1040-5488/100/7703-0150/0 VOL. 77, NO. 3, PP. 150–155
OPTOMETRY AND VISION SCIENCE

ORIGINAL ARTICLE

Accommodation Causes With-the-Rule Astigmatism in Emmetropes

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ABSTRACT: ***Purpose:*** **To measure the changes in astigmatism when bilateral emmetropes accommodate.** ***Methods:*** **Bilateral emmetropes accommodative responses were measured with an improved photorefractometer PR-1100, which measured binocular refraction in all meridians simultaneously as a fixation target was shown in natural space.** ***Results:*** **The accommodative responses in the vertical meridian are greater than those in the horizontal meridian. In the horizontal meridian, the accommodative responses are less than the accommodative stimulus.** ***Conclusions:*** **When accommodating the majority of bilateral emmetropes show with-the-rule astigmatism and lag of accommodation in the horizontal meridian. (Optom Vis Sci 2000;77:150–155)**

Key Words: accommodation, bilateral emmetropia, astigmatism, meridian, photorefractometer

Accommodation has conventionally been measured by subjective methods since Donders in 1864.[1–4] The main reason for this approach has been the lack of objective means for evaluating accommodation, with the exception of retinoscopy. In the illumination and observation systems of retinoscopy, however, the patient's pupil must be aperture-stop, the examiner's retinal conjugate point must be at the patient's pupil, and the examiner and the patient must share the same ocular optic axis, a retinoscopic axis.[5, 6] Therefore, it is difficult to place a visual target with a relatively large visual angle on a patient's line of sight, and even if the visual target is placed in a small deviated direction from the line of sight, it is difficult for the patient to fixate the target because of dazzle from the retinoscope beam. Recently, because of the development of infrared optometers,[7] researchers have been able to objectively measure accommodation. However, they have not been able to measure binocular accommodation simultaneously and in all meridians. With this measuring system, the fellow eye's accommodative behavior is difficult to assess simultaneously.

In 1990, we developed the PR-1000 photorefractive refractometer (Topcon, Tokyo, Japan),[8, 9] which enables us to measure binocular eye refraction simultaneously in vertical and horizontal meridians (Fig. 1). This instrument was originally developed to measure infant refraction. The PR-1000 was improved to detect all meridians' refraction (the PR-1100) by changing the software included. We then modified the PR-1100 to measure accommodation.

In our preliminary experiments, we used a Canon R-1 (which can measure refraction in all meridians and permits a presentation of a fixation target in real space but cannot measure simultaneous binocular refraction).[10–12] Therefore, we were not able to detect simultaneous interaction between both eyes. Then, as Cornsweet described,[13] we also had the impression that there might be a difference in accommodative behavior in well-trained subjects compared with untrained subjects.

We planned to measure accommodative behavior under ordinary visual circumstances in this experiment. To maintain such circumstances, dolls were shown in real space to stimulate accommodation, and no trained subjects were employed. In our first study of binocular accommodation, we chose only subjects with bilateral emmetropia, as the most fundamental state of refraction, for this study. We found that bilateral emmetropes caused with-the-rule astigmatism, and less response than stimulation in the horizontal meridian.

MATERIALS AND METHODS

Instrument

The PR-1000 refractometer was developed for measuring infants' refraction, employing Howland's photorefraction theory.[14] We originally introduced a diffuse light source in the illuminating system, and a knife edge in the detecting system, as shown in Fig. 2.[8, 9] The PR-1000 has these functions: an infrared light source is mounted as the illuminating source to prevent dazzling the patient;

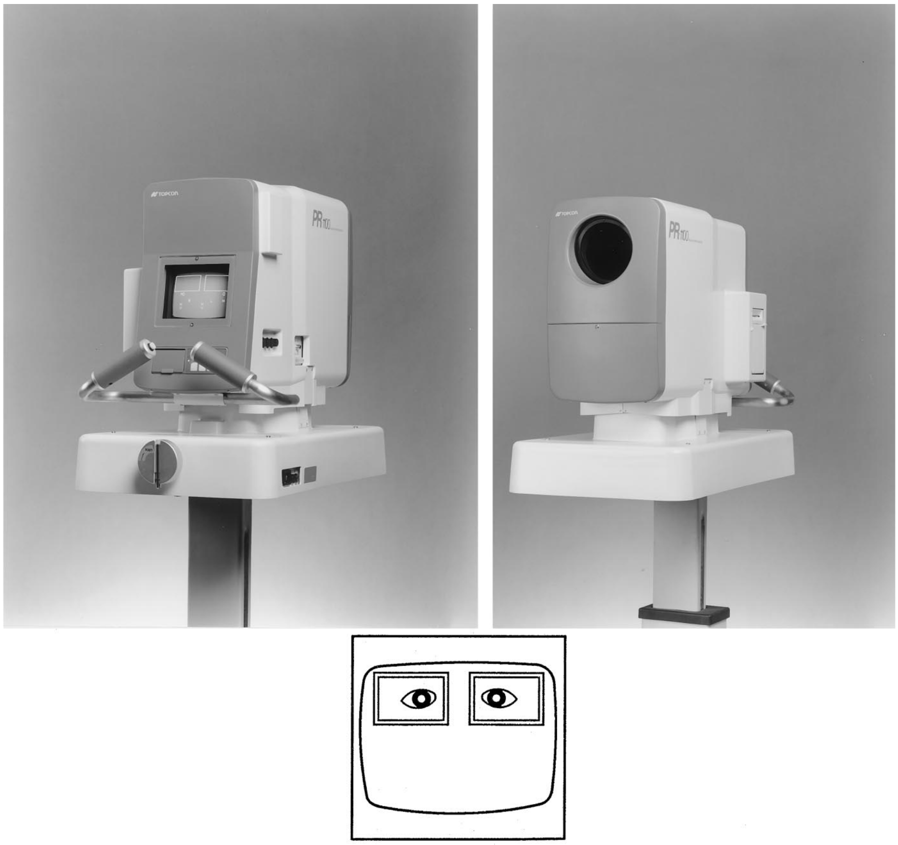

FIGURE 1.

The external form of the PR-1100. The left panel shows the view from the operator's side. The operator positions the subject's eyes in the lined frames on the monitor display (illustrated at bottom) with the two control handles, focuses both eyes' images, and pushes the measurement button to store a record. The right panel shows the view from the subject's side. In ordinary use as a pediatric refractometer, inside the measuring window a visual fixation target is blinking and makes a sound for attention. In this experiment, the subject looked at a visual fixation target through a mirror. The lower panel shows the view of the monitor display. The subject's eyes are positioned in the frames and then focused.

simultaneous binocular measurement is made during binocular viewing; the measurement does not need a dark room; the wavelength of the light source is 830 to 950 nm; the instrument is placed 1.2 m away from a patient; the amount of energy at the patient's eye is 3.98×10^{-5} W/cm^2; the measuring range is -5 to $+5$ diopters in each meridian, the measuring time is 0.15 s for one record; four measurement records can be stored, and after the fifth measurement, the first (oldest) record disappears; and the minimum pupil diameter required is 3.0 mm. The operator views both eyes of a patient on the monitor, chooses the appropriate moment (no blinking, no moving of the patient, etc), and pushes the button. One record is then stored.

The second version of the PR-1000, the PR-1100, can detect refraction in all meridians. This improvement was achieved by changing the original software. The accuracy of the PR-1100 is shown in Fig. 3. We modified the PR-1100 for this experiment as shown in Fig. 4. Two 30 × 50 cm dichroic mirrors were placed 20 cm from the subject and declined at 45°. The subject's head position was controlled using a chin rest holder set behind the mirrors. Visual fixation targets to stimulate accommodation were presented through the dichroic mirror at 5 m and 0.5 m, with the axis of the refractometer aligned with the subject's eyes (except for the error

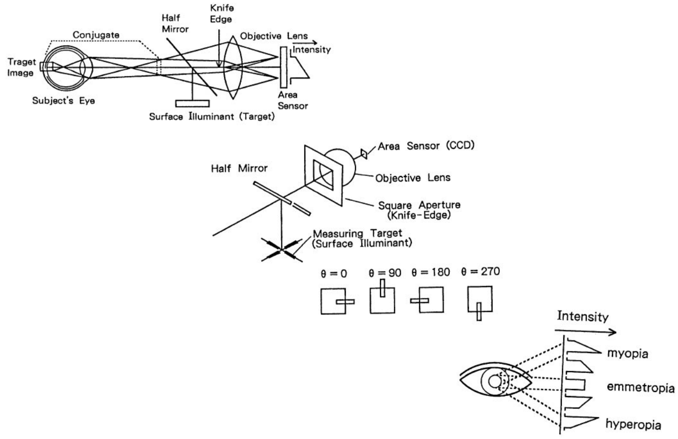

FIGURE 2.

Optical principle of a PR-1100. The left panel shows a schematic diagram, which uses a surface illuminant and a knife edge. The middle panel shows the distribution of the surface illuminant and the knife edge. A part of the light which emerges from the subject's retina is blocked by the knife edge, and the rest of the light flux reaches a CCD area sensor which is set on the optical conjugate plane of the subject's pupil. The right panel shows the light intensity distribution which appears in the subject's pupil. The slope of the intensity distribution depends on the subject's refraction.

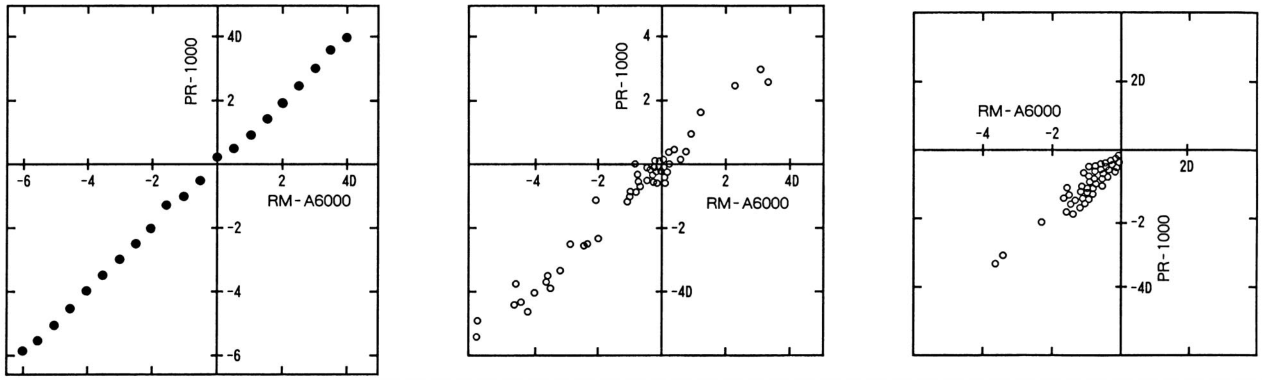

FIGURE 3.

The accuracy of a PR-1100. The left panel shows a comparison of PR-1100 and RM-A6000 (a commercially used conventional autorefractometer developed by Topcon) by using schematic eyes. The horizontal axis shows the values measured with a RM-A6000. The vertical axis shows the values measured with the PR-1100. The standard deviation is 0.1D and the correlation coefficient is approximately 1.0. The center panel shows a comparison of the spherical powers measured with PR-1100 and RM-A6000 for volunteer adult subjects (54 eyes). The standard deviation is 0.35 D and the correlation coefficient is 0.98. The right panel shows a comparison of cylindrical powers measured with PR-1100 and RM-A6000 for volunteer adult subjects (54 eyes). The standard deviation is 0.25 D and the correlation coefficient is 0.93.

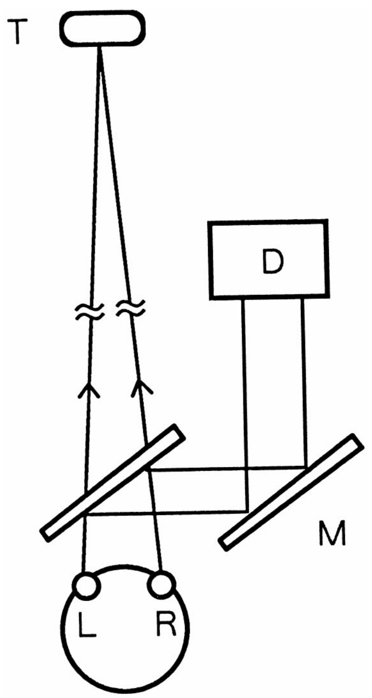

FIGURE 4.

A diagrammatic overhead view of the improved PR-1100; D, PR-1100; M, dichroic mirror; R, subject's right eye; L, subject's left eye; T, visual fixation target. Subjects are positioned so their eyes are aligned with the optical axis of the PR-1100, using the chin rest holder set behind a mirror. The visual fixation target is presented carefully on the visual axis, which is indicated with marks.

TABLE 1.

Selection of subjects. Bilateral emmetropia occurred in only 5.8% (15 subjects) of the primary selection (259 subjects) and in only 0.6% of the general population (2486).

Age	Primary Selection	Male	Female	Bilateral emmetropia	Male	Female
12	11	5	6	0	0	0
13	11	7	4	2	2	0
14	6	3	3	1	0	1
15	21	15	6	2	1	1
16	15	6	9	2	2	0
17	20	13	7	0	0	0
18	32	10	22	1	0	1
19	100	0	100	2	0	2
20	32	0	32	4	0	4
21	4	0	4	0	0	0
22	6	0	6	0	0	0
23	1	0	1	1	0	1
Total	259	59	200	15	5	10

caused by patient's convergence). The error caused by convergence is referred to below as "simulation." Two different-sized small dolls with approximate visual angles of 10° were employed as visual fixation targets.

Subjects

The subjects were selected from a group of students from an elementary school, a junior high school, a high school, and a women's university. These 2486 people, aged 12 to 26 years, indicate the general population of an urban area. Primarily, 259 members, as shown in Table 1, were selected who had corrected decimal visual acuity of 1.0 (corresponds to 5/5) or better, orthophoria, normal binocular function, intact ocular media, and intact ocular fundus. Visual acuity test was measured for each eye using Landolt rings at 5 m, while the fellow eye was occluded. Orthophoria was examined using the cover test. Keratometric records were taken with a Canon RK-2. A binocular function test was administered using a synoptophore (major amblyoscope), with a visual angle of 3° target size. Binocular function was judged as "normal" when subjects had simultaneous foveal perception and fusion (a fusional amplitude of divergence of 4° or more, with convergence of 12° or more on each target under two conditions with and without −2 D lenses). Ocular media was examined by slit lamp microscopy, and ocular fundus was observed using a funduscope.

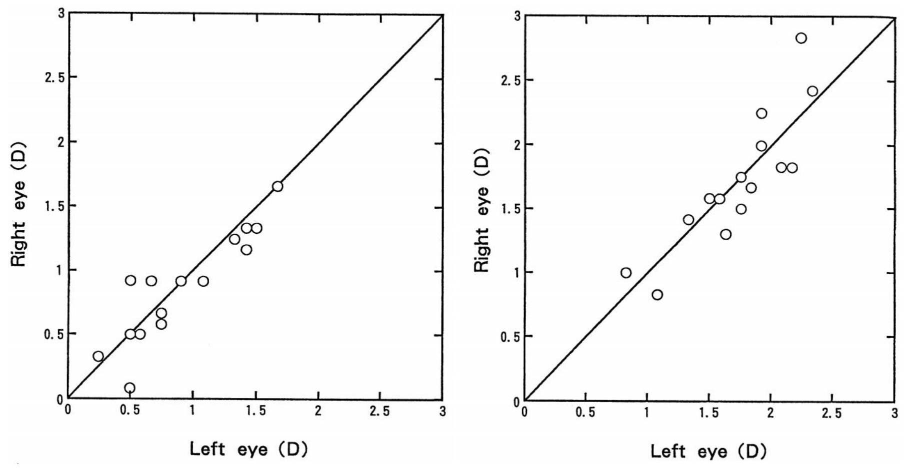

FIGURE 5.

Accommodative responses (refraction stimulated by visual fixation target at 0.5 m) in each meridian (15 subjects). The left panel shows results for the horizontal meridian. The mean values are −1.19 D, and −1.10 D; the standard deviations are 0.36 D and 0.36 D; the minimum refractions are −0.50 D and −0.42 D; the maximum refractions are −1.83 D and −1.67 D in the right eyes and in the left eyes, respectively. A double circle shows two overlapped data points. The right panel shows results for the vertical meridian, the mean values are −1.96 D and −1.91 D; the standard deviations are 0.39 D and 0.37 D; the minimum refractions are −1.25 D and −1.25 D; the maximum refractions are −2.50 D and −2.67 D in the right eyes and the left eyes, respectively. The correlation coefficient values of both eyes are 0.83 and 0.91 in the horizontal and the vertical meridians, respectively.

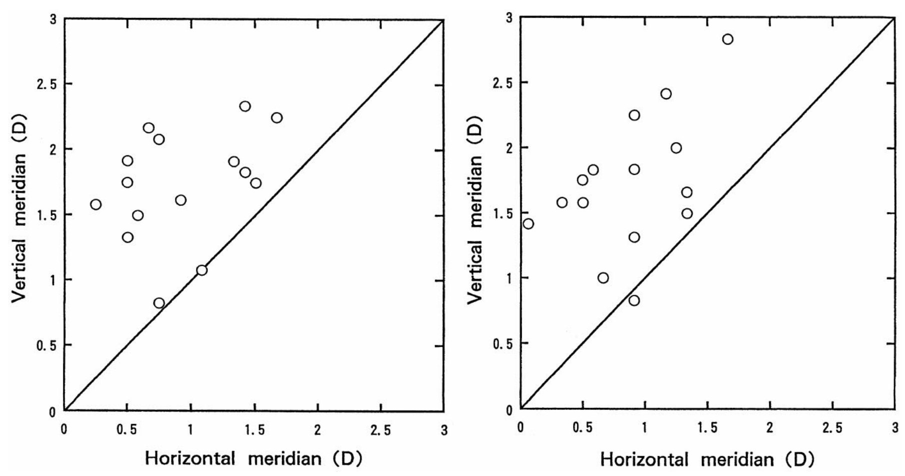

FIGURE 6.

Comparison of accommodative responses between horizontal and vertical meridians (15 subjects). The left panel shows results for the left eye. The right panel shows results for the right eye. The correlation coefficients are 0.20 and 0.12, in the right eyes and the left eyes, respectively. In the data for each eye, 14 subjects show with-the-rule astigmatism, and one subject shows against-the-rule astigmatism of 0.17 D. The cases of the against-the-rule astigmatism belong to one subject. In the subject with with-the-rule astigmatism, the mean values are 0.84 D (in the right eye) and 0.88 D (in the left eye); the minimum values are 0.08 D (right eye) and 0.08 D (left eye); and the maximum values are 1.25 D (right eye) and 1.42 D (left eye). The cases of the minimum value belong to the same subject, and the cases of the maximum value belong to different subjects.

The definition of emmetropia in this paper is as follows: spherical refractive error of ± 0.50 D or less, and a cylindrical error of ± 0.50 D or less (mean of three measurements). Secondarily, only 15 subjects were selected as having bilateral emmetropia from the primarily selected group of 259 members under the above definition. These fifteen people were used as subjects in this study. Even though the astigmatism of the 15 subjects was < 0.50 D, eight subjects showed against-the-rule astigmatism, five subjects showed with-the-rule astigmatism, and two subjects showed a mixture of against- and with-the-rule astigmatism.

Measurement

The subjects were instructed by an operator to fixate the target (having a visual angle of approximately 10°) placed at 5 m, and an instrument operator used the improved PR-1100 to take three

TABLE 2.

Two-way ANOVA on accommodative response between eyes (right: left) and meridians (horizontal: vertical)
The interaction between eyes and meridians is negligible, but the meridians show a highly significant difference between horizontal and vertical. There is no significant difference in the factor between the right eye and the left eye.

	Factors	Degree of freedom	Sum of Square	F_0	P	F(0.05)
Eyes (R:L)	0.0723	1	0.0723	0.5293	0.4699	4.0130
Meridians (H:V)	9.4010	1	9.4010	68.7931	2.542 E-11	4.0130
Interaction	0.0057	1	0.0057	0.04150	0.8393	4.0130
Error	7.6528	56	0.1367	—	—	—
Total	17.1318	59	—	—	—	—

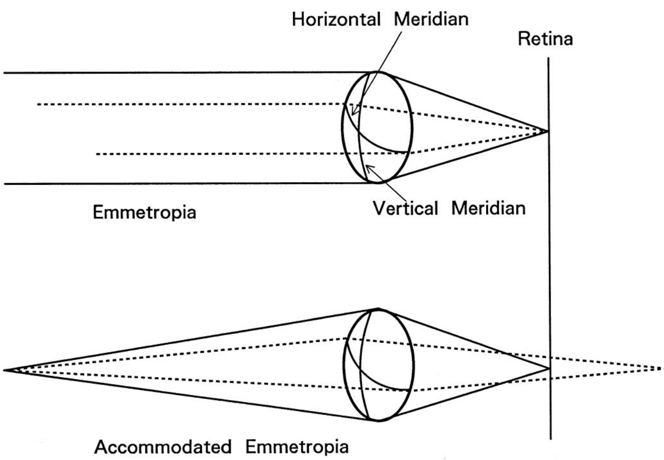

FIGURE 7.

Schematic of accommodation behavior of a majority of bilateral emmetropes.

records. Then the operator presented the new target (having the same visual angle) at 0.5m, and again the instrument operator took three records.

Simulation

Generally, accommodation accompanies convergence. Therefore, when the subjects look at the target set at 0.5 m, the subjects' visual axes are no longer aligned with the refractometer's optical axis. We simulated the effect of this alignment error using ray traces in the non-Gaussian area (not limited to the range where $\sin\theta \approx \theta$) by computer. The program was composed in Mathematica (version 3.0; Wolfram Research, Inc., Champaign, IL). The effect resulted in against-the-rule astigmatism of 0.18 D at 3-mm pupil size on the Gullstrand's schematic eye (accommodation model), assuming 60 mm between the centers of rotation of the eyes. The effect depends on pupil size. The more pupil size increases, the more against-the-rule astigmatism increases.

RESULTS

The accommodative responses, in the horizontal meridian and in the vertical meridian, are shown in Fig. 5. In the horizontal meridian, these mean values are −1.19 D (SD 0.36) and −1.10 D (SD 0.36); the maximum values are −1.83 D and −1.67 D; and the ranges are 1.33 D and 1.25 D for the right and left eyes, respectively. All of the accommodative responses in the horizontal meridian are lower than the 2.0 D accommodative stimulus. In the vertical meridian the mean accommodative response is −1.96 D (SD 0.39) in right eyes and −1.91 D (SD 0.37) in left eyes.

In the vertical meridian, accommodative responses are different from the 2.0 D accommodative stimulus. The mean deviation of the accommodative response from the accommodative stimulation is calculated by the equation:

$$\{[\Sigma(\text{accommodative response} - \text{accommodative stimulation})^2] / \text{number of subjects}\}^{1/2}$$

The calculated values are 0.38 D in right eyes and 0.37 D in left eyes. These values closely correspond to the standard deviations described above. In terms of anisometropic accommodation, there seems to be a greater amount in the horizontal meridian than in the vertical meridian.

Fig. 6 and Table 2 demonstrate the change of cylindrical power caused by accommodation. Of 15 subjects, 14 showed with-the-rule astigmatism, 10 of whom showed astigmatism over 0.5 D; their mean values are −1.08 D and −1.11 D, their minimum values are −0.92 D and −0.67 D, and the maximum values are −1.25 D and −1.42 D, in the right and left eyes, respectively. The other four subjects who had with-the-rule astigmatism showed 0.5 D or lower, and one subject showed against-the-rule astigmatism of 0.17 D. There was no subject showing anisometropia over 0.35 D in both meridians, except for one subject who showed a difference of 0.58 D in the horizontal meridians.

On relaxation of accommodation, as a matter of course, there was no marked astigmatism or anisometropia. On accommodation, most subjects showed some astigmatism as described above and no anisometropia. Concerning corneal astigmatism, all the subjects showed with-the-rule astigmatism, and the mean values were 0.84 D (SD 0.43) and 0.91 D (SD 0.34) in the right and left eyes, respectively. In this study we could not find any meaningful relation to accommodation.

DISCUSSION

Information on the interaction in both eyes on accommodation is limited, because of lack of an appropriate measuring system.[15–17] The development of an infrared optometer has made recording data possible, but detection is only on one eye and in one meridian.[7] Using the Canon R-1, all the meridians could be detected on accommodation. Furthermore, this instrument was able to present a visual fixation target in natural space.[10–12, 18, 19] We performed experiments on accommodation by using the Canon-R1 and were able to get useful impressions concerning interaction in both eyes and in meridians. However, we were not able to reach a conclusion. As far as we know, there is no instrument that simultaneously measures binocular accommodation in all meridians and in natural visual circumstances such as presenting a visual fixation target in natural space.[18–25]

The PR-1100, originally developed for infant refraction, and employing a photorefraction system, can measure both eyes and all meridians simultaneously. However, the detected records using the improved PR-1100 are only static records; to get dynamic or chronological records, further improvement will be necessary.

The results from this experiment would indicate that the majority of bilateral emmetropes exhibit with-the-rule astigmatism when accommodating (Fig. 7). The previously described simulation, demonstrating that convergence causes against-the-rule astigmatism, supports this finding, because the astigmatism is in the opposite direction.

The phenomenon of lag of accommodation was reported in 1922.[26] The subjects markedly showed the lag of accommodation only in the horizontal meridian. The cause of with-the-rule astigmatism and lag of accommodation in the horizontal meridian, when bilateral emmetropes accommodate, is unknown. The one factor may be the noncoaxial optical system of a human living eye, which is widely recognized by the existence of plural optical axes: optic axis, visual axis, fixation axis, line of sight, and pupillary axis. One subject showed a little anisometropia on accommodation. More investigation on anisometropia in connection with accommodation will be necessary.

Received September 4, 1998; final revision received November 8, 1999.

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