Objective: To improve the clinical documentation of strabismus by mathematically predicting and clinically verifying the location of a fixation target that produces a vertically centered corneal light reflex (first Purkinje image) in clinical photographs of the eye using a standard photographic flash unit.

Materials and Methods: Mathematical modeling of the corneal light reflex during clinical photography was based on the schematic eye. Clinical photographs were taken using a range of fixation targets located between the center of the camera lens and the center of the flash. Image quality was also assessed subjectively.

Results: Optimum vertical centration of the corneal light reflex was predicted and produced when the fixation target was located one fifth of the distance from the center of the flash to the center of the camera lens. Placement of the flash below, rather than above, the camera lens provided more uniform illumination of the patient’s eyes and face. Decreasing the distance between the camera lens and the flash minimized the severity of these artifacts.

Conclusions: A poorly positioned corneal light reflex makes it difficult to identify the fixing eye in photographs of patients with strabismus, especially when vertical strabismus is present. Adoption of the aforementioned protocol will reproduce the appearance of coaxially viewed corneal light reflexes and provide much-needed standardization for strabismus case presentation.


WHILE THE importance of geometric analyses of the corneal light reflex (first Purkinje image) has been recognized in photographic calibration of the Hirschberg test, less attention has been paid to the vertical centration of the corneal light reflex in clinical photographs of patients with strabismus. Published photographs frequently demonstrate marked vertical decentration of the light reflex in patients without vertical deviations. These artifactual deviations occur when a vertically mounted flash unit is used and the patient fixes on the center of the camera lens. The image of the flash is displaced superiorly in the entrance pupil of the eye, resulting in the appearance of a hypotropia. When the subject fixes on the center of the flash, the corneal light reflex is displaced inferiorly, resulting in an apparent hypertropia.

When only horizontal deviations exist, and the flash is positioned vertically over the camera aperture, these artifacts do not interfere substantially with assessment of the strabismic deviation. However, when vertical deviations are photographed in primary position, the lack of a standardized fixation point makes it difficult to identify the fixing eye from the position of the light reflex. We used a mathematical model to determine the influence of globe rotation on the position of the corneal light reflex. Calculations were based on corneal radius of curvature, entrance pupil location, and camera flash-lens separation. The predictions of the model were verified in 8 controls.

Mathematical Model

The locations of interest for the schematic eye are shown in Figure 1, with C representing the center of curvature of the anterior surface of the cornea. In the Gullstrand schematic eye, the radius of curvature (r) is 7.7 mm. By assumptions 1 through 3 (see “Materials and Methods” section), C is always located in the horizontal plane passing through the line of sight. The location of the corneal light reflex (first Purkinje image) is L, which for a distant light source is behind the cornea by r/2. In the schematic eye illuminated by a light 40 cm away, L is 3.81 mm behind the cornea. The entrance pupil is the image of the pupil formed by the cornea. The center of the entrance pupil is E. In the schematic eye, the actual plane of the pupil is 3.6 mm behind the front corneal surface, while E is 3.05 mm behind the surface.
MATERIALS AND METHODS

Calculations were based on the measurements of the schematic eye. Three additional simplifying assumptions were made: (1) a spherical corneal surface, (2) a central, symmetrical pupil, and (3) a vertically centered corneal light reflex observed when the subject fixes on a coaxial light source. No assumption was made about the center of rotation of the eye; ie, the center of rotation was considered unrelated to the center of curvature of the cornea.

To verify the mathematical model, 8 normal subjects were photographed using a 35-mm single-lens reflex camera with a 90-mm macro lens and a conventional, detachable flash unit. Prior to photography, the patient was asked to fixate on a handheld penlight to determine the vertical centration of the corneal light reflex within the entrance pupil. For photography, the distance between the flash and the subject was 40 cm, with the camera lens set on 1:4 magnification. The face of the flash unit was held flush with, and above, the front edge of the camera lens.

To exaggerate decentration of the light reflex, the center of the flash was placed 12.5 cm from the center of the camera lens. A card with numbered fixation points was mounted between the camera and flash unit. Photographs of normal volunteers were taken as they fixed on the center of the camera lens and at points 25%, 50%, 70%, 84%, 90%, and 100% of the distance from the camera to the center of the flash. Photographs were magnified ×100 using a projector, and the distance between the vertical center of the pupil and the center of the light reflex was measured in each position of gaze.

In 4 subjects, additional photographs were taken with the flash unit below rather than above the center of the camera lens. These pictures were compared for visualization of the light reflex, illumination of the eye and eyelids, intensity of reflection from the forehead and cheeks, and magnitude of inferior scleral show.

Figure 2. A demonstrates how L₄ is displaced when the subject fixes on the center of the camera lens. The corneal light reflex is located above the center of the pupil, while E does not move; thus, the eye appears to deviate downward. Figure 2, B shows the optimum position of the eye for flash photography. At a fixation point somewhere between the flash and the camera lens, the projected image of L₄ is level with E. At this point, the eye appears to be centered vertically. In Figure 2, C, when the patient fixes on the flash, the globe rotates upward, and E is displaced upward as well, so that L₄ now projects to a point lower than E. Thus, the eye appears to deviate upward.

In Figure 3, the relationships shown in Figure 2, B are diagrammed schematically. The expression x/g equals the fraction of the distance between the camera and flash. The optimum fixation point can be determined by solving for x/g in terms of f (the distance from C to L₄) and p (the distance from C to E). The diagram is solved by constructing a right triangle, extending the segment e past L₄ and down to C. By similar triangles, 

\[ \frac{g}{d₁} = \frac{c}{f} \quad \text{and} \quad \frac{x}{d₂} = \frac{c}{p} \]

and dividing to eliminate c,

\[ \frac{x}{f} = \frac{d₂}{g}, \frac{d₁}{p} \]

At distances ordinarily used for flash photography, where d ≫ e, d₁ is approximately equal to d₂. In this case, equation 1 simplifies to:

\[ \frac{x}{f} = \frac{d}{g}, \frac{p}{p} \]

When the flash is held closer to the eye, it is necessary to solve for d₁ and d₂. This can be done in terms of d, f, and p using the Pythagorean theorem:

\[ d₁² + d₂² = f² + d² + e² \]

Combining with equation 1:

\[ \frac{x²}{g²} = \frac{f²}{p²} \frac{d²}{g² + (d + e)²} \]

Solving for “x/g,”

\[ \frac{x²}{g²} = \frac{f²}{p²} \frac{d²}{g² + (d + 2d + e)²} \]

or:

\[ \frac{x}{g} = \frac{f}{p} \frac{d}{\sqrt{d²(1 + \frac{2e}{d} + \frac{e²}{d²}) + g²\left(\frac{p² - f²}{p²}\right)}} \]
In most cases, $e << d$, $g << d$, and $p^2 \approx f^2$ so that the denominator on the right side of equation 3 approaches $d$. When this is the case, the equation once again simplifies to equation 2: $x/g = f/p$.

In the schematic eye, $f$ is determined by subtracting the distance between LR and the corneal surface from $r$. Similarly, the value for $p$ is determined by subtracting the distance between E and the corneal surface from $r$. Thus:

$$f = 7.7 - 3.81 \text{ mm} = 3.89 \text{ mm},$$
$$p = 7.7 - 3.05 \text{ mm} = 4.65 \text{ mm}.$$

Inserting these values into equation 2, $x/g = 0.84$. Thus, if the point of fixation is 84% of the distance between the camera and the flash (or $\approx 1/5$ of the distance from the flash to the camera lens), LR should be properly centered in photographs.

Since $x/g$ is a function of $f/p$, the optimum fixation point changes when the center of curvature of the cornea or the anterior chamber depth varies from the standard schematic eye. The influence of these deviations, as predicted by the mathematical model, is depicted in Figure 4. A 1-mm shallowing of the anterior chamber or a 1-mm increase in $r$ lowers the optimum fixation point by 5% to 12%.

**VALIDATION OF MODEL PREDICTIONS**

Figure 5 is a representative series of photographs taken with a normal subject fixing at selected points between the camera lens and the flash, with the flash located 12.5 cm above the camera lens. The light reflex is best centered at a deviation of 84% from the center of the camera lens. The deviation of LR from the center of the pupil using the same camera-flash arrangement in 8 normal volunteers is plotted in Figure 6. Six of the subjects conformed closely to the predictions of the model, with the plot crossing the x-axis very close to 84%. The plot of subject 8 crossed the axis with fixation at 50% and the plot of subject 7 at 65% of the distance.
from camera lens to flash. In both of these subjects, $L_8$ was lower than $E$ when inspected with a handheld penlight. In the other 6 subjects, the line of sight was vertically centered in the entrance pupil. Deviations measuring less than 0.3 mm above or below the center of the pupil did not appear decentered on the photographs when appraised subjectively (Figure 5, 70% and 90% displacement).

**OPTIMIZING ILLUMINATION**

Additional photographs of 5 subjects were taken with the flash below the camera lens. In most cases, the positions of the eyelid and eye were more easily seen when the flash was held directly below the camera lens. This was caused by the shadow cast onto the eyes by the upper eyelid margins, or the brow in some cases, when the flash was held above the camera lens (Figure 7, A). There was less scleral show when the flash and fixation point were below, and adjacent to, the camera lens (Figure 7, B).

**COMMENT**

In the office, the clinician views the eyes with a coaxial light source to qualitatively assess strabismus by evaluating the relative centration of the corneal light reflexes. This also allows identification of the fixing eye in most cases. Ideally, photographs that document strabismus in primary position should exactly reproduce this familiar image. However, the geometry of standard photographic equipment makes this difficult to achieve unless the fixation point is carefully specified. Failure to select the proper fixation point causes unfamiliar and confusing vertical displacement of the corneal light reflex (Figure 5, bottom). When both light reflexes are vertically displaced, it may still be possible to identify a vertical deviation by comparing relative displacement of the corneal light reflexes, but it is more difficult to identify the fixing eye in the photograph. Decentration is less of a problem in other gaze positions, where the corneal light reflex is typically not centered in the fixing eye.

In the proposed mathematical model, the optimum point of fixation, $x/g$, is in most cases equal to $f/p$, which is determined by the radius of curvature of the cornea and the depth of the anterior chamber. In the average eye this number is close to 3.89 mm/4.65 mm, or 84% of the distance from the center of the camera lens to the center of the flash. In other words, a fixation target should be placed approximately one fifth of the distance from the center of the flash to the center of the camera lens. Photographs of 8 normal subjects confirmed the accuracy of the mathematical model in most cases (Figure 5).

Two subjects did not conform as well to this model. Assumption 3 (see “Materials and Methods” section) was not true in these cases—ie, the corneal light reflex was not
Moving the flash as close as possible to the camera lens decreases the decentration problem but does not eliminate it. Other ways to prevent decentration of the corneal light reflex include the use of a beam splitter or a ring flash unit. A beam splitter can produce a truly coaxial flash, but produces distracting, bright-red pupils, is difficult to mount, and is not easily available. Szirth et al\textsuperscript{10} recommend a ring flash for strabismus photography because of its more-accurate centration and more-even illumination. However, a ring flash is expensive and, in our opinion, the segmented or annular \( L_r \) is more difficult to interpret than the familiar reflection of a point source. When a ring flash is used, the patient must fix near the center of the camera lens, where there is no precise fixation target. We obtained good results using a segmented ring flash by illuminating only the lower segment and placing a fixation target one fifth of the distance from the center of that segment to the center of the camera lens.

For ordinary flash photography there is a fixation point that provides optimum vertical centration of the corneal light reflex. This point is fairly constant even with variations in ocular anatomy and photographic apparatus. We propose that, when documenting strabismus with photography, the flash unit be held adjacent to, and directly below, the camera lens. The subject should fixate on a target placed one fifth of the distance from the center of the flash to the center of the camera lens (Figure 8). This uniform standard, based on the geometry of the eye, will produce essentially the same vertical centration of the corneal light reflex in strabismus photography as is seen with handheld penlight testing.

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