ARTIFACTS INTRODUCED BY SPECTACLE LENSES IN THE MEASUREMENT OF STRABISMIC DEVIATIONS

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The peripheral prismatic effects of corrective spectacle lenses introduce an artifact when strabismic deviations are measured. Plus lenses decrease and minus lenses increase the measured deviation. This effect begins to become clinically significant with corrective lenses with powers of more than ±5 diopters. We developed a simplified model that predicts the magnitude of this effect. The model agreed with actual ray tracing analysis through commonly used spectacle lenses and also agreed closely with clinical data. The clinical use of this model is facilitated by remembering the artifacts produced by +20, +10, −10, and −20 diopter spectacle lenses and interpolating for intermediate values. Correcting for these artifacts should enhance the predictability of strabismus surgery in patients with significant ametropia.

However strabismic deviations are measured, by the Hirschberg test, the Krimsky prism reflex test, prism and cover testing, or subjective methods, the presence of corrective spectacle lenses before the patient's eyes creates an error in the measurement obtained. With high plus or high minus spectacle lenses this error may be significant. This measurement error may account for anecdotal reports of the surgical overcorrection of strabismus in highly myopic patients or of the undercorrection of strabismus in patients with aphakia.

All ophthalmologists are familiar with Prentice's rule and can calculate the amount of prismatic effect obtained with decentration of a lens. It is also easy to calculate the induced phoria in the reading position with anisometropic spectacle corrections. One seldom thinks, however, of spectacles adding to, or subtracting from, the apparent deviation in a patient who already has strabismus. Yet, this must be the case, for both visual axes of the eyes of a patient with strabismus must pass through noncorresponding areas of the respective spectacle lenses (Fig. 1).

The application of Prentice's rule to the calculation of anisophoria in straight-eyed patients with anisometropia, as well as its application to the "rotational magnification" of a single eye moving behind a spectacle lens, is well documented in texts on ophthalmic optics.[1-3] We found only one reference, however, to the effect of spectacle lenses on the measurement of strabismic deviations. Adelstein and Cüppers[4] briefly discussed the artifacts produced by spectacle lenses in support of their argument for measuring strabismic deviations with haploscopic instruments of their design. Such haploscopic devices have the corrective optics incorporated into the arms of the instrument, avoiding the major artifacts induced by spectacle lenses. These instru-

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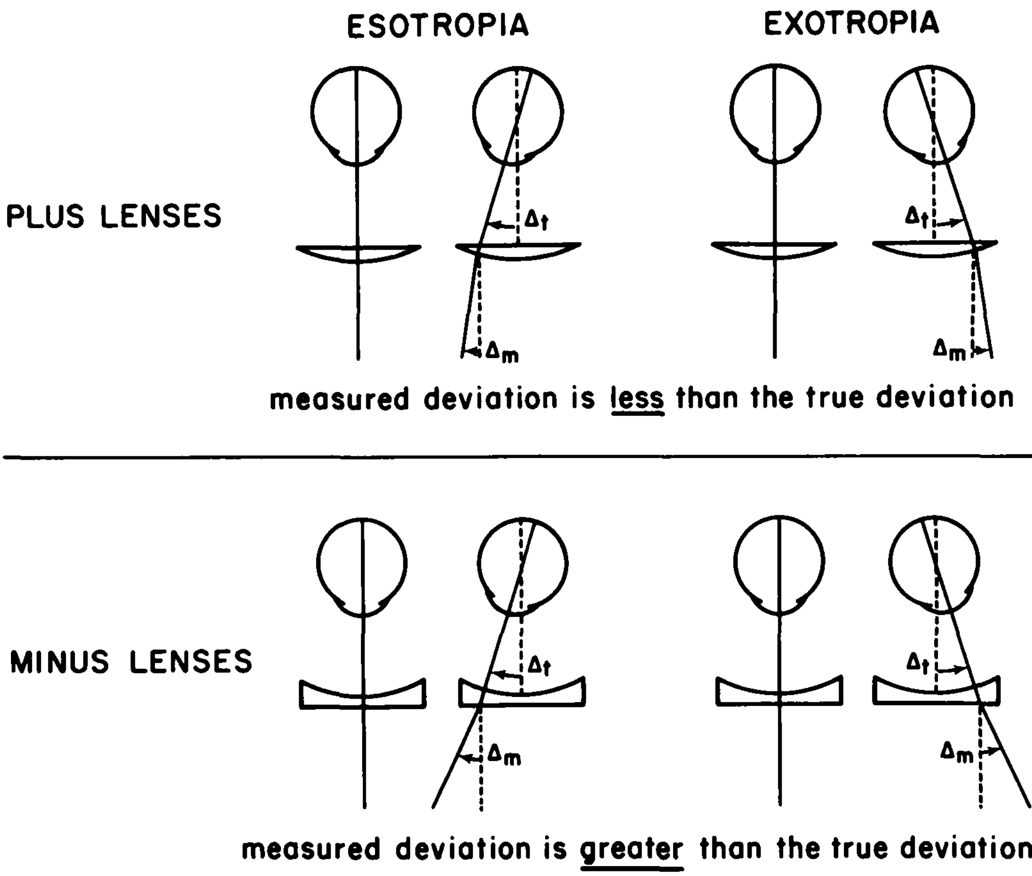

Fig. 1 (Scattergood, Brown, and Guyton). The effect of spectacle lenses on the measured deviation (Δ_m) with respect to the true deviation (Δ_t) in horizontal strabismus. Note that plus lenses always reduce the deviation whether it is an esodeviation or an exodeviation (or a hyperdeviation), and minus lenses always increase the measured deviation.

ments are not often used in the United States, however, and the strabismus surgeon should therefore be aware of the measurement problems caused by spectacle lenses. The data of Adelstein and Cüppers were presented in condensed graphic form, without derivation or simplification, and are difficult to use clinically. We use a simplified model for estimating the measurement errors caused by spectacle lenses.

SUBJECTS AND METHODS

Simplified model—Our simplified model for determining the effect of a spectacle lens on the strabismic deviation is shown in Figure 2. An ideal thin lens of power D diopters is placed 25 mm from the center of rotation of the eye, corresponding to a vertex distance of approximately 11.5 mm. The 25-mm distance is the distance most often used in the optical industry for the design of spectacle lenses. Note that the lens in our model is not meniscus-shaped and that the visual axis passes through the lens obliquely. We make the approximation that the prismatic power of the lens at the point of intersection by the visual axis obeys Prentice's rule even though the angle of incidence is oblique. The validity of this approximation will be examined later.

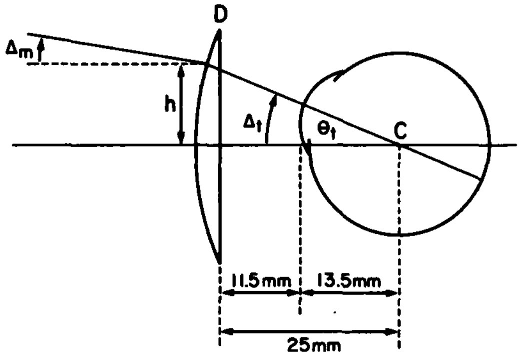

Fig. 2 (Scattergood, Brown, and Guyton). Simplified model relating the measured deviation (Δ_m) to the true deviation (Δ_t in prism diopters and Θ_t in degrees). D, lens power; h, distance of visual axis intercept from the optical center of the lens in centimeters; C, center of ocular rotation.

By inspection of Figure 2:

$$\tan \theta_t = \frac{h}{2.5} \qquad (1)$$

From the definition of prism diopters:

$$\tan \theta_t = \frac{\Delta_t}{100} \qquad (2)$$

By combining (1) and (2):

$$\frac{h}{2.5} = \frac{\Delta_t}{100}$$

or

$$h = 0.025\ \Delta_t \qquad (3)$$

By Prentice's rule:

$$\Delta_m = \Delta_t - h\ D \qquad (4)$$

By combining (3) and (4):

$$\Delta_m = \Delta_t - (0.025\ \Delta_t)\ D$$

or

$$\Delta_m = \Delta_t\ (1-0.025\ D) \qquad (5)$$

Thus, the measured deviation is equal to the true deviation changed by an amount proportional to the power of the glasses. If the glasses are plus, the measured deviation is equal to the true deviation decreased by 2.5 D%; if the glasses are minus, the measured deviation is equal to the true deviation increased by 2.5 D%.

The above relationship is easily remembered, but somewhat awkward to use, for in clinical practice it is the measured deviation that is found first, and the true deviation must then be calculated, rather than the reverse. We therefore need to determine the true deviation as a percentage of the measured deviation. By arranging equation (5) and multiplying both sides by 100, we obtain an expression for the true deviation as a percentage of the measured deviation:

$$\left(\frac{\Delta_t}{\Delta_m}\right) \times 100 = \frac{100}{1-0.025\ D}\ \% \qquad (6)$$

Figure 3 shows a graph of this relationship. Note that the graph is not linear. Probably the easiest way to remember these data is to remember the points on the graph for −20, −10, 0, +10, and +20 diopters (Table 1). Mental interpolation

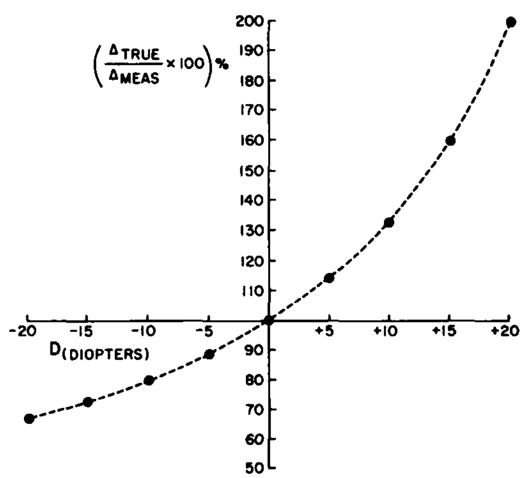

Fig. 3 (Scattergood, Brown, and Guyton). The true deviation as a percentage of the measured deviation for various powers of spectacle lenses from −20.00 to +20.00 diopters.

TABLE 1

SPECIFIC EASILY REMEMBERED POINTS FROM GRAPH*

Spectacle Lens Power (Diopters)	True Deviation as % of Measured Deviation	To Find True Deviation: Change Measured Deviation by	To Find True Deviation: Example
−20	67	Decrease by 33%	4/6
−10	80	Decrease by 20%	4/5
Plano	100	No change	4/4
+10	133	Increase by 33%	4/3
−20	200	Increase by 100%	4/2

*See Figure 3.

between these points is usually sufficient for clinical purposes.

Accuracy of the model—Because our model does not take into account spherical aberration, lens thickness, or the inaccuracies of Prentice's rule for oblique light rays, we performed the following analysis to determine the accuracy of the model.

We used a ray tracing analysis with typical front and back curvatures for commonly used spectacle lenses of −20, −10, +10, and +20 diopters to compare the predictions of our model to the results to be expected in actual clinical situations (Table 2). We chose 30 prism diopters (16.7 degrees) as the arbitrary value of Δ_t, the true deviation. In this analysis a ray from the center of rotation of the eye, at an angle of 30 prism diopters from the optical axis, was traced through both lens interfaces. The light ray path at each interface was determined by Snell's law, and we calculated Δ_t/Δ_m for each case.

TABLE 2

ACCURACY OF THE MODEL COMPARED WITH OTHER MEANS OF ANALYSES

Data	Lens Power (Diopters): −20 (Hilite Glass)	−10: Hilite Glass	−10: Crown Glass	+10: Crown Glass	+10: Plastic	+20: Crown Glass	+20: Plastic
Curves (diopters)							
Front	Plano	Plano	Plano	9.74	9.60	18.54	17.62
Rear	−20	−10	−10	Plano	Plano	Plano	Plano
Index of refraction	1.9	1.523	1.9	1.523	1.491	1.523	1.491
Radius (mm)							
Front	—	—	—	53.64	51.16	28.46	27.70
Rear	45.0	52.3	90.0	—	—	—	—
Center thickness (mm)	2.0	2.0	2.0	4.14	4.2	6.3	6.41
Δ_t (prism diopters)	30	30	30	30	30	30	30
Δ_m (prism diopters)*	48.23	38.8	38.9	21.2	21.3	14.3	13.6
Δ_t/Δ_m prediction							
By ray tracing	0.62	0.77	0.77	1.42	1.41	2.10	2.20
By Adelstein & Cüppers[4]	—	0.75	0.75	1.43	1.43	—	—
By model	0.67	0.80	0.80	1.33	1.33	2.00	2.00

*Predicted by ray tracing.

Both the data of Adelstein and Cüppers[4] and the ray tracing analysis indicated that our simple model slightly underestimated the lens-induced artifact in strabismus measurement for true deviations of 30 prism diopters. The model underestimated the total deviation by as much as 8% for spherical crown glass lenses of −10 to +20 diopters. For a −20 diopter lens, we used Hilite glass for our analysis, and found that the model underestimated the total deviation by 7.2%. Plastic lenses have artifact characteristics similar to those of crown glass in high plus lenses, with the maximum error being 10% for +20 diopter plastic lenses. If we had used aspheric +10 or +20 diopter lenses, the differences between the model and ray tracing analysis would have been less and actually might have been in the opposite direction. For deviations of less than 30 prism diopters, the effect of the asphericity was not significant. One should remember when using our model that it tends to underestimate lens prismatic effects and, hence, slightly underestimates the errors in strabismus measurement.

Subjects—To verify the predictive ability of our model, we retrospectively analyzed preoperative and postoperative prism and cover measurement data from 108 patients undergoing initial strabismus surgery at the Wilmer Ophthalmological Institute between 1978 and 1982. We tried to locate patients with large refractive errors, but included many patients with minimal refractive errors as well.

Two groups of operations were analyzed separately: 81 bilateral medial rectus muscle recessions for esotropia and 27 bilateral lateral rectus muscle recessions for exotropia. We excluded patients who underwent combined cyclovertical muscle surgery and those who underwent vertical transposition of the horizontal muscles. No other selection criteria were used. All measurements were taken with the spectacle corrections in place. In cases of anisometropia, the refractive correction tabulated was that in the horizontal meridian behind the neutralizing prism on prism and cover test. Postoperative measurements were taken four to eight weeks after surgery.

Results

For each case the prism diopters of surgical correction per millimeter of surgery were calculated and plotted against the refractive correction (Figs. 4 and 5). The model predicted that the data in each case would follow a straight line:
From the model (equation 5):

$$\Delta_m = (1-0.025\ D)\ \Delta_t$$

For two different pairs of Δ_m and Δ_t:

$$(\Delta_m)1 - (\Delta_m)2 = (1-0.025\ D)\ (\Delta_t)1 - (1-0.025\ D)\ (\Delta_t)2 \quad (7)$$

Rearranging:

$$\text{change in } \Delta_m = (1-0.025\ D)\ (\text{change in } \Delta_t) \quad (8)$$

If we assume for simplicity that the true surgical correction (change in Δ_t) is proportional to the number of millimeters of surgery:

$$\text{change in } \Delta_t = k\ (\text{mm of surgery}) \quad (9)$$

Substituting (9) into (8):

$$\text{change in } \Delta_m = (1-0.025\ D)\ (k)\ (\text{mm of surgery})$$

or

$$\frac{\text{change in } \Delta_m}{\text{mm of surgery}} = k - 0.025\ k\ D \quad (10)$$

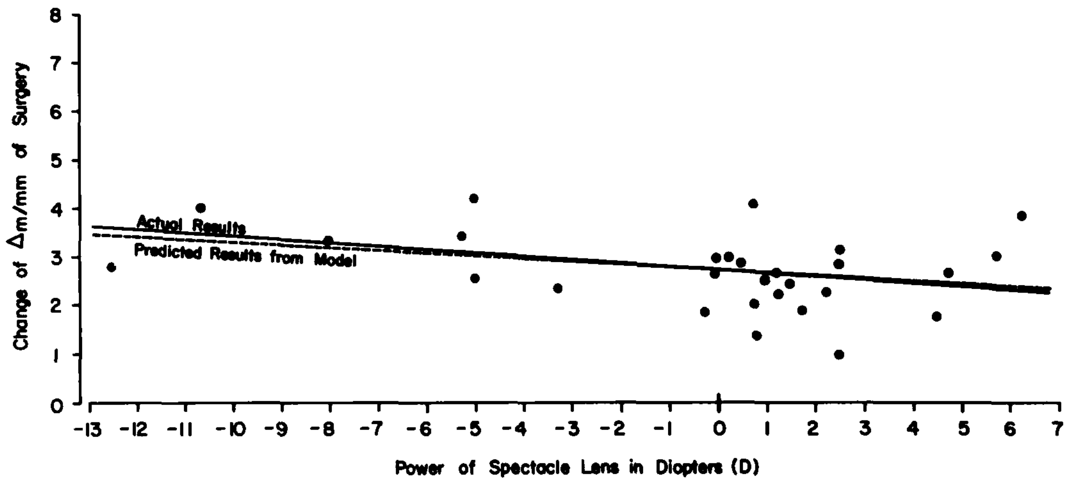

Fig. 4 (Scattergood, Brown, and Guyton). For 27 patients with no previous strabismus surgery who underwent bilateral lateral rectus muscle recessions for exotropia, the effect of surgery (change of measured deviation/millimeter of surgery) is plotted as a function of the power of the corrective spectacle lens behind the measuring prism. Linear regression analysis yields a slope of −0.0706 (S.E., ±0.0330), a y-intercept of 2.70 (S.E., ±0.146), and a standard error of the points from the line of 0.784. The slope is significantly different from zero ($P<.05$). The model closely approximates the actual clinical data.

Equation (10) describes a straight line graph with slope −0.025 k and y-intercept of k. For the clinical data in Figures 4 and 5, the best straight line fit was calculated by linear regression analysis and plotted. The y-intercept of this regression line represents k in equation (10), and therefore the predicted straight

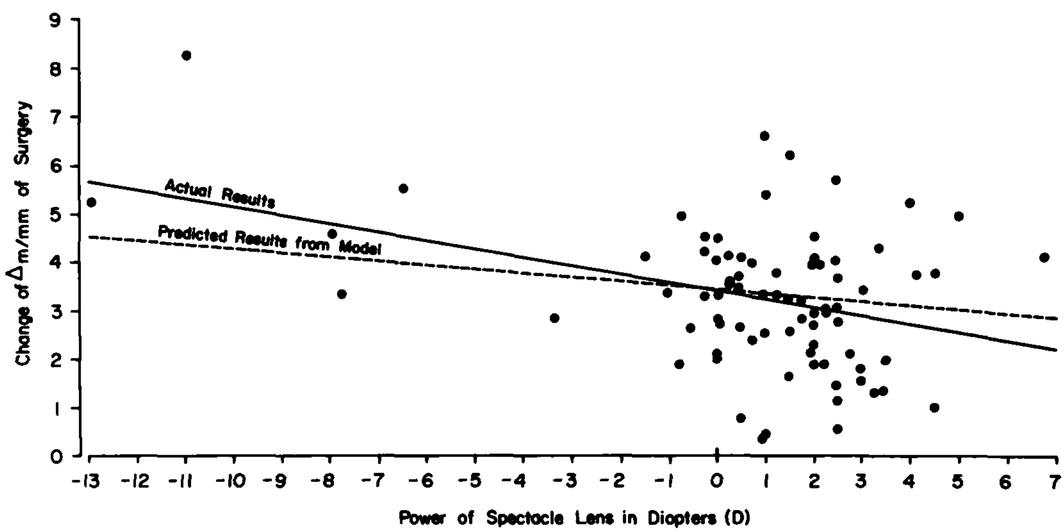

Fig. 5 (Scattergood, Brown, and Guyton). For 81 patients with no previous strabismus surgery who underwent bilateral medial rectus muscle recessions for esotropia, the effect of surgery (change of measured deviation/millimeter of surgery) is plotted as a function of the power of the corrective spectacle lens behind the measuring prism. Linear regression analysis yields a slope of −0.174 (S.E., ±0.0492), a y-intercept of 3.43 (S.E., ±0.158), and a standard error of the points from the line of 1.37. The slope is significantly different from zero ($P<.001$). The model predicts a slope less than but within 2 S.E. of that obtained from linear regression analysis.

line for change in Δ_m/mm of surgery, using this k value, can be plotted as well.

As Figures 4 and 5 show, the measured surgical correction per millimeter of surgery was greater for patients with myopia and less for those with hyperopia, as we had expected. For exotropia surgery (Fig. 4), the clinical data corresponded almost exactly with the prediction of our model. For esotropia surgery (Fig. 5), the clinical data corresponded less well, showing more effect than predicted by the model, but with the slope of the regression line within 2 S.E. of the predicted slope. The clinical results, therefore, were not significantly greater than those expected by our analysis and thus they confirmed the predictability of the model.

Discussion

High plus lenses in both exotropia and esotropia result in a measured deviation significantly less than actually exists. Similarly, high minus spectacles in both exotropia and esotropia increase the measured deviation significantly. For example, in a patient with −10 diopters of spectacle-corrected myopia and measured exotropia of 30 prism diopters, the true deviation would be 24 prism diopters. Therefore, unless the prismatic effect of the lenses is taken into account, a surgical overcorrection of 6 prism diopters would be expected (this would be measured as an unwanted esodeviation of 7.5 prism diopters through the spectacles). A more striking example would be an infant with +20 diopters of spectacle-corrected aphakia and a 40 prism diopter measured esodeviation. The true esodeviation would be 80 prism diopters, twice the measured value. Table 3 provides additional examples.

Some strabismologists believe that the deviations in highly myopic patients tend to be overcorrected by muscle surgery. Similarly, the deviations in patients with hyperopia and myopia tend to be undercorrected. These impressions agree with our observations (Figs. 4 and 5). This error may be attributed partly to the deviation artifact created by the spectacle lenses, and may be corrected by taking the artifact into account before graded muscle surgery is performed. This becomes surgically significant with refractive errors of ±5 diopters and more.

In cases of anisometropia, these same measurement artifacts may produce a surprising incomitance of the measured deviation. For instance, in a patient wearing a plano lens before the right eye and −10 diopter lens before the left eye, a true comitant exotropia of 32 prism diopters will be measured as 40 prism diop-

TABLE 3

CLINICAL EXAMPLES OF MEASURED DEVIATIONS AND THE ARTIFACTS PRODUCED BY SPECTACLE LENSES OF VARIOUS POWERS

Patient	Measured Deviation (Δ_m) in Prism Diopters*	Spectacle Lens Powers (Diopters)	Δ_t/Δ_m	True Deviation (Δ_t) in Prism Diopters*
Patient 1	XT, 20	−10 in both eyes	0.80	XT, 16
Patient 2	ET, 20	−10 in both eyes	0.80	ET, 16
Patient 3	Right HT, 35	+10 in both eyes	1.33	Right HT, 47
Patient 4	ET, 30	+5 in both eyes	1.17	ET, 35
Patient 5				
R.E. fixing	XT, 40; left HT, 20	−10 in L.E.	0.80	XT, 32; left HT, 16
L.E. fixing	XT, 32; left HT, 16	Plano in R.E.	1.00	XT, 32; left HT, 16

*XT, exotropia; ET, esotropia; HT, hypertropia.

TABLE 4

A TRUE COMITANT EXOTROPIA OF 32 PRISM DIOPTERS IN PRIMARY POSITION AND ON GAZE 20 DEGREES TO EACH SIDE IN AN ANISOMETROPIC PATIENT WEARING A PLANO LENS IN THE RIGHT EYE AND A −10 DIOPTER LENS IN THE RIGHT EYE

	Deviation (Prism Diopters)*	
Position	R.E. Fixing	L.E. Fixing
Right gaze	XT, 31	XT, 23
Primary	XT, 40	XT, 32
Left gaze	XT, 49	XT, 41

*XT, exotropia.

ters of exotropia with the right eye fixing but 32 prism diopters with the left eye fixing. The apparent incomitance produced on side gaze, however, is even more striking (Table 4). With the right eye fixing, the measured exotropia decreases from 40 to 31 prism diopters on right gaze and increases to 49 prism diopters on left gaze. With the left eye fixing, the measured exotropia decreases from 32 to 23 prism diopters on right gaze, and increases to 41 prism diopters on left gaze. Such incomitance may lead the strabismus surgeon to suspect a muscle paresis or a mechanical restriction, when the incomitance actually is the result of the effect of the spectacle lenses. These effects were noted by Friedenwald[5] in nonstrabismic patients with anisometropia in 1936, but the effects are even more

$$\Delta_{surg} = 100 \tan\left(\tan^{-1}\frac{\Delta_\alpha}{100} - \tan^{-1}\frac{\Delta_n}{100}\right)$$

$$\Delta_m = 100 \tan\left[\tan^{-1}\left\{\left(\frac{PD}{2} - Y\frac{\Delta_\alpha}{100}\right)/L\right\} - \tan^{-1}\left\{\frac{\Delta_\alpha}{100}(1-YD)\right\}\right]$$

$$\Delta_n = \frac{100PD}{2L}\left(\frac{1}{1-DY+Y/L}\right)$$

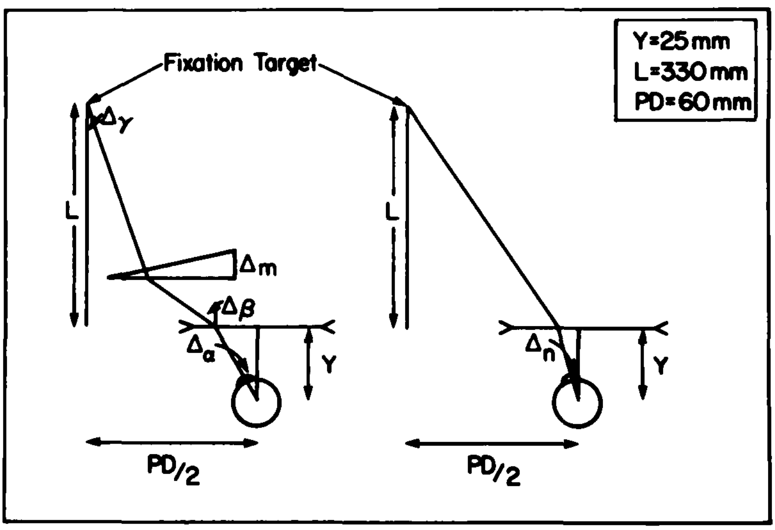

Fig. 6 (Scattergood, Brown, and Guyton). Fixation at near (33 cm) through a spectacle lens, showing proper convergence on the right (a nonstrabismic case) and fixation corrected by a prism on the left (a strabismic case). On the right, Δ_n, given by the third formula, represents the monocular convergence necessary for near fixation through the spectacle lens. D is the dioptric power of the lens, PD is the interpupillary distance, L is the distance of the fixation target from the spectacle plane (330 mm), and Y is the distance of the spectacle lens from the center of rotation of the eye (25 mm). In the strabismic case on the left, the amount of prism necessary to neutralize the strabismic deviation under these conditions is Δ_m, in prism diopters, given by the second formula. Δ_α is the angle of deviation of the strabismic eye from the straight-ahead position. We define Δ_{surg}, therefore, as equal to the difference between Δ_α and Δ_n, with this difference in prism diopters given by the first formula. Δ_{surg} is the angle of surgical correction necessary to allow exact near fixation through the spectacle lens.

striking in strabismic patients with anisometropia.

Our model can be used with spherocylindrical spectacle lenses, but calculation of the artifact becomes more complicated. For example, a +3.00 +5.00 × 90 spherocylindrical lens has +8.00 diopters of power in the 180-degree meridian that alters the measurement of a horizontal deviation accordingly.

Another consideration when dealing with strabismic deviations in corrected myopia or hyperopia is the minification or magnification produced by the spectacle lenses. The minus lens of a highly myopic patient minifies the image of the patient's eye as it is viewed by the observer. This makes any deviation appear smaller than it is, although, as we have shown, the measured deviation is actually greater. Consequently, the cosmetic effect of a high minus lens is opposite to the real effect of the lens on the measured deviation. Similarly, high plus lenses magnify the patient's eye, increasing the cosmetic deviation, although such lenses actually decrease the measured deviation.

Results with near fixation—These analyses dealt with strabismus measurements taken with distance fixation. For near fixation measurements the model is also valid, but only with modification. Near

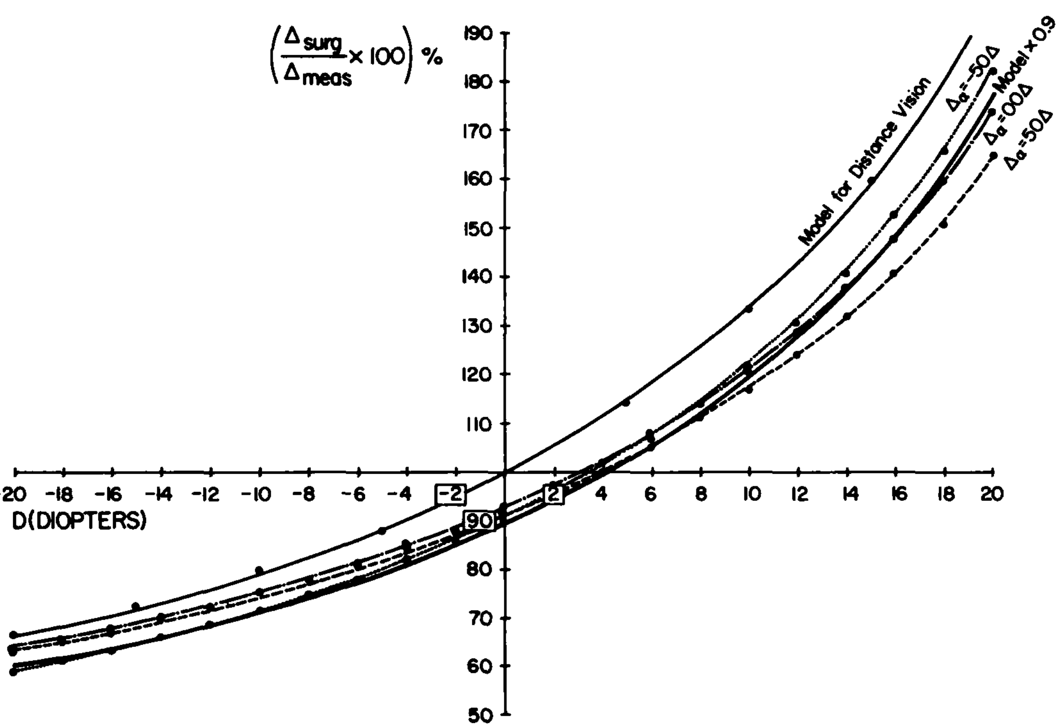

Fig. 7 (Scattergood, Brown, and Guyton). With near fixation, the desired surgical angle as a percentage of the measured angle of deviation is plotted as a function of spectacle lens correction from −20 to +20 diopters. This percentage also varies according to the amount of strabismus present. With Δ_α representing the angle of the deviating eye from the straight-ahead position (Fig. 6), curves are plotted for Δ_α equal to −50, 0, and +50 prism diopters. Also plotted are the results from the distance fixation model (Fig. 3) and a curve of the distance fixation model multiplied by 0.9. The 0.9 curve gives a good estimate of the near fixation results. Note also that at 0 diopters of spectacle correction, the near fixation curves do not pass through 100%. Rather, the desired surgical angle is about 0.9 times the measured angle. This is the result of the "effectivity" of the prism held 25 mm from the center of rotation of the eye. If the prism could be held closer to the eye, this artifact would be less.

fixation presents several complicating factors that are not present for distance fixation. When nonstrabismic eyes converge to fix on a near target while looking through spectacle lenses, the visual axes no longer pass through the optical centers of the lenses. Prismatic effects away from the optical center become important. Therefore, the eyes of a myopic patient with corrective minus lenses converge less than those of a patient with emmetropia and the eyes of a patient with hyperopia with corrective plus lenses converge more than those of a patient with emmetropia when fixating and fusing on the same near object. A simple geometric analysis mathematically describes the amount of necessary convergence (Fig. 6).

In the case of a strabismic patient fixing on a near object through corrective spectacle lenses, the geometric analysis is more complicated (Fig. 6).

The error between the desired surgical angle and the measured angle of deviation is a function of the power of the correcting spectacle lenses but also varies with the amount of strabismic deviation present. This can be seen in Figure 7, in which the desired surgical angle, as a percentage of the measured deviation, is plotted for various powers of spectacle lenses from −20.00 to +20.00 diopters for a wide range of strabismic deviations.

Also plotted in Figure 7 is the distance fixation graph from Figure 3. The distance model predicts the near situation rather well if the distance graph is multiplied by 0.9.

Clinically, therefore, to estimate the desired surgical angle from the measured angle at near fixation, one can simply apply the distance model to the near measurement and multiply the result by 0.9.

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