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Short Communication

Diffuser Contact Lenses Retard Axial Elongation in Infant Rhesus Monkeys

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In each of five monkeys, one eye was fitted with a diffuser lens at birth. This lens allowed pattern vision, but also reduced contrast by about 1 log unit. In four out of five monkeys, the treated eyes were shorter and more hyperopic than the untreated fellow eyes. At 25 weeks of age, interocular differences (OD − OS) of the experimental group were significantly greater than interocular differences of age-matched normal monkeys for both axial length ($P < 0.05$) and refractive error ($P < 0.02$). In addition, while the treated eyes were significantly different from normal eyes for both axial length measurements ($P < 0.01$) and refractive error ($P < 0.01$), there were no significant differences between the untreated fellow eyes and normal eyes. In primates less severe pattern deprivation appears to produce an effect on eye growth that is opposite to that of severe pattern deprivation (little or no pattern vision), which typically results in axial myopia.

Rhesus monkey Emmetropization Hyperopia Axial length Deprivation

The eyes of human neonates undergo an extensive period of postnatal growth before they reach adult size. At birth most neonates are hyperopic, due to the fact that the axial length of the eye is too short for the focusing power of its optics [e.g. humans (Fulton, Dobson, Salem, Mar, Petersen & Hansen, 1980); rhesus monkey (Bradley, Tigges & Boothe, 1993; Tigges, Tigges, Fernandes, Eggers & Gammon, 1990); cynolmogus monkey (Kiely, Crewther, Nathan, Brennan, Efron & Madigan, 1987); chick (Schaeffel, Glasser & Howland, 1988; Wallman, Adams & Trachtman, 1981)]. Hyperopia decreases during postnatal development, typically resulting in an eye that is emmetropic. The mechanisms regulating emmetropization are unknown. It is well documented, however, that pattern deprivation, early in development, can disrupt emmetropization. Results from a variety of species have shown that a substantial reduction of pattern vision (e.g. lid-suture, occlusion via opaque external lenses, ptosis), consistently induces excessive axial elongation and subsequent myopia [human (Hoyt, Stone, Fromer & Billson, 1981; Rabin, Van Sluyters & Malach, 1981); macaque (Criswell & Goss, 1983; Greene & Guyton, 1986; Raviola & Wiesel, 1985; Smith, Harwerth, Crawford & von Noorden, 1987; Tigges *et al.*, 1990); tree shrew (McBrien & Norton, 1992); chick (Hodos & Kuenzel, 1984; Troilo, Gottlieb & Wallman, 1987; Wallman, Turkel & Trachtman, 1978; Wildsoet, Howland, Falconer & Dick, 1993) [for exceptions see von Noorden and Lewis (1987) for clinical studies and Smith *et al.* (1987) for animal studies].

The results of several recent studies suggest that it is not pattern deprivation *per se* that induces axial myopia, but instead, it may be that only severe pattern deprivation produces this type of perturbation. That is, studies of chicks and non-human primates reared with comparatively less severe pattern deprivation (achieved by optical defocus, aphakia, or diffusion) have shown that the treated eyes become shorter and more hyperopic than their untreated fellow eyes (Crewther, Nathan, Kiely, Brennan & Crewther, 1988; Kiorpes & Wallman, 1995; O'Leary, Chung & Othman, 1992; Schaeffel, Troilo, Wallman & Howland, 1990; Smith, Hung & Harwerth, 1994; Wilson, Fernandes, Chandler, Tigges, Boothe & Gammon, 1987). In addition, the axial elongation of chick eyes has been shown to proceed in a manner that compensates appropriately for the sign of the experimentally imposed refractive error (e.g. Schaeffel *et al.*, 1990). Finally, Bartmann and Schaeffel (1994) have shown that progressive increases in the reduction of contrast in the retinal image can produce corresponding progressive increases in the axial elongation of chick

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eyes. Taken together, it is reasonable to propose that the type of perturbation of postnatal eye growth (i.e. accelerated axial elongation vs retarded axial elongation), may vary as a function of the quality of the retinal image generated by the particular method of pattern deprivation. That is, the mechanisms that regulate eye growth may utilize some components of the retinal image, and attempt to "correct" axial elongation to achieve emmetropia. In the carefully studied chick, there is increasing evidence to support the existence of a such a regulatory mechanism, which has the ability to adjust the rate and extent of axial elongation in response to changes in the amount of contrast within the retinal image. For the primate, however, while there is abundant documentation that severe pattern deprivation (little or no pattern vision) induces excessive eye growth, the effects of less severe pattern deprivation have yet to be established unequivocally. Although aphakic eyes consistently exhibit axial hyperopia (Tigges *et al.*, 1990; Wilson *et al.*, 1987), retinal blur produced by negative power lenses, positive power lenses, or chronic atropine administration can result in treated eyes that exhibit relative hyperopia, relative myopia, or emmetropia (Crewther *et al.*, 1988; Kiorpes, Boothe, Hendrickson, Movshon, Eggers & Gizzi, 1987; Smith, Harwerth & Crawford, 1985; Smith *et al.*, 1994).

The purpose of the present study was to examine the effects of a different type of less severe pattern deprivation on postnatal eye growth in rhesus monkeys. This was achieved by rearing newborn monkeys with a contact lens that acts as a translucent diffuser. The optical properties of this lens allow patterned input to reach the retina, but the diffuser lens also scatters light from throughout the visual field, thereby superimposing a mask of "noise" on the patterned input that reduces contrast equally across all spatial frequencies.

METHODS

In each of five rhesus monkeys (*Macaca mulatta*), a diffuser contact lens was placed on the right eye within a few hours after birth. The home cage room was on an 8 hr light–16 hr dark schedule. Monkeys were checked every 2 hr during daylight hours, and a missing lens was replaced immediately. Lens wear compliance throughout the rearing period was excellent for all five monkeys. On average, lenses remained in the eyes 97.3% of the time; poorest compliance was 96.2%. Monkeys were housed in individual cages. For several hours each week the monkeys were allowed to engage in rough-and-tumble play within a social group, which required them to use their vision across a range of distances.

Daily wear diffuser contact lenses, with parameters appropriate for monkey eyes, were manufactured in our own contact lens laboratory (Fernandes, Tigges, Tigges, Gammon & Chandler, 1988; Gammon, Boothe, Chandler, Tigges & Wilson, 1985). Diffuser lenses were inserted at the beginning of the light cycle. The fit of the contact lenses was monitored regularly, and lenses of increasing diameter and decreasing steepness were fitted as the eyes grew. The low oxygen permeability of the diffuser lens material was sufficient for daily wear but not for extended wear. For this reason, the diffuser lenses were removed at the start of the dark cycle. On the basis of previous experience rearing monkeys with contact lenses, we were concerned that compliance with lens wear during the daytime would be disrupted if the eyes did not have a contact lens in place overnight. Therefore, during the dark cycle, the monkeys wore an extended wear opaque occluder lens in the right eye, which allowed sufficient oxygen to maintain the cornea in good physiological condition.

To evaluate the effects of the diffuser lens, a human observer (one of the authors) performed a monocular simultaneous discrimination between a sinusoidal grating field and an isoluminant blank field. Psychophysical tests were conducted at three spatial frequencies while the observer performed the discrimination task with, and without, a diffuser contact lens on one eye; the fellow eye was occluded. The observer adjusted contrast to threshold for low (1.45 c/deg), medium (5.78 c/deg), and high (23.0 c/deg) spatial frequency gratings. When viewed through the diffuser lens, contrast sensitivity was reduced by about 1 log unit at each of the three spatial frequencies.

Ophthalmic examinations, performed by a pediatric ophthalmologist (AF), occurred under general anesthesia (ketamine 10 mg/kg, acepromazine 90 mg/kg) and included the following: cycloplegic (3 drops of 1% cyclopentolate, 3 drops of 2.5% phenylephrine, at 5 min intervals) refraction by retinoscopy, biomicroscopy, A-scan ultrasonography, keratometry, applanation tonometry, pupil and corneal diameter measurements, and fundus examination. The diffuser lens was removed for the duration of the examination (typically less than 30 min). The initial ophthalmic examinations for the experimental group occurred within the first postnatal month (mean = 1.4 weeks). Thereafter, examinations occurred approximately every 5–7 weeks. Axial length measurements are reported in mm and are the mean of 10 consecutive ultrasound measurements. Refractive errors are reported as the spherical equivalent in diopters (D). Keratometry measurements are reported in D and are the mean of three horizontal and three vertical measurements.

Each fellow untreated eye served as an interocular control for the effects of the diffuser lens on axial length, refractive error, and corneal curvature. In addition, the results for both eyes of the experimental monkeys were also compared to ocular data of five normal monkeys at the same postnatal developmental period (25 ± 6 weeks of age), drawn at random from a population of normal monkeys. The normal monkeys were housed in the same room with the experimental monkeys, and were reared with identical social play experiences and light–dark schedule. Statistical analyses (Student's *t*-test) were conducted on measurements of axial length, refractive error, and corneal curvature between the following data: (i) interocular differences (OD − OS) of the experimental

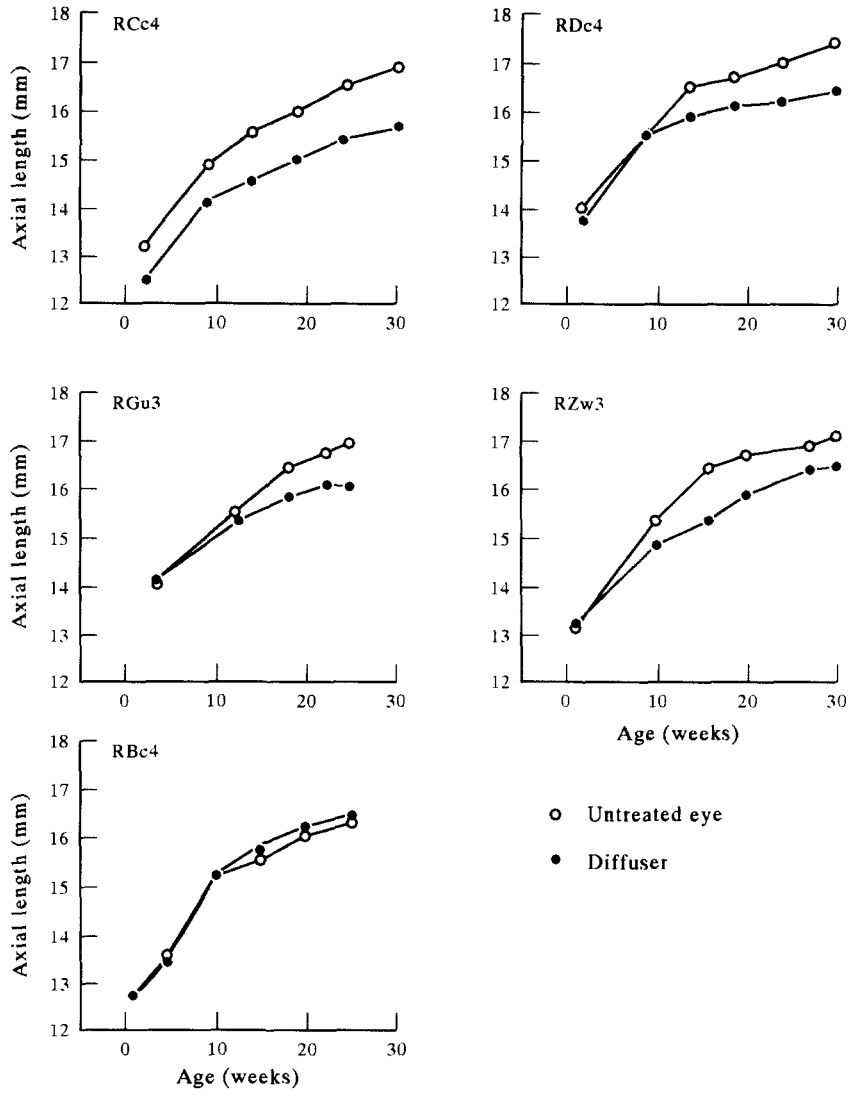

FIGURE 1. Longitudinal measurements of axial length (mm) of each monkey reared with a diffuser contact lens on one eye (●), compared with the untreated fellow eye (○) as a function of age. Monkeys differed in the age at which the initial measurements were taken (RCc4, 2.1 weeks; RDc4, 1.3 weeks; RGu3, 3.1 weeks; RZw3, 0.3 weeks; RBc4, 0.4 weeks). While both eyes of each monkey grew throughout the rearing period, with one exception (RBc4), the eyes fitted with a diffuser lens grew at a slower rate, becoming shorter than the untreated fellow eyes.

group and interocular differences (OD − OS) of the normal monkeys; (ii) absolute measurements of treated eyes (OD) and normal eyes (OD); and (iii) absolute measurements of untreated eyes (OS) and normal eyes (OS). All research protocols and the procedures associated with the care and handling of our monkeys conformed to NIH guidelines as outlined in their *Guide for the care and use of laboratory animals.* The Yerkes Regional Primate Research Center (YRPRC) is fully accredited by the American Association for Accreditation of Laboratory Animal Care (AAALAC).

RESULTS

Figure 1 shows axial length measurements as a function of age of the treated and untreated eyes of each monkey. As shown in Fig. 1, with one exception (RBc4), the eyes fitted with a diffuser lens (●) exhibited a retardation in the rate of axial elongation relative to the untreated fellow eyes (○). Table 1 shows the results of the main ophthalmic measurements of the five experimental monkeys (top) and the five age-matched normal monkeys (bottom) at approx. 25 weeks of age. As shown in the first column, with one exception (RBc4), each eye fitted with a diffuser lens (OD) was substantially shorter than its untreated fellow eye (OS). The range of axial length measurements of the treated eyes (OD: 15.7–16.4 mm) was below that of the untreated eyes (OS: 16.3–17.4 mm), and significantly different from the eyes of normal monkeys (OD: 16.4–17.1 mm) ($P < 0.01$). The range of axial length measurements for the untreated eyes (OS: 16.3–17.4 mm) was not significantly different from normal monkeys (OS: 16.5–17.1 mm), indicating that the untreated eyes grew normally. Interocular comparisons of the difference (OD − OS) in axial length measurements between the two eyes of monkeys reared with diffuser lenses (mean = −0.66 mm) was significantly greater than the difference in axial length measurements

TABLE 1. Ocular measurements at 25 weeks of age of monkeys fitted with a diffuser contact lens (OD) at birth, compared with age-matched normal monkeys

	Axial length (mm)			Refractive error (D)			Corneal curvature (D)		
Monkey	OD*	OS§	OD−OS‡	OD*	OS§	OD−OS†	OD§	OS§	OD−OS§
Experimental group									
RBc4	16.4	16.3	0.10	5.50	5.00	0.50	50.30	51.70	−1.40
RCc4	15.7	16.9	−1.20	5.50	1.50	4.00	52.15	52.95	−0.80
RDc4	16.4	17.4	−1.00	10.0	2.50	7.50	48.35	50.60	−2.25
RGu3	16.0	16.7	−0.70	7.00	3.00	4.00	53.45	53.85	−0.40
RZw3	16.3	16.8	−0.50	7.00	4.75	2.25	53.00	52.95	0.05
Mean	16.2	16.8	−0.66	7.00	3.35	3.65	51.45	52.41	−0.96
Normal group									
RAb4	17.1	17.1	0	2.00	1.75	0.25	51.90	52.00	−0.10
REc4	16.6	16.6	0	2.50	2.25	0.25	53.75	54.10	−0.35
RQb4	16.9	17.1	−0.20	2.00	2.25	−0.25	52.60	52.55	0.05
RVl4	16.4	16.5	−0.10	0.50	0.50	0	52.55	54.10	−1.55
RZh4	17.0	17.0	0	2.50	2.50	0	53.75	53.95	−0.20
Mean	16.8	16.9	−0.06	1.90	1.85	0.05	52.91	53.34	−0.43

Student's t-test: *$P < 0.01$; †$P < 0.02$; ‡$P < 0.05$; §no statistically significant difference.

between the two eyes of normal monkeys (mean = −0.06 mm), $t(8) = 2.63$, $P < 0.05$. Examination of ultrasound echograms revealed that the locus of the interocular differences in axial eye elongation was the vitreous chamber. While the anterior chamber of the treated and untreated eyes was similar in depth, the vitreous chamber of the eyes fitted with a diffuser lens was shorter than that of the fellow untreated eyes. Measurements of intraocular pressure of the treated and untreated eyes were nearly identical for each monkey, at each examination. All other ocular findings were also unremarkable.

Four out of five monkeys in the experimental group exhibited a pronounced anisometropia following 25 weeks of monocular deprivation, with the treated eyes more hyperopic than the untreated fellow eyes. Interocular comparisons (OD − OS) showed that the difference in refractive error between the two eyes of monkeys fitted with a diffuser lens (mean = 3.65 D) was significantly greater than the difference in refractive error of the two eyes of normal monkeys (mean = 0.05 D), $t(8) = 3.09$, $P < 0.02$. There was little overlap between the range of refractive errors for the treated eyes (OD: 5.50–10.00 D) with that of the untreated fellow eyes (OS: 1.50–5.50 D), and the treated eyes were significantly more hyperopic than normal eyes (range OD: 0.50–2.50 D) ($P < 0.01$). There was no significant difference between the untreated fellow eyes (range OS: 1.50–5.50 D) and normal eyes (range OS: 0.50–2.50 D), indicating that the reduction in neonatal hyperopic refractive error was proceeding normally for the untreated fellow eyes.

Unlike the pronounced effect on axial elongation and refractive error, there appeared to be no effect of 25 weeks of lens wear on the curvature of the cornea of the treated eyes. There was no significant difference between the interocular (OD − OS) corneal curvature differences of monkeys fitted with a diffuser lens (mean = −0.96 D) and interocular differences (OD − OS) of normal monkeys (mean = −0.43 D), $t(8) = 1.07$, $P = 0.31$. Likewise, there was no significant difference between the absolute values for corneal curvature of the treated eyes (range OD: 48.35–53.45 D) and normal eyes (range OD: 51.90–53.75 D), nor between the untreated eyes (range OS: 51.70–53.85 D) and normal eyes (range OS: 52.00–54.10 D).

DISCUSSION

The present results show that in four out of five rhesus monkeys reared from birth with a diffuser contact lens, the eye fitted with the diffuser lens exhibited a pronounced retardation in axial elongation, as well as a marked relative hyperopia. While interocular differences (OD − OS) of both axial length and refractive error of the experimental monkeys were statistically significantly greater than interocular differences of age-matched normal monkeys, there was no significant difference in the interocular differences of corneal curvature, or the absolute values of corneal curvature, between experimental and normal monkeys. Thus, the relative hyperopia does not appear to be the result of mechanical effects of the diffuser contact lens on the curvature of the cornea. Instead, the results indicate that the relative hyperopia of the eyes fitted with a diffuser lens is due to the shorter length of the treated eyes, specifically, a shorter vitreous chamber depth. No differences were found on any of our other ocular measurements (e.g. intraocular pressure) between treated eyes and untreated fellow eyes. Finally, while the treated eyes were significantly different from age-matched normal eyes for absolute measurements of axial length and refractive error, there were no significant differences between the untreated fellow eyes and the eyes of normal monkeys. We conclude that the relative axial hyperopia observed for the treated eyes is a direct effect of some quality of the less severe pattern deprivation produced by the diffuser lens.

The present results are in good agreement with a

previous study in which 12 cynolmogous monkeys (*Macaca fascicularis*) were reared with a white diffusing contact lens on one eye; this lens reduced contrast by about 24 dB across all spatial frequencies (O'Leary *et al.*, 1992). With the exception of one monkey, the eyes fitted with a white diffusing lens were more hyperopic than the untreated fellow eyes. The present results also agree qualitatively with those from studies of young monkeys reared with optical defocus from contact lenses (Crewther *et al.*, 1988; Smith *et al.*, 1994), which have shown that such deprivation can produce axial hyperopia much of the time (the latter study produced hyperopia in 5 out of 8 rhesus monkeys, the former in 4 out of 9 cynomolgus monkeys). Finally, the present results also agree with previous results from our laboratory, in that rhesus monkeys rendered aphakic early in postnatal development also exhibit pronounced relative hyperopia (Bradley *et al.*, 1993; Tigges *et al.*, 1990; Wilson *et al.*, 1987). Taken together, these studies, from different species, suggest that when the primate eye receives some patterned input with a reduction in image contrast, eye growth is retarded. On the other hand, methods of deprivation that eliminate patterned input (e.g. lid-suture or occlusion) must then serve either as a signal to accelerate growth, or more likely, fail to provide any signal to slow eye growth.

There are, however, several interesting differences between the results obtained from studies using optical defocus and the present study. First, while both of the studies using mild defocus (Crewther *et al.*, 1988; Smith *et al.*, 1994) obtained one or more monkeys with a relative myopia, the present study did not. Second, the interocular differences (OD − OS) between the treated and untreated eyes in the present study were larger than that following monocular optical defocus for both axial length and refractive error (cf. Crewther *et al.*, 1988; Smith *et al.*, 1994).

There are several possible explanations for these differences. First, defocus degrades primarily high spatial frequencies, whereas our rearing condition degrades all spatial frequencies equally. Second, the present study began lens wear within a few hours of birth, with only a brief opportunity for normal binocular exposure, while the optical defocus studies began lens wear several weeks after birth [4 weeks for Smith *et al.* (1994); 7–46 weeks for Crewther *et al.* (1988)]. Given that the period of postnatal plasticity is brief (< 52 weeks), it would be expected that pattern deprivation at birth would result in greater perturbation than would pattern deprivation that was initiated later in the postnatal developmental period. Third, monkeys in the present study wore lenses for a longer period of time [cf. 9–19 weeks (Smith *et al.*, 1994)], and with no interruptions (cf. Crewther *et al.*, 1988). In fact, Smith *et al.* (1994) showed that longer periods of defocus produced a greater retardation of axial elongation compared with shorter periods of defocus.

To conclude, increasing evidence indicates that during the process of postnatal emmetropization, the primate eye appears to be able to respond differentially to severe pattern deprivation (axial myopia) compared to less severe pattern deprivation that allows some pattern vision, but also reduces contrast in the retinal image (axial hyperopia). As has been suggested for the chick, the regulatory mechanisms for postnatal eye growth in the primate may also utilize some qualitative aspects of the retinal image to either accelerate or retard axial elongation.

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