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Surgical Intervention and Accommodative Responses II. Forward Ciliary Body Accommodative Movement is Facilitated by Zonular Attachments to the Lens Capsule

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Abstract

Purpose—To determine the role of the lens and the lens capsule in the three-dimensional architecture of the ciliary muscle at rest and during accommodation, in live rhesus monkeys and in histological sections, by removing the entire lens, or only the lens nucleus and cortex, while leaving the posterior capsule in place.

Methods—In 15 rhesus monkey eyes, aged 6–27 yr, accommodation was induced by central stimulation of the Edinger-Westphal (E-W) nucleus before and after intra- or extracapsular lens extraction (ICLE, ECLE). Forward ciliary body movement and ciliary body width were measured by ultrasound biomicroscopy (UBM, 50MHz). The monkeys were then sacrificed, the eyes were examined morphologically in 1 micron sections, and the shape of the ciliary muscle was compared with that obtained from UBM images.

Results—The shape of the ciliary muscle in eyes undergoing ECLE (n=5) did not differ from controls. In contrast, following ICLE (n=10), accommodative forward ciliary body movement ($p<0.01$) and thickness was decreased ($p<0.001$), length was increased ($p=0.058$), and the inner apex was located more posteriorly than in controls ($p<0.005$). Histological and *in vivo* data were similar and showed that the ciliary muscle maintained its triangular shape only if the lens capsule (with or without the lens substance) was present.

Conclusion—The posterior lens capsule and anterior zonular attachments facilitate forward accommodative ciliary body movement. Lens substance extraction procedures that leave the posterior capsule intact, similar to those used clinically, do not affect the capsule/zonular/muscular system movements, an important finding for accommodating intraocular lens development.

Introduction

According to Helmholtz,¹ accommodation is induced by the ciliary muscle moving forward and inward, releasing tension on the zonula and allowing the lens equator to move away from the sclera.¹ Rohen showed that the zonula consists of two major systems. The posterior zonula covers the pars plana epithelium and runs straight forward from the region of the ora serrata

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toward the ciliary valleys, where it is attached and intermingles with the anterior zonula in the area of the zonular plexus. From there, the anterior zonula, comprising the posterior and anterior zonular tines, courses directly to the posterior and anterior aspects of the equatorial lens capsule.⁴ Rohen theorized that during accommodative anterior-inward movement of the ciliary muscle, and thereby of the zonular plexus, the tension is mainly taken over by the posterior zonula, while the anterior zonula relaxes.⁴ Due to the elasticity of the lens capsule, the lens can achieve a rounded shape. The lens equatorial diameter decreases, and the lens anterior-posterior thickness increases.^{1, 5-8}

To study human accommodation and presbyopia, the best animal model has proven to be the rhesus monkey. Its accommodative apparatus and mechanism are very similar to that of the human,⁹⁻¹¹ whereas subprimate species either do not accommodate or accommodate by mechanisms very different from that of humans. Also, rhesus accommodation declines on an essentially identical relative time scale to that of humans.¹² Surgical procedures that facilitate the study of accommodation and presbyopia (such as total iridectomy and lens extraction) can readily be performed on rhesus monkeys. Several high-resolution contact imaging techniques, superior in resolution and magnification to the magnetic resonance imaging (MRI) techniques reported elsewhere,^{13, 14} can be performed during accommodation in anesthetized monkeys but are not possible in humans.^{3, 6, 15-17} High-resolution imaging of the dynamic accommodative movements in the normal primate eye and following surgical intervention to perturb the accommodative apparatus is needed to determine normal accommodative function and its change with age.

We have reported studies of centripetal ciliary process movement by using goniovideography methods, [IOVS # 0001] but both centripetal and *forward* movements of the ciliary muscle are required for accommodation. Thus, we investigated the forward ciliary muscle/body movements in the same animals using ultrasound biomicroscopic (UBM) imaging, and determined the role of the lens capsule and lens substance in ciliary body configuration and forward movement during accommodation through surgical intervention in pre-presbyopic and presbyopic rhesus monkeys. Since the resolution of UBM images have limitations, the morphology and shape of the muscle, encompassing its entire circumference, were also investigated histologically in the same monkey eyes.

Materials and Methods

The *in vivo* data were collected during UBM (50MHz) imaging, using the same equipment, animals, animal handling procedures, stimulus settings, and experimental time window reported in Croft et al. [IOVS# 0001]

Monkeys

Fourteen rhesus monkeys (*Macaca mulatta*) of either sex, ages 6-27 yr and weighing 5.7-14.8 kg, with normal eyes were studied. The monkeys were bilaterally iridectomized and a bipolar electrode was placed in the Edinger-Westphal nucleus to stimulate accommodation.^{3, 18} Baseline measurements of the normal accommodative response in both eyes of each animal were taken before the lens surgical procedures were performed, thus providing ipsilateral and contralateral control eye data for each eye.

Based on the time course of presbyopia in rhesus monkeys and humans, the animals were grouped according to age as follows: Young = 6-13 yr; Older = 17-26 yr (respectively equivalent to humans aged ~ 15-30 years and 45-65 years old). Additional subgroups were identified according to the surgical procedures used (see below).

Surgical Procedures

Intracapsular lens extraction (ICLE: removal of the lens nucleus, cortex and capsule) and extracapsular lens extraction (ECLE: ~4 mm anterior capsulorhexis, removal of the lens nucleus and cortex) surgery procedures were performed as described elsewhere. [IOVS# 0001] The surgery procedures were assigned to the 15 eyes of the 14 study monkeys as follows:

Seven monkeys (3 young; 4 older) each provided one eye for surgical intervention (ICLE, n=5; ECLE, n=2); the opposite eye was iridectomized but otherwise surgically untouched and served as a contralateral control eye for morphological examination. Two of these monkeys (older ICLE, n=1; older ECLE, n=1) did not undergo UBM imaging but the eyes did undergo measurements of the ciliary muscle during morphological examination.

One additional young monkey also received unilateral ICLE (Wieger's ligament remained intact) but was not euthanized and was retained for another study.

Another older monkey contributed 1 eye to the ICLE group and the opposite eye to the ECLE group. Surgery in this monkey's second eye was allowed by the veterinary staff of our institution and the Institutional Animal Care and Use Committee, since the surgery was carried out at a separate time point from the first eye and cognitive behavior was observed by laboratory personnel and veterinary staff to ensure that the animal was functioning normally before and after surgery. If signs of visual or other distress had been observed, the animal would have been euthanized. However, no overt signs of distress were noted in any animal.

In the 5 other monkeys (n=3 young; n=2 older), surgical procedures were performed in one eye (ICLE, n=3; ECLE, n=2). However, the post-surgical clinical examination of these 5 eyes uncovered surgical or technical complications: ciliary body degeneration (n=2, ICLE); severing of the posterior zonular attachments (n=1, ICLE); perforation of the posterior capsule, capsular fibrosis and lens cell regrowth with pronounced presence of pearls and Soemmering's ring (n=2, ECLE). These complications likely would have impacted the accommodative apparatus in ways not intended by the surgery, which was designed to disrupt a specific part of the accommodative apparatus. Therefore the decision was made, before post-surgical imaging, not to include post-surgical imaging data for these 5 eyes in the study. Subsequently, in each of these 5 monkeys the contralateral eye also underwent surgery (ICLE, n=3; ECLE, n=2). These eyes were free of post-surgical complications, based on clinical examination, and the post-surgical imaging of these eyes was completed according to protocol. Again, cognitive behavior was observed for overt signs of distress following surgery in the second eye. However, the animals' function in their cage environment appeared normal. For the older animals, the loss in accommodative ability (through either ECLE or ICLE) is not really a change since most, if not all, of their ability to accommodate has already been lost. For the younger animals, this meant an adjustment to the presbyopic condition at an earlier age. In either situation (young or older animals), the visual space is restricted when looking around the room. The strategy of using the second eye in these monkeys under the careful constraints indicated was utilized to avoid major intracranial surgery in additional monkeys. All of the eyes underwent morphological examination with the exception of the monkey that was retained for further study and not euthanized (see above).

In total, 15 eyes from 14 monkeys were included: for ICLE (n=10 monkey eyes; 5 young, 5 older); and for ECLE (n=5 monkey eyes; 2 young, 3 older).

Accommodation Stimulation and Response Measurements

Refractometry—Accommodation was induced by midbrain electrical stimulation and measured by Hartinger coincidence refractometry as described elsewhere.³ Stimulus settings were chosen that induced maximum accommodative responses (i.e., maximum centripetal

ciliary process and lens/capsule movement, maximum forward ciliary body movement) and maximum accommodation, allowing comparisons to be made between pre- and post-surgical accommodative responses.

Ultrasound Biomicroscopy (UBM)—Dynamic UBM images were obtained during stimulation of accommodation and then recorded to videotape.³ Pre- and post-surgery UBM imaging was performed in the same region of the eye temporally, encompassing ~25% of the entire circumference. The temporal region was selected because this region provides the best and most distinct ultrasound imagery, with clear and distinct edges of the ciliary body and cornea. The post-surgery imaging sessions were carried out 2.5 weeks to 3 months after surgery. Twelve of the animals were imaged within 1 month of surgery. Six of these animals were imaged within 2.5 weeks, as the eyes were completely healed and the cornea and anterior chamber were clear. The remaining eyes required additional time for issues to resolve, such as corneal edema, anterior chamber cells, and flare, etc. Care was taken to be sure that the eyes were in a completely recovered and healthy state, to ensure that accommodative responses during stimulation, image clarity, and image contrast would be optimal.

A 50 MHz UBM instrument (Model # 840, Humphrey Instruments, San Leandro, CA) was used to image the lens edge, zonula, and ciliary body of the eye at rest and during accommodation,^{15, 17} allowing measurement of the resting ciliary body apex width, and accommodative forward movement.³ The eye was stabilized with extraocular muscle sutures during UBM imaging, so that during accommodation there was minimal convergence eye movement, if any. The stabilizing arm of the ultrasound instrument held the transducer in place. Thus, there was very little if any change in angle of the transducer to the eye during accommodation.

Using the UBM images, measurements were taken of the angle between the anterior aspect of the ciliary body and the inner aspect of the cornea (CB-Cornea angle) in the unaccommodated (resting) eye and during supramaximal stimulation, with the change in angle (narrowing) serving as a surrogate indicator of forward ciliary body movement (since the sides of the angle are better defined than the anterior insertion, and it is more difficult to outline muscle tissue by UBM).¹⁵ The width of the ciliary body apex was also measured from UBM images, analogous to those taken from histological sections by Tamm et al (1992).² For each group, the mean $\pm$ s.e.m. width of the resting ciliary body apex, CB-Cornea angle, and forward ciliary body movement were calculated. We did not measure ciliary muscle length by UBM, since we did not view the posterior extent of the ciliary muscle in the image and did not wish to extrapolate.

Histology

The monkeys were sacrificed and the eyes were fixed for morphological examination: immediately (n=1); 1 month (n=2); 3 months (n=3); 5 months (n=1); 6 months (n=1); 8 months (n=1); 16 months (n=1); 3 years (n=2); and 5 and 6 years (n=2) after post-surgical imaging.

The animals were perfusion-fixed through the heart with 4% paraformaldehyde, after perfusion with one liter of 0.1 molar PBS (phosphate-buffered saline). After enucleation, slits were cut in the posterior sclera and a window cut in the anterior cornea to enhance fixative penetration and preserve the architecture of the ciliary muscle and its posterior attachment to Bruch's membrane. The eyes were then immersed in Ito's fixative¹⁹ until they were sent to Erlangen for morphological investigation. None of the eyes were exposed to pharmacological stimulation before or during fixation. Small sectors of the anterior globe, including the entire ciliary body and adjacent cornea and sclera, were embedded in Epon, and 1 μ m semi-thin sections were cut and stained with Richardson's stain.²⁰ In semi-thin sections from the different quadrants encompassing the entire circumference of the eye, the width, length and apical

position of the ciliary muscle (Fig. 1) were determined in 6 control eyes and 6 surgery eyes (n=4, ICLE; n=2, ECLE) of 6 adult monkeys following random selection. The opposite eye of each monkey served as control. The apical position is defined as the distance between the scleral spur and the mid-region of the ciliary muscle apex. Quantitative evaluation of the width and apical position relative to the scleral spur was performed using a Leica Q Win program adapted to a Leica microscope (Leica, Wetzlar, Germany).²

A two-tailed paired t-test was used to detect significant differences. A p-value ≤ 0.05 was considered significant; $0.05 \leq p \leq 0.10$ was considered to indicate a trend, given the small number of monkeys.

All procedures conformed to the ARVO Statement for the Use of Animals in Research and were in accordance with institutionally approved animal protocols.

Results

Baseline Data/Technical Comparison

The three-dimensional structure of the ciliary muscle and the morphology of the muscle fibers were not affected by the surgical procedures. The same was true for the trabecular meshwork, indicating that valid results and conclusions can be obtained from this material. Even after ICLE, the posterior zonula appeared normal; only the anterior zonula was clumped, as expected [IOVS #0001]. Comparing histology with UBM showed similar absolute biometrics of the various ciliary muscle parameters and little variation around the circumference within individual eyes (histology) or between eyes (UBM) (Fig. 2, Table 2, 3).

UBM (Table 2) confirms previous UBM findings³ and earlier histological findings that forward ciliary body movement diminishes significantly with age but is never completely lost, even in the oldest animals (e.g., 27 yr in this series, comparable to about 65-70 yr in humans).² Resting ciliary muscle width, corresponding to the histological specimens, showed no age-related differences, analogous to earlier histologic findings in atropinized rhesus eyes.²¹

Surgical Results

There was no difference in ciliary muscle width (mm), forward ciliary body movement, or apical position between post-ECLE vs. ipsilateral control baseline (Fig. 2; Table 2, 3) or contralateral control (iridectomized-only control group; Table 2). There were no differences in any parameter by either technique between ECLE and controls, as defined above.

Following ICLE, there were significant differences in shape of the resting ciliary body between experimental and control eyes (Fig. 2). By UBM, the ciliary muscle at rest was thinner (length not measured; see Methods), and the apex appeared to be positioned more posteriorly compared to ipsilateral control baseline or contralateral control eyes (Table 2, Fig. 3). Further, there was a 50% loss in accommodative forward ciliary body movement following ICLE compared to the ipsilateral (pre-treated) or contralateral control (untreated) eyes (Fig. 3, Table 2, and see Video Clip), with no change in ciliary body width or accommodative forward movement in the contralateral untreated control eyes (Table 2). This loss of movement was seen in both the young and older eyes, even if the absolute width of the muscle and the forward movement differed (Table 2). By histology, following ICLE, the ciliary muscle was thinner and longer (i.e., extended further posteriorly), and the inner apex was located more posteriorly than in the controls (Table 3). The inner edge of the ciliary muscle was absent, but the circularly running fibers formed a band-like structure (Fig. 4) along the muscle portion facing the pars plicata of the ciliary processes stopping posteriorly at the transition zone between the pars plicata and the pars plana.

The pre- vs. post-surgery changes in accommodative responses (UBM) were not dependent upon the time lapse between surgery and post-surgical imaging. Further, the morphological differences between the control eyes and the surgically treated eyes were not dependent upon the time lapse between surgery and morphological examination.

Discussion

Anterior capsulorrhexis and removal of the lens substance did not affect either the static geometry or the functional response of the ciliary muscle to central stimulation, so long as the posterior capsule remained. Removal of the entire lens and capsule caused changes in resting ciliary body geometry and a loss of forward ciliary body movement upon central stimulation. The effect of leaving the posterior capsule in place but compromising its structural integrity remains unknown. Despite the large corneal incision and frequent vitreous loss with ICLE, the muscle retained a normal histopathologic appearance (i.e., healthy muscle fibers, no degeneration or connective tissue infiltration, normal anterior and posterior tendinous connections), as was true for the ECLE eyes. In both operations, the posterior zonula covering the pars plana appeared normal. Following ICLE only, the anterior zonula, disconnected from the lens, appeared clumped together adjacent to the ciliary processes.[IOVS 0001] The loss of forward/inward “pull” from the anterior zonula may explain the thinner and more posteriorly positioned muscle after ICLE. Thus, in normal eyes, the presence of the lens and anterior zonula contribute to normal ciliary body configuration.

The ciliary muscle structural findings were similar by two different techniques, one postmortem and one *in vivo*. The width of the ciliary body apex in the phakic eyes (0.79 ± 0.03 mm; Table 2) was nearly identical to that reported by Tamm et al (1992),² measured histologically (i.e., 0.74 mm in atropinized sections, prepared in the same way but without surgical interventions).² This gives confidence that our biological conclusions are accurate, that the techniques are predictive for each other, and that the parameters under study do not change after death, enucleation, fixation, sectioning, staining, etc. This is important for studying scarce nonhuman primates and of course for clinical studies in humans.

We used the accommodative ciliary body-corneal angle change as a surrogate marker for forward ciliary muscle movement³ rather than the vector change in the ciliary body center of mass. Indeed, the angle is quite distinct, thus dampening variability of the data, and no more subjective than determining the center of mass. Additionally, since the zonula attach to the walls of the ciliary processes (internal periphery ciliary body), the change in angle may be a more important indicator of ciliary body forward movement, accommodative mechanism, and accommodative amplitude. Further, during UBM imaging, the stabilization arm held the transducer in place and the anterior and posterior ends of the ciliary body were oriented in a horizontal direction within all images to ensure stability and reproducibility. The eye was also stabilized with extraocular muscle sutures during UBM imaging, so that during accommodation there was minimal convergence eye movement, thus eliminating change in the angle of the transducer to the eye during accommodation. Nonetheless, choosing the center of mass and its vector may provide a separate and distinct piece of information and could be undertaken in a subsequent study, but this was beyond the scope of this paper.

In our previous study (Tamm et al. 1992)² by histologic examination of the ciliary muscle apical position in pilocarpinized sections, in the older vs. the young rhesus eyes, we reported an ~80% loss in accommodative forward positioning of the ciliary muscle. The present study showed ~50% loss in the older vs. the young monkeys by UBM during central electrical stimulation. The 30% difference in the age-related loss of forward ciliary body movement between the eyes undergoing accommodation induced by cholinomimetic drugs vs. the eyes

undergoing central electrical stimulation most likely reflects that pharmacological stimulation is a more potent inducer of accommodation.¹⁸

Using both UBM and histological methods, forward ciliary body movement decreased with age, but some mobility was maintained even in the oldest eyes. While removal of the lens substance increased centripetal ciliary body movement [IOVS 0001], it neither increased nor decreased forward ciliary body movement. This suggests that the older lens substance does not play a role in the age-related loss of forward ciliary body movement. On the other hand, the fact that there was a loss in forward accommodative movement of the ciliary body post-ICLE but not post-ECLE suggests that the zonular/capsular attachments, and not the lens substance, facilitate forward accommodative movement of the ciliary body.

The design and properties of putatively accommodating intraocular lenses (IOLs) must take into account the decreased mobility of the driving system. However, recall findings from another study [IOVS# 0001] showed that centripetal ciliary body movement increased after ECLE even in old eyes and could contribute to accommodation in the presence of an appropriately designed IOL.

There was uniformity of the measurements within the circumference of and between eyes, which demonstrated both the precision of the techniques and the small biological variance of the parameters. If humans are similar to monkeys, this replication would be important for sample sizes and repetitive measurements in clinical trials. In addition, this uniformity of the data indicates that day-to-day variations in experimental technique, tissue processing, data analysis, and animal biological factors are small in terms of the parameters being measured; i.e., the signal-to-noise ratio may be high. Day-to-day variability in experimentally induced accommodative responses cannot account for all of the findings: 1) In the resting eye, the ciliary body apex width was thinner in all monkeys post-ICLE versus pre-ICLE, regardless of age; 2) Accommodative forward movement was lost following ICLE in 7 out of 8 monkeys. These post-surgical accommodative movement responses occurred consistently from monkey eye to monkey eye in spite of the complex nature of the surgical procedures and the varied time periods between pre- and post-surgical measurements.

Forward ciliary body movement was not reduced after ECLE, and there was increased centripetal ciliary body accommodative movement following ECLE and ICLE in which Wieger's ligament remained intact.[IOVS #0001] Collectively, these findings alleviate concern that these surgical procedures caused intraocular scarring that would likely diminish accommodative movements.

The results of this study provide new insights into accommodative ciliary body function. In summary: 1) Following ICLE, UBM showed that accommodative ciliary body forward movement decreased and resting thickness decreased. 2) The lens capsule and its zonular connections to the ciliary body are necessary for the inner edge of the muscle to be well defined. 3) Ciliary body resting thickness and the magnitude of the accommodative forward ciliary body movement were not altered by ECLE.

This study is the first to show that opening the anterior chamber, creating a ~4 mm anterior capsulorrhexis, removing the lens nucleus and cortex, but leaving the posterior capsule intact, does not change the operation of the zonular/muscular system as a whole, even without replacement of the lens content. This finding is important for accommodating IOL development. In contrast, removing the entire lens does make a difference. Yet to be determined is the effect of opening the posterior capsule (i.e., to treat posterior capsule opacification).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1. Diagram showing how measurements of muscle width, length, and apical position with respect to the scleral spur were taken from histological sections. The eyes were not exposed to any pharmacological agents to induce accommodation or relaxation

Figure 2.

In vivo ultrasound biomicroscopy (UBM) images from both eyes of 2 rhesus monkeys (right panels), with the corresponding histological sections of each of the imaged eyes (left panels) following euthanasia. Each monkey contributed one control (iridectomized phakic) eye and one surgically treated eye. One monkey underwent unilateral intracapsular lens extraction (ICLE; upper panels) and the other monkey underwent unilateral extracapsular lens extraction (ECLE; lower panels). The numbers in the histological sections represent the ciliary muscle width and apical position relative to the scleral spur (AP)² in the surgically altered and control eyes. In the ICLE histological section, the detachment of the ciliary body from the sclera was an artifact; it was not included in the measurement of ciliary muscle width and did not impact the AP distance measurement from the scleral spur.

Figure 3.

Ultrasound biomicroscopy images (UBM) in the temporal quadrant of a 7-year-old rhesus monkey eye pre- and post-intracapsular lens extraction (ICLE). Resting (A, B) and accommodated (C, D) ciliary body before (A, C) and after (B, D) ICLE. The width of the ciliary body apex was $0.73 \pm 0.01 \text{ mm}$ pre-ICLE (A) and decreased to $0.56 \pm 0.01 \text{ mm}$ post-ICLE (B). The amount of accommodative forward movement diminished from 74.2° to 22.1° pre- versus post-ICLE, respectively, as measured by ciliary body-cornea angle change.³ During maximum accommodation, the anterior aspect of the ciliary body moved past the scleral spur before, but not after, ICLE. Following ICLE, the ciliary body apex was flattened against the sclera. The numbers in the panels in units of degrees represent the angle between the inner aspect of the cornea and the anterior aspect of the ciliary body.

Figure 4.

Images are of 1 μ m thick sagittal sections through the ciliary muscle of a) a 16 year old monkey following unilateral intracapsular lens extraction (ICLE); and b) contralateral control eye (Richardson's stain). Even in the extremely small muscle following ICLE there are circularly arranged muscle fibers. In contrast to the controls, in which the circular fibers form an anterior inner edge (indicated by a white line) in the ICLE eye they form an elongated area at the inside of the muscle. The insets show that in both areas outlined the muscle fibers are cross sectioned.

Table 1
Division of study animal eyes according to age and surgical procedure

	ICLE	(ME*)	ECLE	(ME*)
Young (n=7 eyes) (6-13 yr)	5**	(1)	2	(1)
Older (n=8 eyes) (17-27 yr)	5	(3)	3	(1)
Total (n=15 eyes)	10		5	

* ME (Morphological Exam) = Number of monkey eyes, within each surgical procedure group, undergoing measurements of ciliary muscle width and apical position by morphological examination. (ICLE = intracapsular lens extraction. ECLE = extracapsular lens extraction.)

** The presence (n=2) or absence (n=3) of Wieger's ligament [IOVS #0001] did not impact forward ciliary body movement nor ciliary body width; thus these data were not separated according to whether Wieger's ligament was intact or not [IOVS #0001] and remained grouped together.

Table 2
Ciliary Body Width, CB-Cornea Angle Before and During Supramaximal Stimulation and Forward Ciliary Body Movement

A) Resting ciliary body apex width (obtained with UBM) in young and older monkey eyes pre- and post-intracapsular (ICLE) or extracapsular (ECLE) lens extraction, along with mean pre- minus post-ICLE or ECLE differences; p values are for the mean difference by the two-tailed paired t-test (NS, not significant). B) Ciliary body/cornea angle (CB-Cornea angle; obtained with UBM) in young and older monkey eyes pre- and post-ICLE, or post-ECLE when the eye is at rest and during supramaximal stimulation (Smax). C) The difference between the CB-Cornea angle at rest and during Smax stimulation was used as a surrogate indicator of forward ciliary body movement.¹³

A. Resting Ciliary Body Apex Width (mm)				B. CB-Cornea Angle (degrees)				C. Forward Ciliary Body Movement (degrees)					
Intracapsular Lens Extraction (ICLE)				Pre ICLE		Post ICLE		Pre ICLE		Post ICLE		Pre-Post	
				Resting	Smax	Resting	Smax						
Young	Mean s.e.m. n=5	p=	0.015	155.8	95.5	159.9	134.7	60.3	25.2	35.1			
				4.0	4.0	5.2	9.5	6.1	6.1	10.9			
										0.032			
Older	Mean s.e.m. n=4	p=	0.062	158.1	130.0	152.3	135.8	28.1	16.6	11.6			
				5.1	6.1	6.1	5.8	2.8	6.0	4.8			
								0.006		0.095			
Young & Older	Mean s.e.m. n=9	p=	0.001	156.8	110.8	156.5	135.2	46.0	21.4	24.6			
				2.6	6.9	3.9	5.5	6.6	4.3	7.3			
										0.01			
Contralateral Control Eyes (Surgically Unaltered)				Session 1		Session 2		Session 1		Session 2		Session 1 Minus Session 2	
				Resting	Smax	Resting	Smax						
Young & Older (2 young; 3 older)	Mean s.e.m. n=5	p=	0.01	152.1	123.1	152.6	122.8	29.1	29.9	-0.8			
				4.2	6.0	4.9	10.3	6.5	8.7	3.5			

A. Resting Ciliary Body Apex Width (mm)				B. CB-Cornea Angle (degrees)				C. Forward Ciliary Body Movement (degrees)			
Intracapsular Lens Extraction (ICLE)											
p=				Pre ICLE		Post ICLE					
				Resting	Smax	Resting	Smax				
Extracapsular Lens Extraction (ECLE)				Pre ECLE		Post ECLE					
				Resting	Smax	Resting	Smax	Resting-Smax		Pre-Post	
Young	Mean	s.e.m.	n=2	151.2	93.4	160.2	90.7	57.8	69.5	-11.7	
Older				4.8	18.2	2.6	19.6	22.9	17.0	8.3	
	Mean	s.e.m.	n=2	145.9	110.8	156.5	120.4	35.1	36.0	-1.0	
				3.8	7.0	5.6	0.5	10.9	5.1	22.5	
Young & Older	Mean	s.e.m.	n=4	148.5	102.1	158.3	105.5	46.4	52.8	-6.3	
				2.9	9.4	2.7	11.7	12.3	12.1	7.6	
			p=	NS							
Contralateral Control Eyes (Surgically Unaltered)											
				Session 1		Session 2					
				Resting	Smax	Resting	Smax				
Young & Older (2 young; 2 older)	Mean	s.e.m.	n=4	142.7	116.6	151.8	123.1	26.1	28.8	-2.6	
				10.2	7.1	8.5	5.2	3.1	3.4	0.3	
			p=	NS							

Table 3
Histological Measurements of Ciliary Muscle Width and Apical Position

Data represent mean $\pm$ s.e.m. width and length of the ciliary muscle, and the distance of the ciliary muscle apical position from the scleral spur (AP),¹⁸ obtained from histological sections in control (iridectomized phakic) eyes and in eyes that had undergone intracapsular lens extraction (ICLE) and extracapsular lens extraction (ECLE). The p values represent the probability of no significant difference between surgically treated eyes and the contralateral control eyes by the two-tailed paired t-test. NS=Not significant.

Intracapsular Lens extraction (ICLE)						
Ciliary Muscle Width (mm)				Apical Position (mm)		
Control	ICLE	Control -ICLE	p	Control	ICLE	Control -ICLE
Mean	0.84	0.66	0.047	0.79	0.99	-0.20
s.e.m.	0.01	0.06		0.03	0.05	0.03
n	4			4		
Length (mm)						
Control	2.95	3.43		Control	2.95	-0.52
s.e.m.	0.10	0.15		s.e.m.	0.10	0.13
n	4			n	4	
p						
			0.005			0.058
Extracapsular Lens extraction (ECLE)						
Ciliary Muscle Width (mm)				Apical Position (mm)		
Control	ECLE	Control -ECLE		Control	ECLE	Control -ECLE
Mean	0.81	0.90		0.69	0.67	-0.02
s.e.m.	0.03	0.04		0.09	0.03	0.06
n	2			2		
Length (mm)						
Control	3.01	3.06		Control	3.01	-0.06
s.e.m.	0.08	0.15		s.e.m.	0.08	0.06
n	2			n	2	
p						