Natural Strabismus in Monkeys: Accommodative Errors Assessed by Photorefraction and Their Relationship to Convergence Errors

Michael W. Quick,*Jeffrey D. Newbern,* and Ronald G. Boothe*†‡

Purpose. To examine accommodation and accommodative convergence relationships in naturally strabismic monkeys.

Methods. Photorefraction was used to measure accommodative responses of each eye under monocular and binocular viewing conditions. These accommodative results were then compared to assessments of vergence state made under monocular viewing conditions using methods previously described.

Results. Accommodation was always accurate under monocular viewing conditions, with the exception of the inability of one myopic eye to focus distant targets. The accommodative response in the two eyes was always consensual. In animals with an anisometropia, the fixating eye was focused accurately on the target, and the fellow eye was in error by an amount predicted by the magnitude of the anisometropia. Some animals alternated fixation, and, under these conditions, control of accommodation and fixation switched in tandem. Accommodative convergence ratios (AC:A) were abnormally low in animals with strabismus syndromes, similar to human essential infantile esotropia, and were excessively high in animals with syndromes, similar to human early onset accommodative esotropia.

Conclusions. There was no evidence that the strabismus seen in any of the monkeys was related to errors in accommodation. However, the crosslink gain between accommodation and vergence was abnormal in some of the animals. These abnormalities have the effect of driving vergence toward a misalignment that can only be overcome by other factors, such as fusional vergence. Thus, the authors speculate that these abnormalities in synkinesis between accommodation and convergence were present during early postnatal development when fusional vergence is weak, and that they acted as predisposing factors for the development of strabismus. Invest Ophthalmol Vis Sci. 1994;35:4069–4079.

In the previous article of this series, we documented the characteristics of convergence errors in a group of monkeys that have naturally occurring infantile strabismus. Some of the results from that investigation suggested that abnormal accommodation, or abnormal accommodation—convergence synkinesis, might be associated with the patterns of misalignment seen in some of the monkeys. For example, retinoscopy revealed that most of the monkeys had large, hypermetropic refractive errors; several exhibited anisometropia, as well. Also, several monkeys showed greater esodeviations when viewing targets at near than when viewing targets at distance. The purpose of the present investigation was to examine directly the accommodative responses and accommodative convergence relationships in these naturally strabismic monkeys.

There are general theoretical grounds for hypothesizing that at least some types of infantile strabismus are related to errors in accommodation or in abnormal accommodative convergence. The rationale for this hypothesis comes from an assessment of the computational requirements of maintaining binocular alignment in comparison to the relative immaturity of the visual system in infants.

The task of using binocular disparity information...
to drive vergence to maintain binocular alignment continuously in real time appears to be formidable if it is approached as a computational problem that requires an exact mathematical solution. Yet normal primates are able to maintain binocular alignment effortlessly as fixation is moved from place to place about the field of gaze. Primates are probably able to accomplish this at least in part because their brains take advantage of simplifying approximations to the alignment problem, as opposed to finding exact computational solutions. An argument along these lines was made elegantly by Hering when he asserted that the binocular oculomotor control system is based on "...very simple relationships in comparison to the inexhaustible variety of movement."3

One of the processes by which the brain achieves a simplifying approximation to the problem of binocular alignment is to take advantage of information provided by neural subsystems. A prime example is accommodative convergence, in which the vergence state is closely tied to the accommodative state. That is, information provided by the accommodative system is used to obtain a first-order approximation of the amount of vergence needed. The near reflex operates in such a way that for any given amount of accommodative effort, a corresponding amount of convergence is automatically produced. This synkinesis between accommodation and vergence was initially described by the German physiologist Müller and has received extensive study in recent years.4-6 The gain of this relationship is known as the accommodative convergence (AC) to accommodation (A) ratio, or simply as the AC:A ratio. A potential disadvantage of relying on this simplifying approach to help achieve binocular alignment is that if the accommodative system is in error, or if the gain or other links between accommodation and convergence are faulty, then additional demands will be made on other binocular subsystems such as fusional vergence to try to overcome the error.

These issues have received extensive discussion in the human clinical literature regarding the probable etiology of strabismus.5-12 For example, when an individual with a hypermetropic refractive error attempts to view near objects, a tightly coupled accommodative convergence reflex with a gain near unity will drive the oculomotor system toward overconvergence. If fusional vergence is incapable of correcting this error, the subject has only two choices: accept blur to eliminate diplopia, or accept diplopia to eliminate blur. A subject who adopts the latter strategy will exhibit an esotropia when viewing near targets. Similarly, a subject with an abnormally high AC:A ratio will be predisposed to overconverge to near targets, even in the absence of hypermetropic refractive error.

Small abnormalities along these lines will ordinarily not lead to strabismus in adults, because other subsystems such as disparity-driven vergence can compensate and maintain alignment. However, increased demands on other subsystems are likely to be more disruptive in infants than they are in adults because of the immaturity of all of the visual system during infancy. Neither accommodation,13-17 nor convergence,18-21 nor the synergistic link between accommodation and convergence22 are fully mature in infants. Also, binocular sensory fusion systems such as stereopsis do not emerge until after the third postnatal month in humans23-25 and after the third postnatal week in monkeys.26 Thus, if an infant is challenged by an error in one or more of its binocular subsystems, such as an abnormal synkinesis relationship between accommodation and convergence, the result may be a maldevelopment of binocular vision that becomes permanent in the form of a strabismus.

The traditional clinical view has been that disorders in accommodative convergence were associated primarily with late onset strabismus. If that point of view were correct, then we would not expect to find these factors to be operating in any of our naturally strabismic monkeys, because they all have syndromes similar to early onset forms of human strabismus. However, there is now a growing consensus that some forms of early onset esotropia in humans have an accommodative component.10,27

In the present study, we used infrared photorefraction to assess errors in accommodative responses in naturally strabismic adult monkeys during monocular and binocular viewing of fixation targets. We then compared the accommodative data to convergence data obtained from the same subjects using methods described in the previous paper.1 One reason for conducting these studies was to characterize more fully the oculomotor characteristics of these animals. Additionally, assuming that one is willing to speculate that abnormalities found in the adults were also present during infancy, then any abnormalities we find become candidates for predisposing factors in the developmental etiology of the strabismus.

MATERIALS AND METHODS

Subjects

Ten macaque monkeys (Macaca nemestrina) with a naturally occurring infantile strabismus were used in this study, in addition to one normal control of the same species. All procedures performed on these monkeys were done in strict compliance with the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research. The monkeys are listed in Table 1 according to their permanent monkey identification number, as well as by a mnemonic name that reflects the nature of their strabismus. The magnitudes and subtypes of

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TABLE 1. Oculomotor and Refractive Status of Experimental Subjects

<table>
<thead>
<tr>
<th>Descriptive Monkey Name</th>
<th>Monkey ID</th>
<th>Alignment State †</th>
<th>Clinical Refractive Error (D)</th>
<th>Photoretinoscopic Refractive Error (D)</th>
<th>AC/A Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Right</td>
<td>Left</td>
<td>Right</td>
</tr>
<tr>
<td>ESSENTIAL_1</td>
<td>ESSENTIAL_2</td>
<td>T82327</td>
<td>Alternating accommodative esotropia; right eye fixation preference; 18° at near; 5° at distance</td>
<td>+1.8</td>
<td>+9.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T81324</td>
<td>Alternating accommodative esotropia; 12° at near; 3° at distance</td>
<td>+9.5</td>
<td>+8.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T81008</td>
<td>Left eye accommodative esotropia; 14° at near; 0° at distance</td>
<td>+4.5</td>
<td>+5.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F84115</td>
<td>Alternating accommodative esotropia; “V” pattern; left eye fixation preference; 15° at near; 0° at distance</td>
<td>+8.0</td>
<td>+6.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T79139</td>
<td>Alternating accommodative esotropia; right eye fixation preference; 9° at near in lower gaze; 0° at distance</td>
<td>+3.5</td>
<td>+7.0</td>
</tr>
<tr>
<td>INDUCED</td>
<td></td>
<td>F82366</td>
<td>Alternating esotropia; 15° right eye; 11° left eye</td>
<td>+6.8</td>
<td>-2.5</td>
</tr>
<tr>
<td>EXOPHOR</td>
<td></td>
<td>T85330</td>
<td>6° exophoria</td>
<td>+8.5</td>
<td>+8.0</td>
</tr>
<tr>
<td>RESOLVED</td>
<td></td>
<td>T81345</td>
<td>Orthophoria</td>
<td>+0.5</td>
<td>+0.4</td>
</tr>
<tr>
<td>NORM_1</td>
<td></td>
<td>PMH</td>
<td>Normal control; orthophoria</td>
<td>+0.3</td>
<td>0.0</td>
</tr>
</tbody>
</table>

† For a complete description, see Quick et al.1
‡ Measured only in primary gaze.

The 11 monkeys used in this experiment were grouped according to their alignment state, their refractive errors assessed clinically and with the infrared photoretinoscope, and their AC/A ratios.

strabismus were determined by photographic methods and by standard prism and cover tests performed on awake monkeys seated in a primate restraining chair. The classification of the types of strabismus, as well as the bases for the classification, have been described in detail previously.1 Briefly, two of the strabismic monkeys (ESSENTIAL_1, ESSENTIAL_2) showed patterns of misalignment consistent with essential infantile esotropia. One monkey (INDUCED) experienced bilateral retinal hemorrhage at birth and showed a pattern of alternating, constant-angle esotropia that may have been induced by the neonatal visual deprivation. Two of the monkeys that had a well-documented large-angle esotropia during infancy demonstrated a different pattern of alignment as adults. In one (EXOPHOR), an abnormally large exophoria was seen when examined under monocular viewing conditions, and in the second (RESOLVED), the strabismus has resolved to an orthophoria. The five other strabismic monkeys showed patterns of misalignment consistent with accommodative esotropia. Two of these (ACCOMM_1, ACCOMM_2) were esotropic at all target locations and exhibited alternating fixation. One monkey (ACCOMM_3) exhibited esotropia at near target locations and showed a strong fixation preference for the right eye. Finally, two of the accommodative monkeys (ACCOMM_4, ACCOMM_5) exhibited alternating esotropia for near targets but appeared orthotropic when viewing distant target locations. These last two monkeys also exhibited differences in deviation magnitude with vertical gaze angle, with the largest esodeviations present in lower gaze.

Apparatus

Infrared (IR) photoretinoscopy was used to assess the monkeys’ accommodative state. A photoretinoscope attachment was mounted in front of the aperture of an IR-sensitive video camera (model WV-1460, Panasonic, Secaucus, NJ), equipped with a standard 55-mm lens. The attachment shielded approximately the lower half of the camera aperture. Rows of IR light-emitting diodes (model LTE-239, Technical Sales, New York, NY) were mounted on the shield at various known distances from the top of the shield and were controlled by an electronic circuit that produced IR pulses at an adjustable fixed rate and intensity. During each pulse, a cone of IR rays entered the pupil of the subject and radiated the fundus. Some of these rays were reflected from the fundus, passed back out of the eye, and captured by the nonoccluded por-
tion of the camera aperture. These reflected rays appeared in the video image as a crescent of light in the pupil. Individual video frames of interest were stored in a computerized video acquisition and display system (model IP512, Imaging Technology, Woburn, MA) for later data analysis.

A quantitative estimate of the eye's defocus relative to the plane of the camera is given by

\[
D = E/(2 \times R \times A \times DF)
\]

where \(D\) is the amount of defocus in diopters, \(E\) is the eccentricity of the IR diodes from the top of the shield, \(R\) is the radius of the pupil, \(A\) is distance of the camera to the subject's eye, and \(DF\), the dark fraction, is the ratio of the dark part of the pupil to the pupil diameter.\(^{29,30}\) The sign of the defocus is determined by whether the light crescent appears near the top (hyperopic) or bottom (myopic) of the pupil. The range of defocus that could be measured was adjusted by varying the eccentricity of the IR diodes (1.2 mm, 4.0 mm, 7.0 mm, 15.0 mm, and 23.0 mm). The camera-to-eye distance was always 200 cm. Nominal defocus values were adjusted for camera distance to provide measures of accommodative response relative to the observer and the fixation target. The accommodative response was always specified in diopters. Similarly, we specified the accommodative stimulus distance in terms of the reciprocal of the distance in meters between the observer and the stimulus. Finally, accommodative errors were specified in dipters in terms of the discrepancy between the accommodative stimulus and the accommodative response.

**Procedures**

Cycloplegic refractive error was independently assessed by retinoscopy, performed by an ophthalmologist during a routine examination of the monkeys, and by photoretinoscopy. In both cases, the monkey was first lightly anesthetized (ketamine, 10 mg/kg), and then two drops of cycloplegic (2% cyclogyl) were administered to each eye at 5-minute intervals; assessments began approximately 20 minutes after administration of the second drop. During clinical retinoscopy, the monkey was examined while lying supine on an examination table. In the case of photoretinoscopy, the anesthetized monkey was placed in a primate restraining chair with its face positioned toward the camera.

Photoretinoscopic assessments of the accommodative state in noncycloplegic eyes were made under both monocular and binocular viewing conditions. These measurements were made on awake monkeys while they sat in a primate restraining chair and viewed fixation targets that consisted of food pellets and other small objects. The fixation targets were placed directly in front of the monkey at distances of 33 cm, 50 cm, 100 cm, and 200 cm (corresponding to accommodative distances of 3 D, 2 D, 1 D, and 0.5 D). Between 10 and 20 accommodative attempts were measured at each target distance under each viewing condition. Monocular assessments were accomplished by occluding the fellow eye with an opaque contact lens.

Many of our monkeys alternated fixation, and thus it was necessary during binocular fixation attempts to specify whether the accommodative response being measured on a given trial was from the fixating or nonfixating eye. This was determined at the time of scoring of the photoretinoscopy video frames by examining the position relative to the pupil of the corneal reflection that could be seen in the same image as the accommodation-related blur circle. The corneal reflexes that could be seen in these images were not of good enough quality to give a precise estimate of convergence angle, but they were adequate to allow us to differentiate the eye fixating the target from the deviated eye.

A primary goal of the present study was to obtain a quantitative comparison between the monkey's accommodative state and its binocular misalignment. We measured accommodative convergence for each monkey in a separate session using methods described in greater detail elsewhere.\(^{28}\) Briefly, the monkey was placed in the same apparatus and viewed the same targets at the same locations as those used for the accommodative measurements. Appropriate placement of polarizing filters allowed us to photograph corneal reflections from both eyes under conditions in which the monkey could only see the fixation target with one eye. We illuminated our small fixation targets by a penlight in a dimly lit room in an attempt to elicit a vergence response that was driven predominantly by the accommodative response of the viewing eye. Comparable viewing conditions were used for both the accommodation and the vergence measurements.

The quantitative measure of convergence response that we derived from these measurements was expressed in meter-angles to facilitate comparisons to our accommodative measurements that are specified in units of dipters. Specifically, we specified the convergence response in terms of the reciprocal of the distance in meters between the subject and where the lines of sight cross. Details of these calculations are elaborated elsewhere in our specification of the technical term Cross-Error.\(^{28}\) Finally, our estimate of the Response Accommodative Convergence-to-Accommodation Ratio (AC:A) was based on the magnitude of the convergence response elicited by a unit amount of accommodative response. Specifically, we calculated this value by taking the slope of the least squares linear regression line relating convergence magnitude to accommodation magnitude. The Stimulus AC:A Ratio was obtained the same way except that we used
values of the accommodative stimulus instead of the accommodative response.

RESULTS

Cycloplegic Refractive State

We made photoretinoscopic measurements of the cycloplegic refractive state to validate this procedure against the more traditional clinical method of retinoscopy. The cycloplegic refractive errors of each eye of each monkey obtained by photoretinoscopy and by clinical retinoscopy are shown in Table 1. The photoretinoscopic values shown for each eye represent the mean of 10 measurements. During the clinical examinations, we obtained a refraction that consisted of both spherical and cylindrical components. During photoretinoscopy, we obtained defocus values only in the vertical meridian. Therefore, to make comparisons between the two methods, we express all cycloplegic values in terms of the magnitude of the defocus in the vertical meridian. The results obtained by the two methods were similar. The average discrepancy between the two methods was approximately 0.3 D. The greatest discrepancies were found for the refractive errors that were large relative to the camera plane, as expected because of the decrease in sensitivity of the photoretinoscopic methods at large defocus values.

All of the results reported in the remainder of this paper involve accommodative attempts to targets that were placed within 3 D of the camera plane, and Table 1 reveals that within this range of distances, the average discrepancy between photoretinoscopy and clinical retinoscopy is approximately 0.2 D.

Accommodative Responses Under Monocular Viewing Conditions

Figure 1A shows the accommodative responses of our normal control monkey, NORM 1, under non-cycloplegic conditions. The accommodative response for each eye (measured while viewing monocularly) is plotted as a function of the accommodative stimulus. A perfect observer having no accommodative error would be expected to perform along the dashed line where the accommodative response is the same as the accommodative stimulus. The responses of each eye during monocular viewing were accurate, as evidenced by the fact that the standard deviation error bars around each of the symbols overlap the dashed line.

The monocular results from each eye of all of our strabismic monkeys were indistinguishable from those shown in Figure 1A for the normal control monkey, with one exception. The left eye of monkey INDUCED exhibited an inability to bring distant targets into focus. These results, shown in Figure 1B, are not surprising given the approximately −2.5-D cycloplegic myopia in the left eye of this monkey (see Table 1). The asymptote exhibited by the left eye values in this figure is consistent with the cycloplegic resting state.

Accommodative Responses Under Binocular Viewing Conditions

The accommodative responses of both eyes of our normal control monkey under binocular viewing con-
FIGURE 2. Accommodative responses during binocular viewing for the normal monkey and four strabismic monkeys. All fixation targets were placed in primary gaze at four different distances. Symbols and dashed lines are the same as those described for Figure 1. (A) Monkey NORM_1, (B) monkey ESSENTIAL_1, (C) monkey INDUCED. Note that the scale is different for monkey INDUCED than for the other monkeys. (D) Monkey ACCOMM_3, (E) monkey EXOPHOR. All of the deviations from the dashed line seen in the data sets in this figure are accountable based on the cycloplegic refractions (see text, this section, and Table 1).

ditions are shown in Figure 2A. The binocular results for this monkey are essentially identical to those shown in Figure 1 for monocular viewing conditions. The binocular viewing accommodative response functions obtained from some of our strabismic monkeys were different from those obtained from our normal control. In Figure 2B, we show results obtained from strabismic monkey ESSENTIAL_1. Examination of the raw data from each eye (not shown) revealed a bimodal distribution at each target distance. One distribution always clustered around accurate accommodation, whereas the other distribution clustered...
Accommodation in Strabismic Monkeys

Binocular viewing accommodative responses for monkey EXOPHOR are shown in Figure 2E. This monkey shows a bimodal distribution of accommodative error for each eye at each fixation distance. The magnitude of the difference between the two distributions was approximately 0.5 D, a value consistent with the amount of cycloplegic anisometropia that was measured in this monkey. There was an important difference between the bimodal distribution seen in this monkey and that seen in our other monkeys exhibiting binocular accommodative error: In the other monkeys, we were able to relate the two distributions to fixation behavior; that is, an accurate accommodative distribution was always associated with the fixating eye, whereas the accommodative distribution that was in error was related to the nonfixating eye. However, in monkey EXOPHOR, there was no measurable convergence error during binocular viewing conditions.

Accommodative Convergence

The relationships between accommodation and accommodative convergence that we found in our monkeys are shown in Figure 3. The horizontal axis in each plot represents accommodative distance in dipters (see Methods). It should be noted that the results just presented in the previous section demonstrate that monocular accommodation is always accurate for each eye when measured under monocular viewing conditions. Thus, this scale of accommodative distance represents both the Accommodative Stimulus and the Accommodative Response. The vertical axis shows the convergence response in meter-angles. The dashed line in each figure illustrates the expected response for an observer in which the accommodative system drives convergence accurately. Data that fall on a line parallel to the dashed line but shifted upward or downward indicate a constant error, that is, a convergence error that does not vary with the accommodative state. Data that fall on a straight line that is not parallel to the dashed line indicate an error in gain, that is, an abnormal AC:A ratio. Figure 3A shows the results for monkey NORM_1 during monocular viewing by each eye and illustrates that the results in our normal observer fall along the dashed line as expected. The AC:A results for monkey NORM_1 calculated from the results shown in Figure 3A have the expected values of 1.0 (Table 1).

Both monkeys with syndromes comparable to human essential infantile esotropia exhibited a similar pattern of results. We illustrate this pattern in Figure 3B for monkey ESSENTIAL_2. There appears to be a fairly constant convergence of the eyes to a near point in space, and the crosslink gain between accommodation and vergence is abnormally low. The AC:A ratios calculated for both eyes of both essential infantile monkeys are less than 1.0 (Table 1). A different pat-
tern of results was obtained from our monkeys with accommodative esotropia. We illustrate this pattern in Figure 3C, in which we show the accommodation and convergence data for monkey ACCOMM_1. Note that there is a convergence error that increases with the magnitude of the required accommodative response. The AC:A ratios of monkeys ACCOMM_1, ACCOMM_2, ACCOMM_3, and ACCOMM_4 were all similar to those shown in Figure 3C, and their AC:A ratios were all larger than 1.0 (Table 1). Our previous assessment of convergence errors in monkey ACCOMM_5 showed esotropia only for targets placed in the lower field of gaze.\(^1\) In the present study, only middle gaze measurements were performed. At these locations, ACCOMM_5 showed results indistinguishable from our normal control monkey, with AC:A ratios near 1.0 (Table 1).

The results for monkey EXOPHOR are shown in Figure 3D. Note that the AC:A function falls below the dashed line, indicating a constant convergence insufficiency during monocular viewing, consistent with the exophoria present in this monkey. However, the AC:A ratios are near 1.0 for each eye in this monkey (Table 1). During binocular viewing, the function overlaps the dashed line, demonstrating that the binocular fusion system is able to overcome the monocular error.

The results from monkey INDUCED were comparable to those of our normal control monkey, with AC:A ratios near 1.0 (Table 1). Monkey RESOLVED

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**FIGURE 3.** Accommodative convergence functions for the normal monkey and three strabismic monkeys. Circles represent right-eye viewing, and squares represent left-eye viewing. Open symbols are used in cases where a normal accommodative convergence response was obtained. Filled symbols are used for abnormal responses. Dashed lines represent an expected relationship between convergence and accommodation for a normal subject. Diamonds show results obtained from monkey EXOPHOR during binocular viewing. (A) Monkey NORM_1, (B) monkey ESSENTIAL_2, (C) monkey ACCOMM_1, (D) monkey EXOPHOR.
also showed results indistinguishable from the normal control monkey and exhibited AC:A ratios near 1.0 (Table 1).

DISCUSSION

We used infrared photorefraction to investigate the accommodative responses of 10 monkeys that show a naturally occurring strabismus. All monkeys except one showed accurate monocular accommodative responses in each eye to targets placed at four different distances in primary gaze. The inaccurate fixation by one eye of monkey INDUCED to distant targets could be explained by myopic refractive error. We did not systematically assess the accommodative range in these strabismic monkeys. However, except for the myopic eye of INDUCED, all monkeys showed accurate fixation to targets placed as close as ½ m. Because we had several monkeys with hypermetropic refractive errors as high as 8 and 9 D, our results demonstrate an accurate accommodative range of at least 11 to 12 D. We conclude that none of the strabismus in any of our monkeys could be accounted for by an inability to accommodate accurately to the distances of the fixation targets.

Measurements during binocular viewing revealed that for all, monkeys the magnitude of the accommodative response always appeared to be consensual, at least within our error of measurement, across the accommodative range that we measured. Therefore, errors in accommodation occurred only in monkeys with an anisometropia. Examination of the raw data from the anisometropic animals revealed a bimodal distribution of accommodative responses. Accommodative responses while the eye was fixating were accurate, but responses measured while the eye was deviating were in error by an amount predictable if the amount of cycloplegic anisometropia is known.

The results from our monkey with an abnormally large exophoria are interesting in this regard. This monkey alternated accommodation fixation preference but did not show a tropia. It is possible that a tropia is present in this monkey that is too small to be picked up with our methods for assessing the convergence state. However, it seems more likely that monkey EXOPHOR alternates the eye that controls accommodation, even though this alternation is not evident in terms of alternating convergence fixation. We interpret these results to indicate that only one eye is in control of the near reflex at any one instant, and that this control alternates from eye to eye over time.

We also measured accommodative convergence relationships and found that in our two monkeys with essential infantile esotropia, there was a reduced AC:A ratio, which allowed the eyes to remain in a converged state at a near distance regardless of accommodative state. Accommodation may contribute to the esotropia in these monkeys in a passive sense. In normal animals, the synkinesis between accommodation and convergence places convergence at a far point during accommodation to distant targets. In the essential infantile animals, there is no strong tendency for accommodative convergence to accomplish this, thus increasing demands are placed on disparity vergence when viewing distant targets. In the four monkeys exhibiting accommodative esotropia in primary gaze, the convergence error could be caused by, or at least exacerbated by, their high AC:A ratios, which predispose them to overconvergence when focussing on targets at near distances. Once again, there would be an increased demand on disparity vergence to overcome this error. The AC:A ratios appeared to be normal in the remainder of our monkeys.

It is interesting to note the accuracy to which accommodation and the AC:A ratio occur in normal monkeys and in the nondeviating eyes of the naturally strabismic monkeys. Their accommodative responses appear to be somewhat more accurate than is typically seen in humans. For example, there is often a lazy lag in human accommodation such that the subject's accommodative response is insufficient compared to the stimulus distance for near targets. This lag was not observed in our monkeys. In humans, this lag is typically only a fraction of a meter-angle, so it may be that monkeys also show this lag but it is obscured within our measurement error. Furthermore, the lag is known to decrease with age, at least in humans, and all of our monkeys were adults. We also found that the AC:A ratio in our normal monkeys was approximately unity. In humans, this value is usually reported to be less than 1.5 given that the prism dipters of vergence divided by the sphere dipters of accommodation has a value of approximately 4 and that the interpupillary distance is 6 cm. However, a typical interpupillary distance in monkeys is 4 cm to 5 cm, and this geometric difference may be sufficient to account for the greater accuracy in monkeys than in humans when the results are expressed in units of meter-angles. Alternatively, it is possible that monkeys are more reliant on accommodative vergence mechanisms to position the eyes than are humans.

The neuropathology of our animals with abnormal AC:A ratios is unknown but may be found in the neural pathways that subserve the near response. Mays made measurements of electrophysiological activity generated by neurons involved in vergence in the mesencephalic reticular formation that lies just dorsal and dorsolateral to the oculomotor nucleus in the monkey. Judge and Cumming demonstrated that some neurons in this region are related to accommodation, some to vergence, and some to both. These
neurons send output to medial rectus motoneurons, which are the sites at which vergence and versional signals are combined,35,36 and probably receive input from a number of cortical and subcortical regions.12,33–37

Finally, there are some obvious limitations of our study that should be mentioned. Our measurements were confined to static binocular fixation responses, and we made no measurements of dynamic characteristics of the relationships between accommodation and convergence, which have been extensively studied in normal monkeys.38 Another limitation of our study is that we did not look at changes in torsion during convergence.39 We also did not attempt to correct the refractive error in any of our monkeys. One reason for this was that we wanted to use the monkey as a model to study strabismus and accommodation unconfounded by treatment, conditions that are not usually possible in human clinical studies. That the accommodative responses during monocular viewing were found to be similar to the normal monkey obviated somewhat the importance of this issue. Also, our main findings are consistent with results obtained in human strabismic patients without significant amblyopia.5,39

Current views regarding the development of eye alignment in primates suggest that binocular eye alignment is immature and unstable at birth, and that achievement of normal alignment takes place through an active process during normal postnatal development.11,18–21 We adopt the working hypothesis that there are multiple predisposing factors that are capable of disrupting this developmental process. If the strength of the predisposing factors exceeds some threshold amount, disruption of binocular alignment occurs and strabismus results. Recent reviews have discussed many of these potential predisposing factors.11,12,41

In this paper, we have demonstrated that abnormalities in the synkinesis between accommodation and vergence are candidates for predisposing factors for the development of strabismus seen in some of our monkeys. Prior studies with humans have demonstrated that strabismic patients show a general lack of disparity vergence and a preference for relying on accommodative vergence.5 Thus, it is not unreasonable to speculate that constellations of predisposing factors that include a combination of abnormal accommodative convergence and weak disparity vergence are responsible for the development of some forms of strabismus. Recent evidence from our laboratory has also suggested other possible predisposing factors for strabismus. These include the loss or reduction in size of the accessory lateral rectus muscle seen in all humans and occasionally in monkeys,42 the increased trial-to-trial fixation variability we have observed during binocular viewing in monkeys with essential infantile esotropia,1 and asymmetric optokinetic nystagmus present in all of our strabismic monkeys (unpublished observations, 1993), a predisposing factor that has been emphasized by Tychsen.11

Key Words
accommodation, strabismus, convergence, ACA ratio, photorefraction

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