The effect of pupil size on accommodation, convergence, and the AC/A ratio

Harris Ripps, Newton B. Chin, Irwin M. Siegel, and Goodwin M. Breinin

The present report describes the effect of pupil size on the accommodation-convergence relationship. Measurements of accommodation and associated changes in convergence were made with a Fincham coincidence optometer and modified haploscope. Responses were obtained over a wide range of stimulus levels with the observer viewing the target through a graded series of artificial pupils. Increasing the dioptric stimulus to accommodation resulted in a nearly linear increase in both the accommodative response and associated vergence. However, with pupil sizes of 1.0 mm. or less there was a reduction in the slope of these stimulus-response functions. There was, accordingly, a significant decrease in the stimulus (clinical) AC/A ratio for these pupil diameters. The response AC/A ratio, on the other hand, was not significantly influenced by variation in pupil size. Since pupil diameters of 1.0 mm. or less are not usually attained with parasympathomimetics in treating accommodative eso deviations, effective control cannot be attributed solely to an increase in depth of focus resulting from pupillary constriction. When the target, imaged at the far point of the eye, was viewed through a 0.5 mm. pupil, some subjects exhibited an increase in accommodation. This effect appears related to the increase in refractive state of the eye that occurs in the absence of an optical stimulus to accommodation.

Although accommodative convergence is more closely related to the change in accommodative response than to a change in the stimulus to accommodation, the accommodative response is not readily measured by routine clinical methods. Consequently, in clinical practice the AC/A ratio refers to the convergence associated with a change in the stimulus to accommodation—the assumption being that, if the fixation target remains clear, changes in accommodative response parallel those of the stimulus. Under certain circumstances, however, the subjective judgment of image clarity cannot provide a useful criterion for estimating the accommodative state of the eye. For example, when the depth of focus of the eye is increased by a reduction in pupil size, a given dioptric change in the stimulus to accommodation may not elicit the same accommodative response obtained with a large pupil. This becomes an important consideration when the clinical
AC/A ratio is used to evaluate the results of miotic therapy in accommodative esotropia.

The parasympathomimetic action of miotics affects both iris and ciliary musculature, and it is still not clear as to what factors contribute to their therapeutic effectiveness. According to the view held by Tour, a large part of the benefit of miotics is derived from pupillary constriction. He suggests that the resultant increased depth of focus decreases the amount of accommodation needed to maintain sharp retinal imagery and thereby reduces the associated convergence. No experimental evidence is available to support this view. Studies of the depth of focus of the eye have not indicated how the accommodative mechanism reacts to stimulation when the depth of focus of the eye is altered.

Costenbader, on the other hand, is of the opinion that miotics normalize the convergence responses to accommodation. This implies that less accommodative effort is required to produce a given accommodative response and hence less convergence is brought into play. A critical result consistent with this hypothesis would be a reduction in the response AC/A ratio (or the stimulus AC/A ratio if it can be demonstrated that they are equivalent) after the administration of miotics. The work of Sloan, Sears, and Jablonski indicates that following isoflurophate (DFP) therapy there is a significant decrease in the stimulus AC/A ratio. However, since their clinical AC/A findings were obtained with natural pupils, the importance of the miosis is difficult to assess.

In the present experiment, accommodation and convergence responses were obtained as a function of dioptric changes in the stimulus to accommodation. Measurements were made over a range of pupil sizes in order to determine whether this parameter can either (a) significantly influence the convergence associated with a change in the stimulus to accommodation (stimulus AC/A ratio), or (b) alter the relationship between convergence and the actual accommodation in play (response AC/A ratio).

Method

The apparatus is shown schematically in Fig. 1. It consisted essentially of a Fincham coincidence optometer and one rotating member of a conventional haploscope. A Badal optometer was mounted on the haploscope arm.

The Badal system provided the stimulus to accommodation for the subject's right eye. Fixation target, T, was transilluminated by source, S, through flashed opal, O. The image of T formed by lens, L, was viewed by reflection in the first surface mirror, M. Lens, L, was placed with its secondary focal point at the anterior focal point of the eye so that retinal image size was independent of target position. With this arrangement the accommodative stimulus (in diopters) is specified from the anterior focal plane and is linearly related to the distance of the target from the optometer lens. The target consisted of a group of four Snellen letters on clear film. Each letter subtended a visual angle of 8 minutes of arc (20/32 equivalent Snellen notation). The letters were arranged in a horizontal line within a 1 degree, 20 minutes, circular field. Pupil size was altered by apertures at A in the anterior focal plane of the eye. The apertures employed were 0.50, 0.75, 1.0, 1.5, 2.0, and 3.0 mm. in diameter. It was originally intended that the pupil range be extended to include a 5.0 mm. aperture and data were obtained on three observers for this condition. Since in every case the results were essentially the same as those found with the 3.0 mm. pupil,
it was decided to omit the 5.0 mm. pupil in order to reduce the length of an experimental session.

Objective measurements of the consensual accommodative response were made on the left eye with the Fincham coincidence optometer, F. This instrument has been described in detail elsewhere. Changes in the spectacle refraction of the eye are indicated by a break in the coincidence of the upper and lower halves of a line image formed on the subject's retina. With the exit pupil of the instrument set at 3 mm., refractive changes of 0.12 diopter were readily detected and the measurements were not influenced by the size of the natural pupil. Although the accommodative response was measured in the consensually activated eye, it is unlikely that the response differs appreciably from that of the fixing eye. Several studies have shown that even when unequal accommodation is required to compensate for different accommodative stimuli to the two eyes, differences greater than about 0.12 diopter cannot be overcome. The haploscope arm rotated about a vertical axis, C, through the center of rotation of the eye. Phoria settings were made by subjective alignment of the fixation target below a stationary reference spot (diameter, 12 minutes) incorporated in the coincidence optometer. Thus, a convergence response was indicated on scale D by a movement of the haploscope arm to compensate for lateral displacement of the images. This movement repositioned the visual axis of the left eye with respect to the fixed axis of the optometer for measurement of the accommodative response. The inset in Fig. 1 shows the subjective appearance of the image configuration when the fixation target, T, was centered beneath the reference spot, R. The inferior border of the line image, I, formed by the coincidence optometer was about 4 degrees from the visual axis of the left eye.

Changes in artificial pupil diameter required that the target luminance be altered in order to maintain a constant apparent brightness. Accordingly, the luminance of the target was adjusted for each artificial pupil to obtain a given critical flicker frequency. The target luminance for the 2.0 mm. artificial pupil was approximately 85 millilamberts.

Measurement of accommodation and convergence responses over the entire range of accommodative stimuli and pupil diameters comprised an experimental session. Beginning with the smallest artificial pupil, accommodative stimuli were presented in ascending order, increasing by approximately 1.3 diopter steps from a negative value of 1.5 diopters to a positive value of 8.0 diopters. Two measurements of accommodative response and phoria were obtained at each stimulus level and the entire procedure repeated for successively larger pupil sizes. Suitable rest periods were provided between experimental runs.

Thirty minutes before the start of an experimental session, one drop of 10 per cent phenylephrine hydrochloride (Neoephrine) was topically administered to each eye and a second drop instilled 15 minutes later. Mydriasis was necessary to insure that the natural pupil exceed the dimensions of the artificial pupil for all stimulus conditions. The dosage level employed does not influence accommodation or the accommodation-convergence relationship. In several control runs, data were obtained before and after instillation of phenylephrine hydrochloride for the 2.0 mm. artificial pupil. The results were in complete agreement with those cited.

Results

Figs. 2 and 3 illustrate the relation of accommodation and convergence responses to the level of accommodative stimulus with each of the 6 artificial pupil sizes. The plotted points are the means of 10 determinations taken during 5 experimental sessions with 1 subject. These data are, for the most part, representative of the results obtained with the 4 other subjects.

Accommodative response as a function of the stimulus to accommodation is shown in Fig. 2. Fig. 3 shows the associated phoria measurements as a function of the accommodative stimulus. Both sets of figures indicate that for each pupil size there is at first an essentially flat portion which ultimately rises as a nearly straight line of positive slope. The base level represents the range of accommodative stimuli that were ineffective in producing a change in accommodative response or a change in associated convergence. With larger pupil sizes the range of stimulus values over which the base level extends is decreased. The rising portion of each function leaves the base level with increasingly greater slope as pupil size is increased. This enhancement in slope magnitude reaches a maximum with the 1.5 mm. pupil and thereafter remains almost constant. It should be noted that the rising portion was not linear over its entire length for all subjects. This was particularly apparent for the larger pupils at the upper levels of the stimulus
to accommodation. A least-squares fit of the data was therefore made over the range of determinations for which the relationship was approximately linear. The values fitted in this manner are shown by the continuous lines in Figs. 2 and 3.

Fig. 2. Accommodative response as a function of the stimulus to accommodation. Results for subject N. B. C. The pupil size in millimeters is indicated for each function. Plotted points are the means of ten determinations obtained in five experimental sessions. Solid lines are drawn through the points for which the slope has been calculated by the method of least squares.

Fig. 3. Convergence responses as a function of the stimulus to accommodation. Results for subject N. B. C. The pupil size in millimeters is indicated for each function. Other conditions are the same as those in Fig. 2.
Table I presents, for all subjects, the calculated slope values of the accommodative response versus accommodative stimulus functions for all pupil sizes. Similarly, Table II contains the slopes representing the rate of change of accommodative vergence per unit change of the stimulus to accommodation: by definition, the stimulus AC/A ratio (AC/Aᵣ).

One other feature of Figs. 2 and 3 is to be noted. A vertical displacement of the base level for the smaller pupil sizes was observed in 3 of the 5 subjects tested. With the 0.5 mm. pupil the displacement amounted to approximately 1.0 diopter on the accommodative response ordinate and about 2 degrees on the convergence response ordinate. The relation between this base level shift and the increase in refractive state of the eye that occurs in the absence of an optical stimulus to accommodation will be considered in the discussion section.

The response AC/A ratio (AC/Aᵣ) is a measure of the rate of change of convergence per unit of accommodative response, expressed in degrees per diopter. If, as is customary, the accommodative response is plotted on the ordinate and convergence on the abscissa, then the reciprocal of the slope of this graph is the AC/Aᵣ. Fig. 4 shows the relation between convergence and accommodative response at 6 pupil sizes for 2 observers. Each point represents an individual determination, all of which were taken during a single experimental session. Only those responses used in the calculations of the stimulus-response slopes in Tables I and II are shown. The response AC/A ratios for all subjects are presented in Table III.

Since both components of the AC/Aᵣ ratio are dependent variables subject to several sources of error, including errors of measurement and interaction, the method of least squares is not considered appropriate for estimation of slope. On the basis of a statistical and theoretical evaluation of the accommodation-convergence relationship, Alpern, Kincaid, and Lubeck have derived an alternate method for determining the AC/Aᵣ. They concluded that

Table I. Slope values of the accommodative stimulus-response functions for all subjects over the complete range of pupil sizes (N = number of experimental sessions)

<table>
<thead>
<tr>
<th>Pupil size (mm)</th>
<th>I.K. N = 1</th>
<th>I.M.S. N = 5</th>
<th>R.C. N = 2</th>
<th>N.B.C. N = 5</th>
<th>A.S. N = 1</th>
<th>Mean</th>
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<tr>
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<td>0.75</td>
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<td>1.00</td>
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Table II. Stimulus AC/A ratios (degrees per diopter) (N = number of experimental sessions)

<table>
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<th>Pupil size (mm)</th>
<th>I.K. N = 1</th>
<th>I.M.S. N = 5</th>
<th>R.C. N = 2</th>
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<tr>
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<tr>
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<td>1.98</td>
<td>1.86</td>
<td>2.37</td>
<td>2.46</td>
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</table>
Fig. 4. Relationship between accommodative convergence and accommodative response for 2 observers. Each point is a single determination. The pupil size in millimeters is indicated above each function. The data for the 3.0 mm. pupil are correctly positioned on the graph. Each successive function has been displaced 6 degrees to the right on the abscissa.

an estimate of the AC/A<sub>s</sub> is obtained from the ratio m<sub>s</sub>/m<sub>n</sub>, where m<sub>s</sub> is the stimulus AC/A ratio (Table II) and m<sub>n</sub> is the slope of the accommodative response versus accommodative stimulus data (Table I). The entries in Table III and the lines fitted to the points in Fig. 4 were determined by this procedure.

The stimulus and response AC/A ratios, given in Tables II and III, respectively, are shown as a function of pupil size in Fig. 5. For all subjects, the AC/A<sub>s</sub> function begins at a lower level than the AC/A<sub>n</sub>. As pupil size increases the AC/A<sub>s</sub> increases, and, beginning with the 1.5 mm. pupil, becomes roughly parallel to the AC/A<sub>n</sub>. With the exception of subject N. B. C., the AC/A<sub>s</sub> function remains below the AC/A<sub>n</sub> for the entire range of pupil sizes. The mean curves, representing average values of AC/A<sub>s</sub> and AC/A<sub>n</sub> over pupil size for all subjects, reflect the individual trends. In order to test the significance of these trends two analyses of variance were performed on the group data: (1) subjects versus pupil size for AC/A<sub>s</sub>, and (2) subjects versus pupil size for AC/A<sub>n</sub>. The column mean-square and row mean-square entries in both instances were tested against the residual error variance. The intersubject variances in both cases were highly significant (p < 0.01). The AC/A<sub>s</sub> values over pupil size were also significant at this level of confidence: F = 29.8, df = 5,20 (F<sub>.01</sub> = 4.10). A partition of this analysis testing the three smaller and the three larger pupils separately revealed that the significant variation is between the smaller pupils: F = 24.8 df = 2,20 (F<sub>.01</sub> = 5.85); not the larger ones: F = 2.20, df = 2,20 (F<sub>.05</sub> = 3.49). Analysis of the AC/A<sub>n</sub> data, on the other hand, showed no significant change in slope over pupil size: F = 0.75, df = 5,20 (F<sub>.05</sub> = 2.71).

Discussion

The results of the present experiment demonstrate that the stimulus and response

<table>
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<tr>
<th>Pupil size (mm)</th>
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<th>N.B.C. N = 5</th>
<th>A.S. N = 1</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
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<td>3.00</td>
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</table>
AC/A ratios do not provide equivalent estimates of the relationship between accommodation and convergence. However, the extent by which they differ depends, in part, upon the diameter of the entrance pupil of the eye. The small but relatively constant difference that exists when the pupil size is 1.5 mm. or greater progressively increases as the pupil size is reduced below 1.5 mm. (Fig. 5). Since the response AC/A ratio is not significantly altered by variation in pupil size, the divergence reflects the decrease in stimulus AC/A ratio that occurs with smaller pupil sizes. It should be emphasized that this decrease was observed despite the fact that the AC/A was determined only for the stimulus range over which convergence increased as the stimulus to accommodation increased (Fig. 3). If the lower stimulus values had been included in the calculation of the stimulus AC/A ratio, the discrepancy between stimulus and response AC/A ratios would have been considerably greater.

On the basis of these findings, it appears unlikely that the successful management of accommodative eso deviations with parasympathomimetic agents is derived from the pupillary constriction. For miosis to contribute to the therapeutic effect, a pupil size of 1 mm. or less is required. Although a 1 mm. pupil is not uncommon after administration of high concentrations of DFP, the pupil diameter is probably not reduced below 1.5 mm. with the dosage levels ordinarily employed for long-term strabismus therapy. Therefore, it seems probable that the reduction in the stimulus AC/A ratio following use of DFP as reported by Sloan and co-workers, reflects a corresponding change in the response AC/A ratio. Their results thus tend to support Costenbader's hypothesis that miotics normalize (reduce) the convergence response to accommodation.

Some related findings from our laboratory are of interest in this regard. Using another of the potent cholinesterase inhibitors, phospholine iodide, we have recently confirmed the results of Sloan and her co-workers. In addition to measurements of the stimulus AC/A ratio, the response AC/A ratio was also determined. After daily instillations of 0.125 per cent phospholine iodide, an almost identical decrease was found in both the stimulus and response AC/A ratios; all measure-
ments having been obtained with natural pupils. The miosis, therefore, cannot have contributed to this effect.

In another preliminary study, we have found that phospholine iodide enhanced the accommodative response to submaximal electrical volleys applied to the ciliary ganglion in the cat. Apparently the enhancement results from a potentiation of neuromuscular transmission. If the synkinesis between the mechanisms of accommodation and convergence stems from a central linkage, then a reduction in the innervational requirement to produce a given accommodative response would result in a decrease in associated convergence.

In view of these observations it should be possible to use a mydriatic in conjunction with parasympathomimetics without appreciably reducing the effectiveness of the latter. This combined drug administration is currently being evaluated with patients in whom the prolonged miosis leads to the annoying side effect of iris cysts.

It was noted earlier that for three subjects the accommodative state of the eye increased when the target, imaged at the far point of the eye, was viewed through the 0.50 mm. pupil. For these observers, the increase in refracting power was approximately 1 diopter. It is possible that this effect is a consequence of the decrease in spherical aberration of the eye with small apertures. Elimination of the peripheral, more highly refracted rays would tend to move the effective focus posterior to the retina, thereby evoking an accommodative response. However, this is probably not an important factor since the refractive state remained relatively constant (base level) over a considerable range of both positive and negative stimulus values. If the subjects were responding merely to a displacement of the optimum focus with respect to the retina, then a further change in position, produced by altering the target position, should have been equally effective in eliciting an accommodative response.

The extended range of stimulus values over which accommodation remains unaltered suggests that the small aperture reduces the effectiveness of light vergence as a stimulus to accommodation. In the absence of an optical stimulus to accommodation the eye may assume a state of accommodation other than zero, comparable to the effect observed with the 0.5 mm. aperture. This is known to occur when the eye is (1) in darkness, (2) exposed to a luminous but completely empty visual field, and (3) viewing a blurred target. Heath has suggested that under these conditions the refractive state is determined by tonic accommodation. The pinhole effect may thus result from a reduction in the optical stimulus to accommodation, and could represent another situation in which tonic accommodation is manifest. Interestingly, in the present experiment the refractive change was observed despite the presence of a fixation target containing resolvable detail, and in each case was accompanied by an increase in convergence.

The results are of further interest in connection with attempts by other investigators to measure convergence accommodation. It is now generally recognized that a relationship exists between accommodation and convergence such that activation of either mechanism results in a change in the other. Study of this relationship requires that the reflexly elicited response be uninfluenced by other effective stimuli. For example, to determine accommodative convergence in the present study, it was necessary to eliminate the stimulus to binocular fusion. Similarly, to determine the amount of accommodation evoked solely by convergence, the clarity of the fixation targets controlling convergence must not change as a consequence of the accommodative response. Were this to occur, it would act to restore the original refractive state and lead to an underestimation of the effect.

*Balsam and Fry reported a similar finding when pinhole apertures were employed for measurements of convergence accommodation.
To obviate the influence of out-of-focus blur, the method of choice has been to have the subject view the fixation targets through small apertures in order to increase the depth of focus of the eye. The present findings indicate that this procedure is not entirely satisfactory even when the effective entrance pupil of the eye is reduced to 0.5 mm. With a 1 mm pupil, a convergence-induced change in accommodation of 2 diopters would be sufficient in itself to serve as a stimulus to accommodation (Fig. 1). With a 0.5 mm pupil the dioptric range over which changes in light vergence are ineffective is increased, but may be exceeded at the higher stimulus levels. If the pupil size were reduced still further, the deterioration of resolving power due to diffraction might preclude adequate control over convergence. More precise determination of convergence accommodation may require, therefore, use of a fixation pattern whose clarity is independent of the refractive state of the eye.

REFERENCES