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Accommodation-Amplitudes following an Accommodative Lens Refilling Procedure — an in vivo Update

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Abstract

Purpose—To investigate whether a newly developed lens refilling procedure can provide some accommodation in monkey eyes and to evaluate the difference in accommodation with different degrees of capsular bag refilling.

Setting—Jinshikai Medical Foundation, Nishi Eye Hospital, Osaka, Japan.

Design—Experimental monkey study.

Methods—Following a central 3–4 mm continuous curvilinear capsulorhexis, phacoemulsification was performed in the usual manner. A novel accommodative membrane intraocular lens for sealing capsular opening was implanted into the capsular bag. Silicone polymers were injected beneath the intraocular lens into the capsular bag through the delivery hole. In three study groups, each with six monkey eyes, the lens capsule was refilled with 0.08 ml corresponding to 65% bag volume, 0.1 ml corresponding to 80% bag volume, and 0.125 ml of silicone polymers corresponding to 100% bag volume, respectively. To calculate the accommodation-amplitudes achieved, automated refractometry was performed before and 1 hour after the topical 4% pilocarpine application before and four weeks after surgery.

Results—The refilling technique was successful in all monkeys without polymer leakage. Accommodation-amplitudes attained were 2.56 ± 0.74 dioptries (D), 2.42 ± 1.00 D, and 2.71 ± 0.63 D, respectively, 4 weeks after surgery in the three study groups.

Conclusions—Using the technique, some accommodation could be obtained in the young monkey eyes. Leakage of the injectable silicone polymer and anterior capsular opacification at least in the visual axis could be avoided. The results suggest that this lens refilling procedure warrants further studies for a possible clinical application.

Refilling of the lens capsule with an injectable malleable material that would restore ocular accommodation has long been the goal for the cataract surgeon. However, two persistent

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problems with capsular bag refilling methods reported have hampered the clinical application of this procedure.^{1–11} The first is the leakage of the injected material, usually a mix of two silicone compounds, from the capsular bag prior to its transformation into a gel-formed, polymerized consistency. The second is capsular opacifications. Despite the circumstance, previous investigators have achieved from 2 to 8 diopters of accommodation in monkey eyes even though for a relatively short postoperative period while attempting to prevent leakage of the injectable material.^{2,4,5,8,11} These methods include use of the pre-cured silicone gel,^{1–3} endocapsular balloon,^{4,5} endocapsular polymerization by applying ultraviolet light,⁶ capsular sealing plug^{7–10} and expandable full-size intraocular lens (IOL).¹¹ Capsular opacification has proven to be extensive,¹² though, in some instances, it has been minimized by treating residual lens epithelial cells.¹⁰ None of these techniques has been proven to be clinically useful.

To address the two problems of silicone leakage and capsular opacification, we recently developed a novel accommodative IOL serving both as an optic as well as a plug for sealing the capsular opening. In our previous studies using rabbit and pig cadaver eyes, the accommodative IOL sealed the large, central 3–4 mm continuous curvilinear capsulorhexis (CCC) opening and successfully prevented silicone leakage.¹³ Posterior capsular opacification in the visual axis could be avoided by a posterior CCC which sealed by means of an inversely implanted posterior accommodative IOL. Silicone polymers were injected between the two IOLs to fill the capsular bag. Thus, the capsular opacification at least in the visual axis was prevented in this way in the rabbit eyes by means of anterior and posterior CCCs which could be sealed by the use of two accommodative IOLs.¹³

In this paper, applying the technique in young monkey eyes, we tested whether this technique can provide some accommodation. We evaluated also the difference in accommodation with different degree of capsular bag refilling. This study design is based on our previous experimental in vitro study⁷: The accommodation-amplitudes varied with different bag volume fillings, and the capsular bag refilled with around 70% bag volume provided an optimal accommodation-amplitude. In this study, however, posterior CCC was intentionally not performed to simplify the technique to attain a high degree of surgical reproducibility because of the high cost of monkey experiments, for the primary purpose of our experiments was to confirm whether this procedure provides some accommodation in young monkey eyes.

MATERIALS AND METHODS

This study was performed at the Japan Life Science Center in Gifu prefecture in Japan. We adhered to the ARVO Statement for the use of Animals in Ophthalmic and Vision Research and the rules of Primate Society of Japan. Eighteen young macaca fascicularis monkeys aged 3 to 5 years weighing 5.5 to 6.3 kg were used.

Anesthesia

Animals were anesthetized with intramuscular ketamine chloride, Ketalar® 0.5 mg/kg, and xylazine chloride, Selactar® 2.0 mg/kg. Additional corneal anesthesia was provided with 1% xylocaine chloride eye drops before and during surgery.

Accommodative Membrane IOL and Injectable Silicone Polymers

We modified the foldable silicone accommodative membrane IOL¹³ previously reported in our rabbit and pig cadaver eye experiments for the monkey experiment. The modified IOL that serves as an optic as well as a plug for sealing the capsular opening to prevent the leakage of injected silicone polymers until their polymerization is made of silicone and has a

thin plate disc-shaped haptic with a 9.0 mm overall diameter (Fig. 1). At the margin, there is a 0.8 mm delivery hole for the insertion of a 22-gauge needle. More central to the optic, there is a 0.2mm positioning pocket (not perforating the plug) through which the IOL can be positioned properly using a Sinsky hook. The IOL which is thick at its margins tapers to a 100 μ m thin center. The substantial change from the original IOL¹³ is the absence of a transitional zone between the optic and the haptic. This region is now represented as a disc-shaped IOL. The anterior and posterior curvatures are 15.5 and 9.0 mm, respectively. The refractive index of the silicone is 1.410. Accordingly, the refractive power of the membrane in the air is calculated to be +19.5 diopters in ray-tracing.

The injectable silicone material is formulated with an optimized mix ratio of silicone polymer Part A to Part B to achieve a modulus of 100 Pa mimicking the young human natural lens using a dynamic mechanical analyzer. The refractive index after polymerization was 1.397 in air.

Primary Treatment – Total Iris Removal

The entire iris of each monkey eye was removed 2 weeks prior to the lens refilling procedure to facilitate an easier postoperative observation of the refilled lens and permit the accurate measurement of the refraction. A 2 mm corneal limbal incision was performed. A fine forceps was used to grasp the iris root and slowly and carefully pull the iris tissue away from the iris root insertion, resulting in an irido-dialysis at the iris periphery. When the irido-dialysis reached about 1/4 of the iris circumference, the iris root just at the corneal incision was regripped. This procedure was repeated until the total irido-dialysis was obtained. This technique¹⁰ resulted in an anterior chamber hemorrhage that ceased spontaneously when the intraocular pressure was raised for one to two minutes.

Surgical Procedure

The refilling technique had been described in the previous report¹³ (Fig. 2). In brief, after phacoemulsification with a 3–4 mm CCC in the middle of the anterior capsule, viscoelastics (Healon V®, Pfizer inc.) was injected into the capsular bag, followed by the foldable accommodative membrane IOL implantation. After removing viscoelastics from the capsular bag, particularly from underneath the IOL, a small amount of viscoelastics is injected above the IOL. An injectable silicone polymer-mix was then injected beneath the IOL into the capsular bag using a special dispenser¹³ which can deliver precisely the arbitrary preset amount of silicone mix. The blunt needle of the dispenser containing silicone polymers was inserted through the delivery hole, while the CCC edge was slightly pulled aside; the silicone polymer polymerized within 2 hours in vitro. After a certain amount of silicone polymers was injected, the needle was withdrawn. The CCC edge returned covering the delivery hole. The IOL was properly centered using a Sinsky hook. 0.2ml of 0.5% atropine sulfate was applied to the lower subconjunctiva at the beginning of surgery, attempting the injected silicone material to conform to disaccommodated capsular bag shape after polymerization, because, according to our previous study,⁴ the disaccommodated form may yield more accommodation. Gentamycin (4 mg) and dexamethasone (0.33 mg) were applied subconjunctively at the end of surgery.

Topical levofloxacin (0.5 % Clavid®), diclofenac sodium (0.1 % Diclod®) and 0.1 % fluorometholon, were applied 3 times a day for 3 days following the surgery.

Preoperative and Postoperative Examinations

Slitlamp examination and anterior segment photography were performed before surgery, two and four weeks following surgery.

Scheimpflug photography (Nidek EAS 1000) and measurement of refraction using an automated refractometer (Nidek ARK-10000) were performed before and 1 hour after the application of topical 4% pilocarpine before and 4 weeks following surgery (Longer follow-up was not possible due to the liquidation of the monkey facility).

In the Scheimpflug photography, each of five microphotographs was analysed for the anterior chamber depth, lens thickness, and anterior and posterior capsule curvatures. The obtained values were averaged.

In the measurement of refraction, five to seven consecutive measurement values in the dioptric power (D) obtained by the automated refractometer were averaged to obtain the final value. The equivalent value in each eye was calculated from spherical and cylindrical powers. The difference between the refractions measured in spherical equivalence before and 1 hour after topical 4% pilocarpine application was calculated as the accommodation-amplitude. The ratio of the accommodation-amplitude before surgery to that after surgery was also calculated.

Measurement of Crystalline Lens Volume and Refilled Lens Volume

By means of Scheimpflug photography, the crystalline lens volume of each monkey was measured before surgery.

First, the curvature of the anterior and posterior lens capsule delineated by Scheimpflug photography was represented as a part of a circle line by plotting manually three points on the capsular contour, so that both lines of the anterior and posterior capsule meet at both sides, delineating and extrapolating a simulated crystalline lens. The lens volume was calculated by adding the volume of each of the two hemispheric cones determined by means of a straight line drawn between the two cross points of each curvature line. The height of the hemispheric cone was mathematically determined from the crystalline lens thickness.

The anterior chamber depth and lens thickness were corrected from the distortion caused by the cornea and aqueous humor by means of ray-tracing. However, the crystalline lens curvature measurement was performed using the dedicated software for the anterior corneal curvature measurement, and was not corrected with the distortion caused by the cornea and aqueous humor.

Postoperatively, the refilled lens volume was also measured in the same manner.

Research Design

Eighteen eyes of 18 monkeys in which total iris removal was performed were involved in the experiments. Two weeks following the iris removal, all eyes underwent the lens refilling procedure using the accommodative membrane IOL. In three groups, with 6 macaca monkeys in each group, the lens capsule of each eye was refilled, respectively, with 0.08 ml of silicone polymers corresponding to 65% of the mean capsular bag volume (group A), 0.1 ml of silicone polymers corresponding to 80 % of the mean capsular bag volume (group B), and 0.125 ml of silicone polymers, corresponding to 100 % of the mean capsular bag volume (group C).

The mean crystalline lens volume of the monkeys was defined as 0.125 ml (see the results).

Statistical Evaluation

The Kruskal-Wallis test was used for statistical evaluation of the accommodation-amplitudes before and after surgery as well as for the accommodation ratio among the three groups.

RESULTS

Preoperative Scheimpflug Analysis and Crystalline Lens Volume

Each mean value of the anterior chamber depth, lens thickness, anterior and posterior capsule curvature, and crystalline lens volume in three groups are shown in Table 1.

The Scheimpflug photography before surgery showed three characteristic findings after 4% pilocarpine eye drops: shallowing of the anterior chamber, thickening of the crystalline lens and steepening of the anterior lens curvature (Fig. 3), which were represented by the each measurement values.

The calculated mean crystalline lens volume before surgery was 0.126 ± 0.008 ml, 0.124 ± 0.007 ml and 0.124 ± 0.073 ml for the groups A, B and C, respectively, with the mean of 0.125 ± 0.029 ml. From the results, 0.125 ml was determined as the mean crystalline lens volume of the monkeys used. Accordingly, 0.08 ml, 0.1 ml and 0.125 ml of silicone polymers being injected were determined as the volume corresponding to 65%, 80% and 100% bag volume filling, for the group A, group B and group C, respectively.

Preoperative Refractions and Accommodation-Amplitudes

They were shown in Table 2, 3 and 4 for the groups A, B and C, respectively.

Surgical Outcome

The surgical time required was 20–30 minutes for each of all monkeys. In some cases, when the injection needle was withdrawn, small silicone spheres were released. This occurred when the CCC edge pulled aside returned in 1–2 seconds covering the delivery hole of the IOL. This fine globule silicone due to its cohesiveness could be distinctly recognized and easily removed by aspiration. During the injection and in the course of surgery, no silicone leakage occurred in any eye. Posterior capsule rupture occurred during phacoemulsification with one monkey (C-1) (Table 4), in which the postoperative Scheimpflug analysis and measurement of refractions and accommodation could not be performed. This monkey was excluded from the postoperative analysis. Once phacoemulsification was completed, there was no case of capsular rupture during and after the silicone polymers injection procedure.

Two weeks and 4 weeks after surgery, all the lens capsules in all three groups were well refilled and showed no silicone leakage. However, in some cases, a tiny, very thin silicone particle –attached at the CCC margin to the delivery hole on the IOL –was seen. This did not involve the central optic of the IOL.

Slight to mild capsular opacification of the remaining anterior capsule was observed 4 weeks after surgery as described in the previous report¹³. Lens epithelial cells did not reach the central area of the posterior capsule yet four weeks after surgery in all eyes. In some eyes, fibrin deposits were observed 2 weeks after surgery but absorbed after 4 weeks (Fig. 4).

Postoperative Scheimpflug Photography Analysis

After surgery, the changes in anterior chamber depth, lens thickness and anterior and posterior capsule curvatures were present but were much less marked than before surgery. The results are shown in Table 5 and Fig. 3.

The mean anterior chamber depth became postoperatively shallower with the increasing bag volume in all three groups. The mean lens thickness became thinner in the group A, and those in the groups B and C became thicker. The mean anterior curvature became significantly steeper with the increasing bag volume in all three groups. The mean posterior

curvature became significantly flatter in the group A after surgery. It was similar in the group B compared to the preoperative condition. In the group C, all the posterior capsule could not be photographed because it was pushed too posteriorly to be sufficiently caught and identified by Scheimpflug photography.

The mean refilled lens volume in the group A ranged from 0.075 to 0.081 ml with the mean of 0.079 ± 0.002 ml, whereby 0.08 ml of silicone polymers was injected. The mean refilled lens volume in the group B could be measured in three eyes and ranged from 0.100 to 0.117 ml with the mean of 0.106 ± 0.008 ml, whereby 0.1 ml of silicone polymers was injected.

Postoperative Refractions and Accommodation-Amplitudes

The results are shown in Table 2, 3 and 4.

In the group A (Table 2), the spherical power ranged from -1.60 D to $+2.58$ D with the mean of $+0.78 \pm 1.55$ D. The equivalent dioptric power ranged from -2.63 D to $+1.25$ D with the mean of -0.83 ± 1.31 D.

In the group B (Table 3), the spherical power ranged from -15.75 D to $+3.25$ D with the mean of -8.56 ± 7.02 D. The equivalent dioptric power ranged from -19.88 ± 0.00 to -1.23 ± 0.05 D with the mean of -11.71 ± 6.96 D.

In the group C (Table 4), the spherical power ranged from -15.85 to -1.44 D with the mean of -8.18 ± 5.25 D. The equivalent dioptric power ranged from -20.15 D to -3.53 D with the mean of -10.83 ± 6.01 D.

The refractions of A-5 and B-6 (Table 4 and 5) could not be measured due to cellular deposits with posterior synechia on the anterior surface of the IOLs.

The mean accommodation-amplitudes and the accommodation ratio were -2.56 ± 0.74 D and 19.7 ± 6.6 %, -2.42 ± 1.00 D and 23.6 ± 8.9 %, and -2.71 ± 0.63 D and 28.1 ± 6.5 %, in the groups A, B, and C, respectively.

There was no statistically significant difference in the accommodation-amplitude or in the accommodation ratio before surgery and after surgery among the three groups.

DISCUSSION

This lens refilling technique again demonstrated that intra- and postoperative leakage of the injected silicone polymers was prevented similar to the findings in our previously reported studies using pig cadaver eyes and rabbit eyes despite of a central large CCC.¹³ The injected polymer presses the IOL from the inside of the capsular bag against the CCC and anterior capsule due most likely to the buoyancy of the silicone. As a result, the injected cohesive silicone polymer with its high molecular weight does not leak through the space between the anterior capsule and IOL, before it polymerizes in a consistent gel form, unless the IOL is forcibly pushed posteriorly.¹³ This simple technique should be recognized in future development of capsular bag refilling for preventing silicone leakage from the capsular bag.

There was a concern that sufficient accommodation can not be achieved, because the middle part of the anterior capsule which contributes physiologically to ocular accommodation by substantial steepening was widely removed for the prevention of anterior capsule opacification. Despite a large central capsular defect created by the CCC, however, a mean of around 2.5D of accommodation-amplitudes could be obtained independent of the different filling degrees, although it, in this present study, was for 4 weeks after surgery. The obtained accommodation-amplitudes may be clinically useful for near vision because

multifocal IOLs with a 3D addition allows reading for patients, and 3D of the IOL in vivo corresponds to around 2.5D of accommodation, provided that the amplitudes will not decline with time.

In this experiment, aged presbyopic monkeys should be used simulating the human condition that would require a lens refilling procedure for presbyopia. But it was extremely difficult to find the aged monkeys. We chose the monkeys mainly from such facial contours as a flatter nose, flatter forehead and non-enophthalmus, which may ease surgery. While these characteristics made for a better surgical approach, they also contributed to a higher incidence of myopia as was seen in group B. Group B monkeys, however, demonstrated preoperative accommodation-amplitudes comparable to the other groups, so that the high myopia of group B may not adversely affect the results.

We were unable to find references to the crystalline lens volume of macaca monkeys. We, therefore, tried to calculate their crystalline lens volume using Scheimpflug photography with its dedicated computer program. This may have resulted in errors in our calculations: Extrapolated graphical representation with the curvatures and lens periphery; The calculated curvatures were not corrected for the distortion caused by cornea and aqueous humor. However, five refilled capsules injected with 0.08 ml (group A) and three with 0.1 ml of silicone polymers (group B), showed the calculated volume of 0.079 ml and 0.108 ml in mean, in the groups A and B (Table 5), respectively, which were very close to the injected silicone volume. Therefore, the calculated crystalline lens volume of 0.125 ml suggests that there may not be too great an error to significantly affect the results.

Since the anterior accommodative IOL used in this technique does not have a refractive power, the steepening of the anterior surface of the accommodative membrane IOL as shown by Scheimpflug analysis may have played the main part in achieving accommodation. Probably the use of an IOL with a thinner softer and more elastic center which attribute is closer to the anterior capsule might result in achieving even higher accommodation-amplitude levels. Furthermore, more flattening of the anterior curvature also might achieve higher accommodation, as the flatter the lens and the smaller the volume of the anterior segment, the more potential energy is stored in the capsule for release by zonular relaxation.¹⁴ The mean anterior curvature of the present membrane IOL was 7.74 mm, 7.35 mm and 6.28 mm, respectively, after surgery and significantly steep compared not only to its own anterior curvature of 15.5 mm but also to the mean anterior curvature values of 10.99 mm, 11.81 mm and 11.07 mm before surgery in the monkey groups A, B and C, respectively. This may explain the postoperative high myopic shift in the groups B and C. Thus, controlling and restoring of the preoperative original capsular bag shape is important and decisive for achieving emmetropia and obtaining an useful accommodation. This issue should be solved in the future studies.

The accommodation- amplitudes were similar among the three study groups ranging from about 2 to 4 D with a mean of about 2.5D, independent of the filling degree of the capsule (Table 2, 3, 4). The Scheimpflug analysis showed the analogous findings, with shallowing anterior chamber depth, thickening of the refilled lens and steepening of the anterior curvature of the IOL (Table 5), though minimal compared to the preoperative conditions.

Previous in vitro studies^{7,9} suggested that there was an optimal filling degree for obtaining a greater accommodation. In these in vitro experiments, underfilling with 60 to 80 % bag volume yielded significantly higher accommodation-amplitudes. However, in the present results, there was no statistically significant difference in the accommodation-amplitudes and accommodation ratio among three groups with the different filling degree before and after surgery. In other words, with this procedure, there was no optimal accommodation-

amplitude that was dependent on the extent of filling of the capsular bag. The reason may be that, in the previous in vitro experiment, the refilled capsule was stretched to generate accommodation implying that the mechanism of accommodation was different.

Another possible explanation may be that the accommodative membrane IOL was much thicker and stiffer than the anterior capsule, not sufficiently thin and resilient, so that the anterior curvature could be only limitedly changed during accommodation. The membrane might have been too stiff to react sensitively and differently with the different amount of silicone polymers, exactly mimicking the accommodation mechanism. Therefore, as discussed, making the membrane much thinner might bring not only a greater accommodation-amplitude but also a different relationship among the groups with a different filling degree in terms of accommodation-amplitude. However, the result might be advantageous for the procedure, for we would not need to consider both factors, achieving an optimal accommodation-amplitude and emmetropia, if clinically useful accommodation independent of the bag filling degree can be obtained. One can concentrate on achieving emmetropia alone in the surgery facilitating the surgical ease and simplicity.

The postoperative accommodation-amplitudes attained were just a small fraction of the preoperative values. This result is similar to the previous finding in our monkey experiments.^{4,8} Koopmans, et al.¹⁰ also reported similar results of 3 to 4D of accommodation (and up to 6D) in their rhesus monkey experiments using the plug-sealing technique, a far low level compared to the preoperative value.

The use of a thick (IOL-like) centrally located plug may be a cause. The polymerized silicone gel is different from natural crystalline lens in the structure, so that it may not be able to comply the shape change of the capsular bag after pilocarpine application as the normal crystalline lens substance. Another reason it may be a reduced adhesion between the lens capsule and polymerized silicone, compared to the preoperative condition, which may result in a less efficient transmission of the capsular forces that would the lens contents during accommodation.^{4,10}

Regarding postoperative refractions, there was a significant tendency toward a myopic shift with the increasing anterior chamber depth, lens thickness and anterior curvature with the increasing bag volume filling after surgery. The results suggest that the postoperative refractive state depends, to a large degree, on the extent of filling of the capsular bag. Koopmans, et al.¹⁰ also reported that the postoperative refraction was influenced by over- and underfilling of the lens capsule. The attainment of emmetropia is an important issue awaiting solution prior to the potential clinical application of this procedure.

The degree of the astigmatism behaved in a similar fashion to the refractive error and increased with the increased filling degree of the capsular bag. This may be caused by an unwanted deformation of the membrane IOL. It remains for future studies to verify this finding and to offer a possible explanation for the toric phenomenon and to prevent it.

As reported previously,¹³ anterior and posterior CCCs eliminated capsular opacification for several weeks at least in the visual axis in the rabbit eyes which have much higher propensity of lens epithelial cell proliferation. Performing posterior CCCs might decrease the accommodation-amplitude attained. But we think that this may be very limited, since posterior capsule does not much participated in the accommodation mechanism. In fact, in the 65% filling group A, the posterior capsule curvature became much flatter, and it was almost same in the 80% filling group B after surgery, and almost the same accommodation-amplitudes were attained. Apart from this series of the experiments, we refilled one monkey lens with both anterior and posterior CCCs, and the accommodation-amplitude of 3.1D could be attained.

However, though capsular opacification may be prevented in the visual axis by both CCCs, how and in what extent capsular opacifications in the other area and residual lens epithelial cell proliferation in the form of Soemmering's ring affect accommodation attained need to be clarified. In the present study, we could not clarify this issue by a prolonged follow-up. This remains the task for future studies.

In conclusion, our new lens refilling procedure, requiring 20–30 minutes of surgical time, was found to be highly reproducible in the monkey eyes. It was without the substantial leakage of the injectable silicon polymer as demonstrated in numerous previous rabbit eye and pig cadaver eye experiments, and around 2.5 diopters of accommodation could be obtained independent of filling degrees of the capsular bag in the young monkey eyes. The results suggest that this lens refilling technique warrants further studies for a possible clinical application.

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WHAT WAS KNOWN

The novel lens refilling procedure using an accommodative membrane IOL prevented the leakage of the silicone polymer injected into the capsular bag in the rabbit eyes. But there was a concern that ocular accommodation can not be obtained, since the central part of the anterior capsule (3 to 4 mm CCC) is removed with this technique to avoid anterior capsule opacification.

WHAT THIS PAPER ADDS

This study demonstrated that, despite central CCCs, around 2.5 diopters of accommodation-amplitudes could be obtained independent of the filling degree of the capsular bag in the young monkey eyes

SYNOPSIS

The novel lens refilling procedure using a thin accommodative membrane IOL was simple and easy to perform, and yielded the accommodation-amplitude around 2.5 diopters in the young monkey eyes.

Figure 1.

Foldable silicone accommodative membrane IOL that serves as an optic as well as a plug to prevent the leakage of injected silicone polymers. The delivery hole is 0.8 mm and positioning pocket (not perforating the plug) 0.2 mm, respectively. The central part is 100 μ m thick (between two arrows).

Figure 2.

Schematic procedure of the lens refilling (Reprinted by permission from *J Cataract Refract Surg*).¹³ The cross section of the accommodative IOL in this figure is different from that in Figure 1, because the latter is modified for the present study. Following CCC with 3 to 4 mm diameter, phacoemulsification is performed in the usual manner. Next, the anterior accommodative IOL is folded and implanted in the capsular bag. An injectable silicone polymer is then injected beneath the IOL through the delivery hole while the CCC edge is pulled aside slightly.

Figure 3. Scheimpflug photography of a macaca monkey eye in the group B before (left) (Table 1) and after surgery (right) (Table 5). The upper figure is prior to and the lower 1 h after 4% pilocarpine application. Note that the content within the lens capsule after surgery is optically empty due to silicone polymers.

Figure 4.

Slitlamp findings of the macaca monkey eye shown in Fig. 3. The finding before surgery (top left). The condition 2 weeks after surgery (top right). Within the CCC, a fine fibrinous membrane deposit is seen. The lens capsule is well refilled and no obvious leakage of injected silicone polymers is seen. Four weeks after surgery (below left), the peripheral posterior capsule is slightly opacified due to lens epithelial cell migration but the visual axis remains clear. The same findings using retroillumination (below right). The CCC edge is clearly seen. The arrows show the delivery hole in the anterior membrane IOL which is located behind the anterior capsule. There is no silicone leakage seen.

Table 1

Preoperative Scheimpflug Photography Analysis of the Macaca Monkeys

Group	4% Pilo	Anterior Chamber Depth (mm)	Lens- Thickness (mm)	Anterior Capsule Curvature (mm)	Posterior Capsule Curvature (mm)
A	Before	2.67±0.17	3.07±0.10	10.99±0.80	7.52±0.68
	1h After	2.19±0.21	3.81±0.12	7.23±0.54	5.78±0.40
B	Before	2.83±0.07	2.89±0.17	11.81±0.79	8.53±0.58
	1h After	2.40±0.11	3.47±0.09	8.41±0.58	6.91±0.39
C	Before	2.64±0.09	3.01±0.16	11.07±0.64	7.35±0.36
	1h After	2.29±0.12	3.33±0.14	8.31±0.76	6.58±0.56

Pilo stands for pilocarpine. All figures show mean value ± SD.

Table 2
Refractions and Accommodation-Amplitudes—Group A: 65% Bag Volume Filling—

Monkey	4% Pilo	Before Refilling			After Refilling			Ratio
		Sph (D)	Cyl (D)	Equ (D)	Sph (D)	Cyl (D)	Equ (D)	
A1	Before	-0.35±0.12	-0.75±0.00	-0.73±0.23	-0.33±0.12	-2.56±0.11	-1.48±0.25	
	1h After	-12.00±0.00	-2.86±0.13	-13.50±0.09	-1.40±0.24	-3.25±0.42	-3.93±0.45	
	Acc			-12.75±0.32			-2.48±0.42	19.6±1.3 %
A2	Before	+0.10±0.00	-0.70±0.19	-0.19±0.12	+1.10±0.12	-1.90±0.12	-0.15±0.09	
	1h After	-12.80±0.77	-3.50±0.27	-14.63±0.73	-1.05±0.10	-1.70±0.10	-1.90±0.05	
	Acc			-14.51±0.77			-2.09±0.05	14.6±1.4 %
A3	Before	+1.00±0.16	-0.95±0.56	-1.54±0.17	+2.13±0.38	-6.63±0.13	-1.13±0.50	
	1h After	-13.50±0.27	-2.00±0.16	-14.50±0.35	+0.75±0.00	-4.25±0.70	-2.36±0.47	
	Acc			-12.97±0.22			-1.73±0.47	13.4±1.1 %
A4	Before	+0.40±0.12	-1.70±0.73	-0.45±0.23	+2.58±0.12	-2.75±0.20	+1.25±0.10	
	1h After	-11.95±0.10	-1.30±0.33	-12.60±0.12	+1.63±0.11	-2.19±0.45	-2.66±0.29	
	Acc			-12.15±0.32			-3.92±0.50	32.1±1.3 %
A5	Before	-0.25±0.16	-1.45±0.10	-0.73±0.05	NA	NA	NA	NA
	1h After	-10.25±0.27	-1.86±0.38	-11.30±0.26				
	Acc			-11.92±1.70				
A6	Before	-1.25±0.12	-0.25±0.00	-1.50±0.00	-1.60±0.12	-2.05±0.10	-2.63±0.11	
	1h After	-15.25±0.00	-0.40±0.12	-15.50±0.06	-4.95±0.10	-0.45±0.10	-5.20±0.10	
	Acc			-13.85±0.06			-2.58±0.19	18.6±0.6 %
Mean	Before	-0.06±0.69	-0.97±0.48	-0.86±0.50	+0.78±1.55	-2.31±2.37	-0.83±1.31	
	1h After	-12.63±1.54	-1.99±1.00	-13.67±1.40	-1.00±2.27	-5.71±3.44	-3.21±1.20	
	Acc			-13.02±0.91			-2.56±0.74	19.7±6.6 %

Pilo, D and Acc stand for pilocarpine, diopters and accommodation, respectively. Ratio stands for the accommodation-amplitude after refilling to that before refilling. All figures show mean value ± SD.

Table 3
Refractions and Accommodation-Amplitudes—Group B: 80% Bag Volume Filling—

Monkey	4% Pilo	Before Refilling			After Refilling			Ratio
		Sph (D)	Cyl (D)	Equ (D)	Sph (D)	Cyl (D)	Equ (D)	
B1	Before	-10.05±0.49	-2.33±0.57	-11.28±0.67	-13.56±0.32	-6.13±0.28	-16.63±0.23	
	1h After	-23.20±0.48	-9.65±0.12	-27.93±0.47	-16.00±0.00	-6.44±0.11	-19.70±0.06	
	Acc			-16.65±0.81			-3.08±0.27	18.5±1.5 %
B2	Before	-8.10 ±0.12	-7.20±1.00	-11.70±0.30	-15.75±0.00	-8.25±0.00	-19.88±0.00	
	1h After	-20.25±1.25	-10.12±0.11	-25.58±1.25	-16.25±0.00	-9.75±0.00	-21.38±0.00	
	Acc			-13.14±1.00			-1.25±0.00	9.5±1.3 %
B3	Before	-5.50±0.00	-0.75±0.00	-5.88 ±0.00	-12.25±0.20	-5.00±0.00	-14.75±0.20	
	1h After	-8.02±0.12	-5.85±0.12	-11.08±0.09	-15.25±0.22	-1.60±0.75	-16.04±0.17	
	Acc			-5.64±0.09			-1.85±0.49	32.6±1.2 %
B4	Before	-5.50 ±0.16	-0.45±0.10	-5.73 ±0.12	+3.25±0.00	-8.95±0.10	-1.23±0.05	
	1h After	-17.15±0.20	-0.56±0.11	-17.93±0.37	-4.95±0.10	-0.75±0.00	-5.20±0.10	
	Acc			-12.33±0.44			-4.04±0.10	32.8±1.1 %
B5	Before	-3.17±0.31	-0.40±0.12	-3.38 ±0.29	-4.50±0.00	-3.13±0.13	-6.05±0.06	
	1h After	-9.75±0.11	-2.63±0.13	-11.06±0.09	-6.25±0.00	-3.20±0.10	-7.95±0.05	
	Acc			-7.68±0.25			-1.88±0.10	24.5±1.0 %
B6	Before	-5.65 ±0.20	-2.70±0.10	-7.00 ±0.19	NA	NA	NA	NA
	1h After	-11.23±0.20	-5.44±0.21	-13.60±0.46				
	Acc			-6.54±0.55				
Mean	Before	-6.33±2.19	-2.31±2.37	-7.50±3.03	-8.56±7.02	-6.92±2.13	-11.71±6.96	
	1h After	-14.93±5.63	-5.71±3.44	-17.86±6.73	-11.74±5.04	-4.35±3.33	-14.05±6.41	
	Acc			-10.33±3.98			-2.42±1.00	23.6±8.9 %

Pilo, D and Acc stand for pilocarpine, diopters and accommodation, respectively. Ratio stands for the accommodation-amplitude after refilling to that before refilling. All figures show mean value ± SD.

Table 4

Refractions and Accommodation-Amplitudes—Group C: 100% Bag Volume Filling—

Monkey	4% Pilo	Before Refilling			After Refilling			Ratio
		Sph (D)	Cyl (D)	Equ (D)	Sph (D)	Cyl (D)	Equ (D)	
C1	Before	+2.25±0.40	-2.50±0.00	-1.00±0.4	NA	NA	NA	NA
	1h After	-9.92±0.68	-9.25±0.81	-14.63±0.61				
	Acc			-15.46±0.49				
C2	Before	+1.81±0.48	-2.65±0.20	+0.35±0.41	-1.44±0.11	-4.19±0.21	-3.53±0.05	
	1h After	-4.23±0.11	-8.06±1.62	-8.47±0.70	-3.25±0.18	-7.56±0.54	-7.05±0.14	
	Acc			-9.10±0.46			-3.48±0.17	38.1±1.0 %
C3	Before	-7.05±0.10	-1.05±0.10	-7.58±0.10	-12.50±0.18	-5.10±0.57	-15.13±0.38	
	1h After	-18.60±0.19	-1.40±0.20	-19.10±0.49	-14.13±0.22	-8.56±0.21	-18.56±0.26	
	Acc			-11.54±0.52			-3.43±0.27	29.8±1.3 %
C4	Before	-1.40±0.22	-2.20±0.37	-2.03±0.56	-4.75±0.00	-3.75±0.00	-6.63±0.00	
	1h After	-10.35±0.20	-1.05±0.10	-10.85±0.19	-6.41±0.20	-4.05±0.37	-8.57±0.56	
	Acc			-8.85±0.34			-1.94±0.56	21.9±1.3 %
C5	Before	-6.60±0.12	-2.05±0.48	-7.63±0.21	-15.85±0.20	-8.60±0.12	-20.15±0.24	
	1h After	-13.94±0.11	-2.50±0.00	-15.19±0.11	-18.90±0.38	-6.90±0.56	-22.50±0.58	
	Acc			-7.64±0.10			-2.35±0.50	30.7±1.2 %
C6	Before	+1.70±0.48	-2.65±0.20	+0.35±0.41	-6.35±0.12	-4.65±0.41	-8.72±0.35	
	1h After	-10.50±0.27	-1.31±0.11	-11.15±0.23	-8.36±0.42	-6.70±1.74	-11.75±1.02	
	Acc			-11.65±0.27			-2.35±1.18	20.2±1.9 %
Mean	Before	-1.55±3.92	-2.18±0.55	-2.92±3.41	-8.18±5.25	-5.26±1.73	-10.83±6.01	
	1h After	-11.26±4.35	-3.93±3.39	-13.23±3.49	-10.21±5.61	-6.75±1.50	-13.69±5.92	
	Acc			-10.71±2.57			-2.71±0.63	28.1±6.5 %

Pilo, D and Acc stand for pilocarpine, diopters and accommodation, respectively. Ratio stands for the accommodation-amplitude after refilling to that before refilling. All figures show mean value ± SD.

Table 5

Postoperative Scheimpflug Photography Analysis of the Macaca Monkeys

Group	4% Pilo	Anterior Chamber Depth (mm)	Lens- Thickness (mm)	Anterior Capsule Curvature (mm)	Posterior Capsule Curvature (mm)	Lens Volume (ml)
A	Before	2.52±0.25	2.50±0.17	7.74±1.01	11.20±1.54	0.079±0.002
	1h After	2.39±0.24	2.66±0.37	7.38±0.92	10.65±1.36	
B	Before	2.43±0.07	3.17±0.34	7.35±0.99	7.64±1.26	0.106±0.008
	1h After	2.32±0.05	3.35±0.24	7.07±0.84	6.91±1.52	
C	Before	2.14±0.24	3.60±0.15	6.28±0.34	NA	NA
	1h After	2.02±0.26	3.85±0.27	6.09±0.40	NA	

Pilo stands for pilocarpine. All figures show mean value ± SD.