distances between the parallel rows of reflections in each eye and \( a_{\text{RE}} \), \( A_{\text{RE}} \) and \( a_{\text{LE}} \), \( A_{\text{LE}} \) are the horizontal distances between the Purkinje reflections in each eye, as defined above.

Study Design

The tenets of Declaration of Helsinki were followed. Institutional human experimentation committee approval was applied for and was judged unnecessary by the committee because of nonsubstantial damaging potential linked to the study. Informed consent was obtained from all subjects who participated in the study.

Ocular alignment data from 62 healthy young volunteers (age range, 20 to 33 years) without a history of strabismus or amblyopia, wearing their glasses if
they had any, were measured and evaluated in this study. In seven of these subjects, the family history was positive for strabismus or amblyopia. A minimum corrected visual acuity of 0.8 (20/25) in each eye was required, and a complete orthoptic and ophthalmologic examination was performed to rule out any strabismus or other ocular disease. Refraction was assessed without cycloplegia with a Canon RK-10 autorefractor. Only subjects with astigmatism <0.75 D and anisometropia <1.25 D of spherical equivalent were included in the study.

Three groups of subjects were included in the study (the computed refraction data statistics given below were rounded to one decimal):

Subjects with emmetropia \((n = 20)\).

Mean spherical equivalent between \(-0.5 \) D and \(0.5 \) D. Median right eye, \(0.0 \) D; median left eye, \(0.0 \) D.

Subjects with myopia \((n = 22)\).

Mean spherical equivalent < \(-0.5 \) D; minimal spherical equivalent right eye \(-4.6 \) D; maximal spherical equivalent right eye \(-0.1 \) D; median right eye \(-0.9 \) D; mean right eye \(-1.5 \) D; minimal spherical equivalent left eye \(-4.9 \) D; maximal spherical equivalent left eye \(0 \) D; median left eye \(-0.9 \) D; mean left eye \(-1.6 \) D.

Subjects with hypermetropia \((n = 20)\).

Mean spherical equivalent > \(0.5 \) D; minimal spherical equivalent right eye \(0.1 \) D; maximal spherical equivalent right eye \(4.4 \) D; median right eye \(0.8 \) D; mean right eye \(1.2 \) D; minimal spherical equivalent left eye \(0 \) D; maximal spherical equivalent left eye \(5.3 \) D; median left eye \(0.63 \) D; mean left eye \(1.2 \) D.

The frequencies of the refractions in each group are shown in Figure 6.

To record the reflection patterns, the subjects were asked to fixate in the primary position and in the four secondary positions with angles of fixation \(\epsilon\) of \(5^\circ\) and \(10^\circ\) to the right and to the left, fixing either binocularly or monocularly. In the latter case, the examiner would cover one of the eyes. In the primary position, three pictures were taken binocularly, and five pictures of each eye were taken monocularly, at near and with distance fixation. In the four secondary positions, one binocular picture, one monocular picture of the right eye, and one monocular picture of the left eye were taken. In all pictures, the vertical angles of fixation were zero.

From the three binocular pictures recorded in the primary position, the individual mean and the maximum absolute individual variation (i.e., the difference \([\text{maximum} - \text{minimum}]\)) of \(\tau_{\text{RE}}\), of \(\tau_{\text{LE}}\), of \(\Delta \tau\)
Purkinje I and IV imagery, the Purkinje Compensation Method. In this technique, the Purkinje images I and IV can be aligned interactively for any gaze position using a single rotatable (infrared) light source. A mechanical setup with a head and chin rest, described in detail earlier, was used to find the direction of the light source that causes a certain alignment of the Purkinje images I and IV. To measure eye rotation or the angle $\alpha$, the relative shift of the Purkinje images I and IV caused by the eye rotation or by the angle $\alpha$ has to be compensated by a rotation of the light source’s direction of incidence until the original alignment of the Purkinje images I and IV is achieved again. The angle covered by the rotatable light source equals the amount of eye rotation or of the angle $\alpha$ that precedes the second alignment of the Purkinje images. In this manner, the angles $\tau_{RE,comp}$ and $\tau_{LE,comp}$ were measured five times in each eye fixating monocularly in the primary position, at near (d = 35 cm) and with distance fixation (d = 4 m), on the same day the other examinations were performed.

From each set of five angles, the individual mean of $\tau_{RE,comp}$ and of $\tau_{LE,comp}$ were calculated, as were the mean and the standard deviation in all subjects.

To assess the thresholds for the detection of small redress movements in the primary position by a comparison of binocular data with monocular data, as in the cover test, the differences $\sigma_{CT,1} = \tau_{bin} - \tau_{mon}$ and $\sigma_{CT,2} = \tau_{bin} - \tau_{mon}$ of the individual mean binocular $\tau_{bin}$ and the first two $\tau_{mon}$ in each eye in that subject were calculated. Of these, means and standard deviations were computed for the entire group.

To check the linearity of $\tau_{RE}$, $\tau_{LE}$, $\Delta\tau = \tau_{RE} - \tau_{LE}$, $\Sigma\tau = \tau_{RE} + \tau_{LE}$, and of the vertical deviation VD with the horizontal fixation angle $\epsilon$, these data were plotted against the horizontal fixation angle $\epsilon$ and were then approximated by linear regression (least squares fit) in a subsample of three subjects with typical data. This was also plotted with the mean of the binocular $\tau_{RE}$, $\tau_{LE}$ data in all gaze positions for the 62 subjects.

Furthermore, the angular ratios $r_{ang,RE}$ in right eyes for eye rotations from the primary position to the lateral fixation targets at 5º and 10º to the right and left were calculated by dividing the measured difference of $\tau_{RE}$ primary position $- \tau_{RE}$ secondary position through the actual angular distance between the lateral fixation targets and the primary position fixation targets, that is, $\epsilon = 5^\circ$ or $10^\circ$ (see equation [3]). In left eyes, the same procedure was used with data from left eyes to calculate $r_{ang,LE}$. All angular ratios were defined to be positive. For instance, if in a right eye, on a gaze position 5º to the left, the difference $\tau_{RE}$ (primary position) $- \tau_{RE}$ (secondary position) $= 4.5^\circ$, the angular ratio is $r_{ang,RE} = 0.9$, or 90%. Of these individual angular ratios, the means and standard deviations in the whole sample were calculated.

The binocular and monocular $\tau$ data served to synthesize angles of strabismus of $\sigma = \pm 5^\circ$ and $\sigma = \pm 10^\circ$ in the primary position whose amounts could be controlled exactly. These artificial angles of strabismus were synthesized in one of two ways:

As simultaneous prism-and-cover test-equivalent angles of strabismus $\sigma_{CT} = \tau_{mon}$ (primary position) $- \tau_{mon}$ (secondary position), for right and left eyes separately (see equation [4]). One was the individual mean from the monocular data $\tau_{mon}$ in the primary position, and the other was the angle of the same, now artificially deviating eye in a secondary position, $\tau_{mon}$ (secondary position).

As the binocular angle of strabismus $\sigma = \tau_{RE,ref} - \tau_{LE,dev}$ (see equation [5]), assuming $\Delta\alpha = 0^\circ$, with each $\tau_{RE}$ and $\tau_{LE}$ from two different binocular pictures. One angle was the reference value $\tau_{RE,ref}$, that is, the individual mean from binocular pictures in the primary position, and the other was the angle $\tau_{LE,dev}$ of the left eye from a binocular picture in a secondary position, or, vice versa, $\sigma = \tau_{RE,dev} - \tau_{LE,ref}$.

**RESULTS**

Table 1 shows the $\tau$ data obtained from the binocular pictures in the primary position in the whole group of subjects.

The smallest measured angles $\tau$ in the primary position (in orthotropia, these correspond to the angles $\alpha$) were approximately 0º in those with myopia, and the largest were approximately 8º in those with hypermetropia. This in good agreement with earlier results, indicating that negative angles $\alpha$ are extremely unlikely in orthotropia and that the mean angles $\alpha$ in adults with orthotropia typically measure approximately 4º with Reflection Pattern Evaluation.

The standard deviations of the mean $\tau$ ranging from 1.2º to 1.5º reflect, apart from the measurement accuracy, the individual variability of the measured angle $\tau$ or $\alpha$. The standard deviations expressed in % of the mean are remarkably constant for $\tau_{RE}$, $\tau_{LE}$ and their sum $\Sigma\tau$, both at near (34% to 35%) and with distance fixation (35% to 96%).

The intra-individual variability and reliability of the binocular and monocular data, which is due to fixational uncertainties, to limited measurement accuracy and individual factors is characterized by the maximal absolute individual variations (i.e. maximum–minimum) or ranges of the data within a data set, for example, from the three binocular pictures. In Table 1, binocular data, the mean of these ranges is consistently of the order of 0.3º to 0.5º, with standard
TABLE 1. Binocular Photographic Data

<table>
<thead>
<tr>
<th>Fixation at near</th>
<th>'RE</th>
<th>'LE</th>
<th>Δτ</th>
<th>Στ</th>
<th>VD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>4.13°</td>
<td>3.69°</td>
<td>0.44°</td>
<td>7.82°</td>
<td>0.09°</td>
</tr>
<tr>
<td>SD</td>
<td>1.41°</td>
<td>1.27°</td>
<td>0.71°</td>
<td>2.59°</td>
<td>0.72°</td>
</tr>
<tr>
<td>SD %</td>
<td>34.0</td>
<td>34.6</td>
<td>31.1</td>
<td>754</td>
<td></td>
</tr>
<tr>
<td>MIA var.</td>
<td>0.29°</td>
<td>0.32°</td>
<td>0.48°</td>
<td>0.41°</td>
<td>0.45°</td>
</tr>
<tr>
<td>SD</td>
<td>0.17°</td>
<td>0.21°</td>
<td>0.28°</td>
<td>0.23°</td>
<td>0.33°</td>
</tr>
</tbody>
</table>

Distance fixation

| Mean | 3.68° | 4.25° | −0.57° | 7.92° | 0.14° |
| SD   | 1.34° | 1.52° | 0.66° | 2.79° | 0.68° |
| SD % | 35.5 | 35.7 | 35.2 | 484 |
| MIA var. | 0.29° | 0.32° | 0.41° | 0.36° | 0.43° |
| SD   | 0.17° | 0.21° | 0.24° | 0.27° | 0.31° |

Mean and standard deviation (SD, also expressed in % of mean) of individual mean and standard deviation of absolute individual variation (MIA var.) of binocular photographic data in primary position, n = 62. All angle data were rounded to the second decimal place.

deviations of approximately 0.15° to 0.35°. The same applies to monocular data variations (Table 2B). These small variations testify to the high intraindividual reproducibility of the measurements with the stationary apparatus. In the stationary apparatus' handheld counterpart, these variations were found to be higher, probably resulting from poorer control of the fixation distance and from occasional relative tilt of the camera or head, leading to increased experimental errors. In the stationary apparatus, there is obviously better control of these factors.

The mean difference Δτ = τ_{RE} − τ_{LE} between binocular τ data in the left eyes and the right eyes does not exactly equal zero. With distance fixation, the mean τ in the left eyes is larger (Δτ = −0.571°), and at near, the mean τ in the right eyes is larger (Δτ = +0.441°). These mean differences Δτ between right and left eyes are not significantly different from 0° tested with paired Student's t-tests, both at near and with distance fixation.

TABLE 2a. Photographic Reflection Pattern

<table>
<thead>
<tr>
<th></th>
<th>τ_{RE \text{mean}}</th>
<th>τ_{LE \text{mean}}</th>
<th>τ_{RE \text{comp}}</th>
<th>τ_{LE \text{comp}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixation at near</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>4.21</td>
<td>3.62</td>
<td>4.02</td>
<td>3.59</td>
</tr>
<tr>
<td>SD</td>
<td>1.42</td>
<td>1.29</td>
<td>1.40</td>
<td>1.25</td>
</tr>
<tr>
<td>Distance fixation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>3.66</td>
<td>4.25</td>
<td>3.67</td>
<td>4.13</td>
</tr>
<tr>
<td>SD</td>
<td>1.36</td>
<td>1.50</td>
<td>1.28</td>
<td>1.39</td>
</tr>
</tbody>
</table>

Mean and standard deviation (SD) of individual mean of photographic reflection pattern and 'Compensation Method' monocular data, (n = 62). All data in degrees.

* Calculated after exclusion of the data where erroneous fixation was suspected (see Figure 7a).

All angle data were rounded to the second decimal place.

Very much the same results and trends are present in the monocular τ data in the primary position listed in the Tables 2A and 2A, both with Purkinje Reflection Pattern Evaluation and with the Compensation Method.

The plots in Figure 7 of the individual mean monocular τ data measured with Reflection Pattern Evaluation versus the corresponding mean monocular α measured with the Compensation Method show close agreement except for the data from right eyes, fixation at near. Here some of the angles measured with the Compensation Method depart substantially from the Reflection Pattern data. This is probably due to fixational errors on the part of the tested subjects because the measuring session usually started with the right eye at near. These Compensation Method data (shown as open squares) were not included in the linear re-

TABLE 2b. Monocular Photographic Reflection Pattern

<table>
<thead>
<tr>
<th>Fixation at near</th>
<th>Δτ_{mean} (°)</th>
<th>Στ_{mean} (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.59</td>
<td>7.83</td>
</tr>
<tr>
<td>SD</td>
<td>0.77</td>
<td>2.59</td>
</tr>
<tr>
<td>MIA var.</td>
<td>0.39</td>
<td>0.31</td>
</tr>
<tr>
<td>SD</td>
<td>0.23</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Distance fixation

| Mean         | −0.60          | 7.89          |
| SD           | 0.69           | 2.78          |
| MIA var.     | 0.41           | 0.36          |
| SD           | 0.24           | 0.27          |

Mean and standard deviation (SD) of individual mean, and mean and standard deviation of maximal individual absolute variation (MIA var.) of monocular photographic reflection pattern Δτ, Στ data, (n = 62). All data in degrees. All angle data were rounded to the second decimal place.
FIGURE 7. The plots of the individual mean monocular $\tau$ data measured with Reflection Pattern Evaluation versus the corresponding mean monocular $\alpha$ measured with the Compensation Method show close agreement except for the data from right eyes, fixation at near. Compensation Method data shown as open squares were not included in the linear regression and in the calculation of the mean $\tau_{RE,mon}$ in Table 2A.

Table 3 shows the calculated $\sigma_{CT1}$ and $\sigma_{CT2}$ in the right and left eyes obtained by subtraction of the first two monocular $\tau_{mon1}$ and $\tau_{mon2}$ from corresponding binocular data (individual mean in that eye) in the primary position.

Figure 8 shows plots of the individual binocular $\tau_{LE}$ versus $\tau_{RE}$, the so-called tropograms, for all five fixation angles, at near and with distance fixation, in all 62 subjects. Because some of the reflection pattern data were lost—some of the pictures could not be evaluated because of spectacle reflections and other artefacts—in some data sets, one of the five gaze positions is not represented. Five separate clusters of partly superimposed data points appear in these two tropograms. A satisfactory linearity is present, for instance, in the two subjects with minimal and maximal angles $\alpha$, whose data points lie slightly off, on each cluster’s longitudinal axis. As predicted, the clusters form a
The mean of the synthesized angles of strabismus is discussed in terms of the reflection patterns in both eyes to different degrees. During the study, this result speaks in favor of an equal trend between right and left eyes.

The slight difference of 92% - 89% = 3% between the 5° and 10° deviations could be due to a symmetrical difference of the fixation lights' positions (3% of D = 3.1 cm and D = 6.2 cm, respectively, or 1 mm and 2 mm, which was difficult to control in the laboratory setup).

No significant differences or trends were found in the angular ratios when comparing data from the three different refractive groups or measurements in subjects with or without glasses. This is in close agreement with previous findings.

The simulated binocular angles of strabismus, \( \sigma \), vary more than their counterparts, \( \sigma_{CT} \). The angular ratios for \( \sigma \) in Table 5 are between 0.8 and 1.1, with standard deviations ranging between 0.1 and 0.17. The marked right–left asymmetry in the angular ratios is best explained by the right–left asymmetry in the binocular primary position data (see Table 1). This asymmetry is not automatically cancelled (as in the calculation of \( \sigma_{CT} \)) because the angle \( \tau \) from one eye is subtracted from that of the other eye. Comparison of Table 4 with Table 5 clearly proves that the diagnosis of strabismus and the measurement of the angle of strabismus can be determined both ways, but angles of strabismus smaller than 5° may escape the solely binocular assessment. The threshold for the binocular detection may be estimated by taking twice the maximum standard deviation of the angular ratio for the 5° simulated strabismus, that is, \( \pm 2 \times 0.17 \approx \pm 0.34 \).

This is in excellent agreement with earlier findings.

### DISCUSSION

The results can be used to establish a reference data base for the interpretation of reflection pattern data obtained with the stationary apparatus, e.g., to differentiate diagnostically adult patients with strabismus, or patients in whom misalignment is suspected, from subjects with orthotropia.

### Primary Positions

The mean monocular Reflection Pattern Evaluation data are similar to their binocular counterparts. The results shown in Figure 7 exhibit good agreement be-

### TABLE 3. Manifest, Objective Angle of Strabismus Calculated From Binocular \( \tau \) Data Minus Monocular \( \tau \) Data

<table>
<thead>
<tr>
<th>Fixation at near</th>
<th>( \sigma_{CT1 RE}(\degree) )</th>
<th>( \sigma_{CT2 RE}(\degree) )</th>
<th>( \sigma_{CT1 LE}(\degree) )</th>
<th>( \sigma_{CT2 LE}(\degree) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>-0.03</td>
<td>-0.05</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>SD</td>
<td>0.11</td>
<td>0.16</td>
<td>0.11</td>
<td>0.13</td>
</tr>
<tr>
<td>Distance fixation</td>
<td>Mean</td>
<td>0.04</td>
<td>-0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>SD</td>
<td>0.07</td>
<td>0.09</td>
<td>0.09</td>
<td>0.12</td>
</tr>
</tbody>
</table>

\( n = 62 \). All data are in degrees. All angle data were rounded to the second decimal place. \( SD = \) standard deviation.
Measurement of Ocular Alignment

FIGURE 8. Tropograms (τ_{LE} versus τ_{RE}) of photographic data in all five gaze directions at near (A) and at a distance (B).

tween the photographic monocular Reflection Pattern Evaluation data and the monocular Compensation Method data. This agreement makes influences stemming from purely experimental errors less likely because the data were collected with two entirely different apparatuses.

The right−left asymmetry of the difference \( τ_{RE} - τ_{LE} \) is also present in the Compensation Method data. Although the mean \( τ_{RE} - τ_{LE} \) is not significantly different from zero either monocularly or binocularly, nor was it measured by the Compensation Method, the threefold occurrence of the same trend raises the question whether a true right−left asymmetry of angle \( α \) measured with Purkinje I and IV imagery, which reverses depending on fixation at near or with distance fixation, can be ruled out completely on the basis of our data. To our knowledge, however, there is no evidence for anatomic differences between right and left eyes in persons with orthotropia that could account for such asymmetry, for example, as assessed with A-scan axial length measurements.

Accommodation or, more generally speaking, influences from the crystalline lens position and refraction asymmetries on angle \( α \), which remain to be studied in detail, may be causes of a suspected right−left asymmetry of angle \( α \). Accommodation is likely to affect angle \( α \) at least to a small degree. Yet this effect would be expected to be the same in both eyes, which was not the case in our data.

Other systematic and nonsystematic measurement errors may contribute to the observed tendencies in \( Δτ \). Variations of head posture or facial asymmetries (for instance, if the left or the right eye is, on average, higher) would create different distances from the corneas to the photoflash units so that the reference angle \( τ_0 \) would not be the same in both eyes. Yet, with distance fixation, this difference would certainly vanish completely, which is not so in our data. Also, the mean of the vertical deviation, VD, is close to zero which speaks against a systematic influence of orbit or head position.

Systematic setup inaccuracies, such as if the fixation target in the primary position was not exactly vertically aligned with the middle light source, could readily explain the \( Δτ \) asymmetries because they would induce shifts in \( τ \) of the same magnitude. However, the different setups were repeatedly controlled in the study for this kind of error.

Secondary Positions

One aim of this study is to verify the relations between the measured angles \( τ \) in conjugate eye movements, that is, versions, as predicted by theoretical considerations of the ocular alignment data.\(^7\) The results give experimental evidence that equations (2) and (3), derived from these principles, are fulfilled to a high degree (Figs. 9, 10, 11; Tables 1, 2B).

The measurement accuracy for ocular rotations is easily characterized by the angular ratios. The underestimation of \(-2\%\) to \(-5\%\) in Table 4, relative to the ideal angular ratio \( r_{mag} = 1 \), could partly be stemming from setup tolerances: Flash units and fixation targets are mounted in a vertical plane. Flash units are mounted with a vertical offset, \( H \), from the corresponding fixation lights. This causes an extra distance of roughly 8 cm in the distance \( d' \) between the light sources (= photoflash units) and...
the pupillary plane compared to the fixation distance, \(d = 4\) m, at a vertical angle of incidence 10° of the photoflash units relative to the visual axis. The systematic error can be explained, in part, by this extra distance that translates into an error of \(-2\%\) in the reference angle \(\rho_0\). This source of error may also influence the data fixating at near. To avoid this error, the distance \(d'\) can be used instead of \(d\) in the formula for \(\rho_0\).

Yet the overall underestimation of the measured angles of approximately \(-10\%\) in Tables 4 and 5 can probably not be explained by the choice of the reference angle alone. Off-axis, oblique observation of the reflection patterns, leading to the observation of projections, and lens tilt and decentration, combined with accommodation, may play a role as posited above. Also, the actual point of rotation of the eyes lies behind the two-mirror system, giving rise to the Purkinje images I and IV, the anterior cornea, and the posterior crystalline lens surface. In adults, the estimate for the position of the ocular rotation point is between 13 and 14 mm from the anterior corneal vertex, whereas the distance between the anterior corneal vertex and the posterior crystalline lens vertex is approximately 7 mm. The assumed point of rotation of the two-mirror system, made of the cornea and of the posterior crystalline lens surface, is thus approximately half that distance (3.5 mm). Consequently, there is a discrepancy in the two points of rotation, which is likely to lead to an underestimation of the actual angle of eye rotation. The effect would be more pronounced with fixation at near, which is the case in our data. These influences are currently investigated by computer ray trace and model eye measurements.

For clinical purposes, an empirical correction of all measured angles \(\tau\) at near with a factor of 1.1 has been suggested\(^1\) to compensate for the experimentally found angular ratios smaller than 1. Formally, this is equivalent to substituting a larger reference angle \(\tau_0 = 1.1 \cdot \rho_0\), or a smaller flash unit and fixation distance \(d\), or a larger distance \(D\) between the photoflash units, because \(\rho_0 = \arctan (D/d)\).
Criteria for the Diagnosis of Strabismus

Criteria for the proper assessment of doubtful strabismic conditions may be derived from knowledge of the statistical distribution of the variational parameters and equations (2) and (3). If, in a sample of three repeated measurements, the binocular data vary more than twice the corresponding standard deviation in the reference group, ocular misalignment or wrong fixation should be suspected. In Table 1, the mean binocular difference \( \Delta \tau \) is negative because at near the mean data show \( \tau_{RE} < \tau_{LE} \) by approximately 0.5°. With distance fixation, the situation reverses: \( \tau_{RE} > \tau_{LE} \) by approximately 0.5°, all \( \Delta \tau \) sharing about the same standard deviation of approximately 0.8°. Hence, with this apparatus, the 95% confidence interval for \( \Delta \tau \) in adult subjects with orthotropia at near is approximately -0.5° ± 0.8°. The same reasoning can be applied to the interpretation of a vertical deviation VD.

The differences in angle \( \alpha \) between right and left eyes, be they of systematic or of individual origin, limit the measurement and detection accuracy of small angle strabismus based on the binocular difference \( \Delta \tau \) to approximately twice the standard deviation, that is, 1.7°.

The detection threshold for \( \sigma_{CT} \), which indicates the amount of the redress movement, is much lower. This is proved by the data in Table 3, with mean differences \( \sigma_{CT1} \) and \( \sigma_{CT2} \) that almost exactly equal zero in each of the two photographic cover-tests performed in the right and left eyes, at near and with distance fixation. More important, the standard deviations hardly exceed 0.15°. This means that the 95% confidence interval for \( \sigma_{CT} \) is approximately ±0.35°, which would allow for the detection of microtropia possibly as small as 0.3° (with distance fixation) to 0.35° (at near) if the photographic data set is complete (three binocular pictures and two monocular pictures of each eye) and if no fixational errors or other errors occurred. This conclusion remains to be validated by measurements in subjects with strabismus.

At least it can be said that the detection threshold
with the stationary apparatus is lower than the detection threshold with the handheld apparatus (0.7°) used for microstrabismus screening in children 1 to 7 years of age. It may also be noted that the standard deviations for \( \sigma_{CT} \) are smaller with distance fixation than they are at near, which reflects a trend toward higher accuracy of measurement when larger distances are involved. Obviously, the exact relative and absolute positioning of the fixation targets and of the flash unit array, critical for accuracy, are more easily adjusted and controlled with larger distances. And, finally, the fixation targets we used (light-emitting diodes of 5 mm diameter) subtend a larger angle at a distance of 35 cm (approximately 0.25°) than at a distance of 4 m, which adds to the fixational inaccuracies. Additional parameters may be used to assess the reliability of fixation in both eyes for the control of proper fixation, which is a prerequisite for safe interpretation of ocular alignment data. In binocular pictures, the sum of \( \tau_{RE} \) and \( \tau_{LE} \) should be constant if the eyes' relative alignment does not change, especially in versions. This is fulfilled, to a large extent, in this group of cooperative adults, as can be seen from the mean of the maximum of the individual variation of about 0.5° and from the corresponding standard deviations in the Table 1, 2A, and 2B. Hence, if the individual mean \( \Sigma T \) departs more than twice the standard deviation (SD = 0.4°) from the mean \( \Sigma T = 0.5° \) in the reference group, this is indicative of a variable misalignment or of a vergence because in a conjugate version, which occurs in erroneous fixation slightly off the fixation target yet still in the same plane, the sum of \( \tau_{RE} \) and \( \tau_{LE} \) would remain constant. Also, if in one eye only the maximum individual absolute variation of \( \tau \) exceeds a certain limit, this points to poor fixation in that eye because it may occur in amblyopia or strabismus with a dynamic manifest angle of strabismus. This threshold can again be chosen as the 2 SD limit. Further parameters may be defined whose means and standard deviations can serve as a means of differentiation based on computational principles in Reflection Pattern Evaluation.
Measurement of Ocular Alignment

**Angles of Strabismus**

By an appropriate combination of measured $\tau$ in different gaze directions in subjects with orthotropia, strabismus is simulated without bias from measurement inaccuracy in the reference measurement, the simultaneous prism-and-cover test, and without fluctuations of the angle of strabismus, which is often seen in strabismus. Although earlier measurements were made at near with a handheld apparatus—more easily prone to measurement inaccuracies than a stationary setup—this study allows a more detailed assessment and the verification of systematic trends in the angular ratios. When measuring angles of strabismus in the primary position quantitatively, accuracy is best represented by the angular ratios whose mean and standard deviations for the simulated strabismic conditions are listed in Tables 4 and 5. Consequently, in the 95% confidence interval, total measurement inaccuracies in the measurement of angles of strabismus of 5° and 10° are limited to 18.6%.

Similar results were obtained when the angles of strabismus were calculated from binocular data only, as shown in Table 5. Here the standard deviations of the mean angular ratios are somewhat larger.

In the primary position, the measured binocular or monocular angles $\tau_{RE}$ and $\tau_{LE}$ correspond to the angles $\alpha_{RE}$ and $\alpha_{LE}$ when the subject fixates bifoveally, that is, if the person does not have strabismus, and provided the optical axes are sufficiently well formed to allow the definition of angle $\alpha$ to be used in its strict meaning. The difference of binocular $\tau_{RE}$ and $\tau_{LE}$, $\Delta \tau$, is a good estimate of the angle of strabismus in the primary position. In orthotropia, $\Delta \tau$ in the primary position should be close to zero because the angles $\alpha$ in the right and left eye are highly correlated. Yet, the angles $\alpha$ are rarely exactly equal in both eyes in one subject so that the approximation $\Delta \alpha = 0°$, leading to the simplified formula for the binocular angle of strabismus $\sigma = \Delta \tau = \tau_{RE} - \tau_{LE}$, can lead to slightly higher errors than in the angle of strabismus $\sigma_{CT}$. 

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**FIGURE 12.** (A) Plot of photographic data, mean of all subjects, fixation at near. Standard deviations are shown as error bars. (B) Plot of photographic data, mean of all subjects, distance fixation. Standard deviations are shown as error bars.
Vertical angles of strabismus are measured along the same principles as is the horizontal binocular angle of strabismus—by subtracting the binocular vertical angle \( \tau \) of one eye from that of the other in the same picture. Because the mean of VD is close to zero and the standard deviation is of the same order as that of the horizontal binocular difference, \( \Delta \tau \) (Table 1), the expected accuracy of binocular vertical strabismus measurement is comparable to that of the horizontal binocular angle of strabismus, though this was not specifically investigated in this study. The threshold for a detection of a vertical misalignment from binocular pictures with the stationary apparatus is therefore thought to be of the same order as that derived from Table 1 for a horizontal misalignment—twice the standard deviation of the mean VD.

The present data base provides threshold data for the evaluation of Purkinje I and IV Reflection Pattern Evaluation data in various positions of gaze, to examine ocular alignment or strabismus, and especially to identify correctly wrong fixation that could mimic or conceal a strabismic condition. Assumptions concerning the relations between the angles \( \tau \) as functions of the fixation angle \( \varepsilon \) were confirmed by this study. On the whole, the mean binocular \( \tau \) data at near and at far in Table 1 show good agreement with previous measurements at near\(^1\) and with distance fixation,\(^{15}\) except for differences of the amount of angle \( \alpha \) in right and left eyes.

The lateral measuring range may easily be extended to angles \( \tau \) up to 20° nasally and 15° temporally without changing the photoflash unit setup and with
no loss in accuracy. If a larger (horizontal) measuring range is desired, additional photoflash units should be added (horizontally) so the optical axis of the eye always points between any two lights. This assures interpolation rather than the less accurate extrapolation for the evaluation of the reflection patterns, where the evaluation of the reflection patterns may be limited mainly to the pupillary area.

In this study, only vertical fixation angles equal to zero were examined. However, because the experimental conditions are virtually identical when up or down gaze is involved, it can be assumed that the stationary apparatus technique is as reliable in assessing ocular alignment under these conditions. This was ascertained with measurements in selected subjects. The present reflection pattern reference data base will have to be extended by a study of the ocular alignment, including up and down gaze.

An advantage of Purkinje I and IV Reflection Pattern Evaluation over ocular alignment measurement methods based on corneal reflex positions alone is that it depends on the reflections' relative positions only and is without recourse to assumptions concerning ocular parameters. This means it can be used with and without glasses; no individual calibration is necessary unless a higher accuracy is required. Complete immobilization of the head is not a prerequisite for detecting small redress movements. The light source distance d' and the fixation distance d, however, should be controlled precisely to ensure that the correct reference angle is computed. Similarly, proper fixation when the picture is taken must be controlled. This can be achieved through repeated measurements and through the application of the computational principles discussed in the accompanying article.

Although in this study a time-consuming photographic technique was used for recording and evaluating reflection patterns, we recently introduced a digital image system for Reflection Pattern Evaluation that makes the measurement of angles of strabismus under natural viewing conditions with a stationary apparatus more viable for clinical applications because the results are immediately available for clinical purposes. The applications include the recording of fluctuations of the angle of strabismus over longer periods of time, as well as routine assessment of incomitant or concomitant angles of strabismus. In the future, an infrared light technique that is combined with infrared transparent covers will also allow for the measurement of the maximal angles of strabismus, as needed, in the preoperative work-up of a patient.

Key Words
angle of strabismus, objective methods, angle α, secondary position

References