Capsular bag refilling using a new accommodating intraocular lens

Okihiro Nishi, MD, Kayo Nishi, MD, Yutaro Nishi, MD, Shiao Chang, PhD

PURPOSE: To describe a capsular bag refilling procedure using an accommodating intraocular lens (IOL).

SETTING: Jinshikai Medical Foundation Nishi Eye Hospital, Osaka, Japan.

METHODS: A disk-shaped anterior foldable silicone accommodating IOL that serves as an optical device and as a mechanical device to prevent leakage of the injected silicone polymers was developed. The IOL optic is 6.0 mm and the overall diameter, 9.0 mm. After a 3.5 to 4.0 mm continuous curvilinear capsulorhexis (PCCC) is created, phacoemulsification and aspiration are performed in the usual manner. Then, a posteriorly placed accommodating IOL with sharp edges is implanted in the capsular bag to prevent posterior capsule opacification (PCO) and leakage of the injected silicone polymer. A PCCC is an option at this point. Then, an anterior accommodating IOL is piggybacked over the existing IOL and silicone polymers are injected between the 2 IOLs.

RESULTS: Experiments in numerous pig cadaver eyes and in 10 rabbit eyes showed minimal to no silicone leakage. In cases in which a PCCC was not created, 2 eyes had no PCO and 3 showed slight to moderate PCO. None of the 5 eyes with a PCCC had no PCO 5 to 8 weeks after surgery within the PCCC.

CONCLUSION: The procedure in rabbit eyes overcame 2 problems of lens-refilling techniques: leakage of the injectable silicone polymer and capsule opacification.

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Refilling the lens capsule with an injectable malleable material while preserving capsule integrity, including zonules and ciliary muscles, offers the potential to restore ocular accommodation.[1,2] As many experimental studies over almost 3 decades show, 2 main problems persist in capsular bag refilling. First is leakage of the injectable material from the capsular opening and second, formation of anterior (ACO) and posterior (PCO) capsule opacification.

Numerous methods to prevent leakage have been developed.[3–7] We developed an inflatable endocapsular balloon and a silicone plug to seal the capsular opening.[8,9] Using this method, we confirmed the preservation of some accommodation in a series of experiments using young Macaca monkeys. We suggest that refilling the lens capsule to preserve accommodation is technically feasible.

For such a technique to restore ocular accommodation in humans would, however, require that certain technical problems be overcome before significant clinical application can be achieved. These include refining and simplifying the technique, preventing ACO and PCO, and reducing the considerable surgically induced astigmatism resulting from even the small unilateral continuous curvilinear capsulotomy (CCC) used in the technique (unpublished data).

Recently, we developed a new concept and lens-refilling procedure that may solve these problems. We describe the technique and report the results in pig cadaver eyes and rabbit eyes.

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From Nishi Eye Hospital (O. Nishi, K. Nishi), Osaka, Japan; Moorfields Eye Hospital (Y. Nishi), London, United Kingdom; and Calhoun Vision, Inc. (Chang), Pasadena, California, USA.

The authors have a proprietary interest in the accomodating intraocular lens and procedure mentioned in the text.

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Corresponding author: Okihiro Nishi, MD, Nishi Eye Hospital, 4-14-26 Nakamichi, Higashinari-ku, Osaka 537-0025, Japan. E-mail: okihiro@nishi-ganka.or.jp.

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Figure 1. Foldable Silicone anterior accommodating IOL serves as an optic and a plug. The overall length is 9.0 mm and the optic, 6.0 mm. An injection hole is seen in the disk-shaped haptic. A 0.2 mm positioning pocket is central to the optic.

MATERIALS AND METHODS

Anterior Accommodating Intraocular Lens

An accommodating intraocular lens (IOL) (Figure 1) was developed. The IOL serves as an optical device and prevents leakage of the injected silicone polymers before they polymerize in the capsular bag. The IOL is disk-shaped, with an overall diameter of 9.0 mm and a central optic diameter of 6.0 mm. In the disk-shaped haptic, there is a small hole for placement of a 22-gauge needle through which the silicone polymers are injected. More central to the optic is a 0.2 mm positioning pocket through which the IOL is positioned using a Sinskey hook. The IOL is foldable and made of silicone.

Surgical Technique

Figure 2 shows an overview of the surgical technique. As in conventional cataract surgery, a 3.5 to 4.0 mm diameter CCC is created in the middle of the anterior capsule in the usual manner. After phacoemulsification and aspiration, ophthalmic viscosurgical devices (OVDs) are injected into the capsular bag. The foldable accommodating IOL is placed entirely in the capsular bag. Then, the OVD that was injected beneath the accommodating IOL within the capsular bag is thoroughly removed using bimanual irrigation/aspiration. During irrigation, the 22-gauge aspiration cannula is introduced through the injection hole and the OVD is aspirated. Then, the OVD is again injected into the anterior chamber in front of the IOL, with care taken not to inject it into the capsular bag. A Sinskey hook is placed in the positioning pocket, and the IOL is pushed slightly downward so the injection hole in the haptic comes close to the CCC edge. While the CCC edge is moved aside with the top of the injection needle attached to a special syringe containing silicone polymers, the needle is inserted through the injection hole underneath the accommodating IOL in the capsular bag. A mixture of silicone polymers 0.3 to 0.4 mL in volume is then injected using the device described below. The silicone polymers polymerize in 2 hours, as determined by in vitro studies.

Posterior Capsule Opacification Prevention

Refilling Without Posterior Continuous Curvilinear Capsulorhexis To prevent PCO, a posterior accommodating IOL was developed. In the procedure, a posterior accommodating IOL is implanted. The posterior IOL is similar to the anterior IOL in design but has no sharp edges and injection hole. First, the IOL is inversely inserted and the anterior accommodating IOL is piggybacked in the capsular bag. The silicone polymers are injected between the 2 IOLs. The posterior accommodating IOL helps prevent PCO by providing a sharp bend in the posterior capsule (Figure 3).

Refilling with Posterior Continuous Curvilinear Capsulorhexis In a second procedure, a small PCCC is created and the accommodating IOL is inversely implanted in the capsular bag against the PCCC. After the anterior accommodating IOL is inserted by piggybacking, the silicone polymers are injected between the 2 IOLs. The PCCC is created to help prevent PCO (Figure 4).

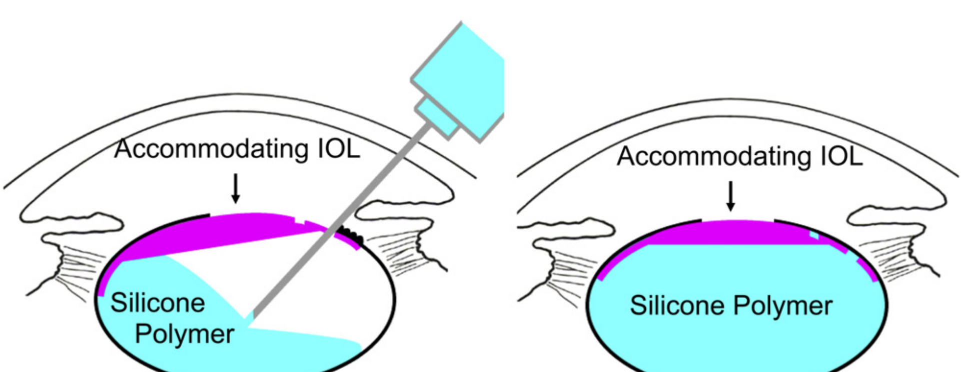


Figure 2. Schematic of the lens-refilling procedure. After phacoemulsification with a 3.5 to 4.0 mm incision is performed, a CCC is created in the usual manner. Next, the anterior accommodating IOL is folded and implanted in the capsular bag. An injectable silicone polymer is then injected beneath the IOL through the delivery hole while the CCC edge is pulled aside slightly.

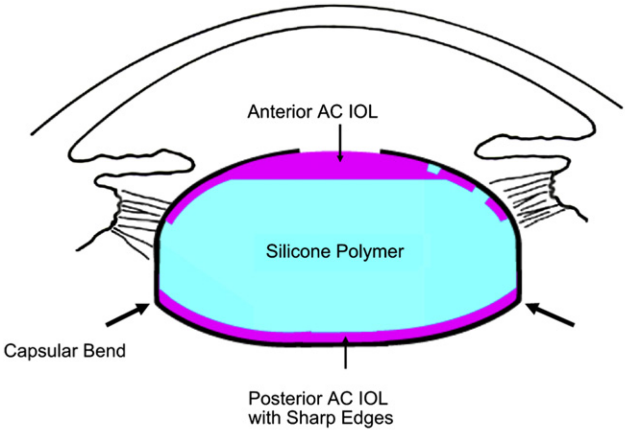


Figure 3. To prevent PCO, a posterior accommodating IOL similar in design to the anterior accommodating IOL but with sharp edges is implanted. Silicone polymers are injected between 2 IOLs. The sharp optic edge should create a capsular bend (AC IOL = accommodating intraocular lens).

Injection of Silicone Polymers

Silicone polymers are injected using an injection apparatus (Dispenser 1500XL, EFD Inc.). A 22-gauge blunt needle is attached to a special syringe (3 mL), and its cylinder is pushed by a gas compressor, which is operated by a foot switch. The speed of the syringe and volume of the injection can be programmed preoperatively.

Pig Cadaver Eyes

Silicone polymers were injected into pig cadaver eyes. When the injected silicone polymers polymerized the day after surgery, the refilled lens was removed from the eye.

To test the security of leakage prevention, the pig cadaver eyes were refilled with 0.3 to 0.4 mL of silicone polymers. The cornea was removed by a circumferential incision at the limbus, and the accommodating IOL was pushed downward with considerable force using a Sinskey hook. After the amount of leakage was noted, the IOL was pushed farther using increasing force.

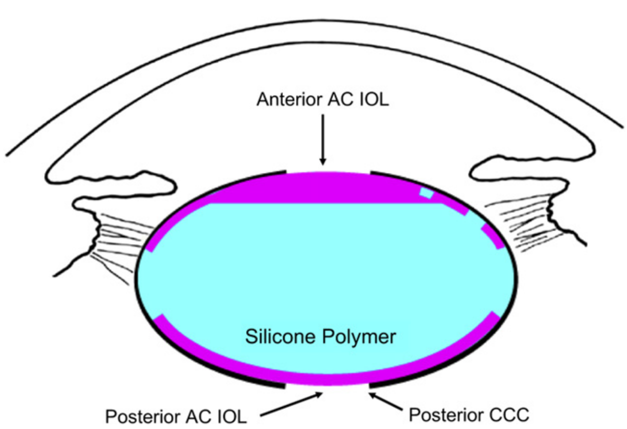


Figure 4. A PCCC is created to prevent PCO. A posterior accommodating IOL is inversely implanted to seal the PCCC. Silicone polymers are injected between the 2 IOLs (AC IOL = accommodating intraocular lens; CCC = continuous curvilinear capsulorhexis).

Rabbit Eyes

The crystalline lens was consecutively refilled in 5 rabbit eyes (Table 1). One eye received a posterior accommodating IOL with sharp edges, and the contralateral eye had PCCC and implantation of a posterior accommodating IOL. After 5 to 8 weeks, the rabbits were killed by an injection of ketamine chloride (0.5 mg/kg) and succinylcholine chloride (0.15 mg/kg) and the eyes were enucleated. Slitlamp observations were noted, and gross stereomicroscopic and histopathologic examinations were performed.

RESULTS

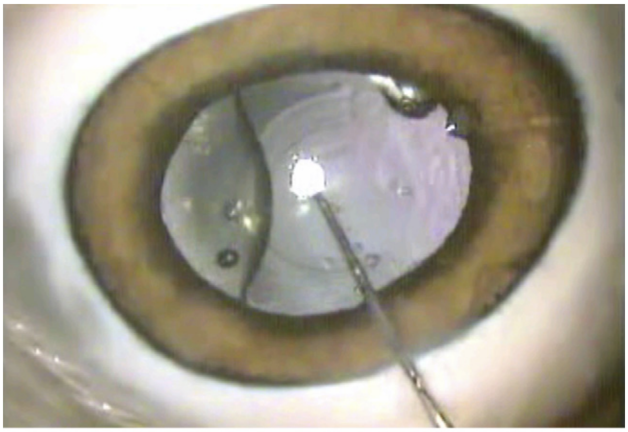
Pig Cadaver Eyes

Initial Refilling A small amount of silicone polymers leaked through the injection hole when the injection needle was withdrawn, and the CCC slowly returned to its original position, covering the injection hole in the disk haptic. This leakage occurred infrequently and could be easily removed by aspiration or irrigation. Once the injection hole was covered by the anterior capsule, there was no further leakage. Even with nonstandard positioning overnight, there was no leakage in any eye the next morning. After the injected silicone polymers polymerized the day after surgery, the refilled lens was removed from the eye. There was a resiliency similar to that of the original crystalline lens.

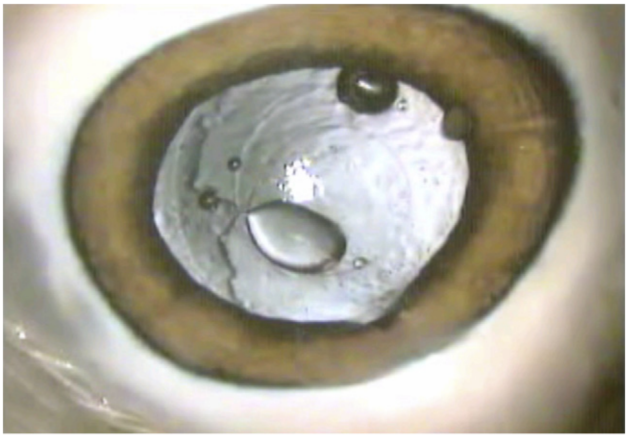
Leakage Test After the pig cadaver eye was refilled with silicone polymers and the cornea removed, and the accommodating IOL was pushed downward to test for leakage. The silicone polymers first appeared over the peripheral haptic. When the accommodating IOL was pushed farther with increasing force, the silicone polymers moved farther centrally to the CCC edge. When the pushing force on the accommodating IOL was stopped, the silicone polymers returned slowly to their original position beneath the IOL (Figure 5, *A*). With continuous pushing force on the IOL, the silicone polymers extended to the CCC edge and in some cases parted, segregated, and leaked into the anterior chamber (Figure 5, *B*). When the Sinskey hook was lifted and the IOL no longer pushed, the IOL returned to its original site, the leaking silicone polymers returned to beneath the IOL, and there was no further leakage. The silicone that did leak could be removed by aspiration or irrigation.

Rabbit Eyes

Figure 6 shows a slitlamp view of a rabbit eye with a refilled crystalline lens, 2 accommodating IOLs, and



A



B

Figure 5. Testing for leakage. *A*: When the IOL was pushed eccentrically, silicone extruded between the IOL and anterior capsule but then returned when the Sinskey hook was lifted, even though the silicone reached the CCC edge. *B*: When the force was continuous, a small amount of silicone leaked. When the force was stopped, the silicone slowly returned to behind the IOL, segregating the leaked silicone, which could be separately irrigated or aspirated.

no CCC. All lenses were successfully refilled. There was a small amount of leakage in some eyes that could be removed by aspiration or irrigation at the end of surgery.

Stereomicroscopy With stereomicroscopic observation, no significant leakage of silicone polymers was seen in any eye. The capsular bag was refilled well in all but 1 eye. When the anterior accommodating IOL was pushed posteriorly and the posterior accommodating IOL was pushed anteriorly with a spatula via the posterior capsule, a resiliency similar to that of the original crystalline lens was noted.

Capsule Opacification The remaining anterior capsule showed almost no fibrosis and remained relatively clear. None of the PCO observed was fibrotic in nature.

Refilling Without Posterior Continuous Curvilinear Capsulorhexis Two eyes (R1 and R2) were free of PCO (Table 1). In these eyes, a distinct capsular bend was seen around the entire circumference (Figure 7). In 2 eyes, slight PCO was observed and the capsular bend was seen only partially throughout circumference. One eye had moderate PCO; no capsular bend formation was seen.

Refilling with Posterior Continuous Curvilinear Capsulorhexis All eyes were PCO free within the PCCC (Table 1). The remaining area of the posterior capsule had slight to moderate PCO in all eyes. The opacification appeared to consist mainly of migrating lens epithelial cells (LECs) (Figures 8 to 10) and was not fibrotic in nature. Histopathologic examination was not performed.

DISCUSSION

When capsule integrity was preserved, there was little to no leakage of the injectable silicone compound in pig eyes or rabbit eyes. Even in the pig cadaver eyes that were maintained deliberately perpendicularly during polymerization, there was no silicone leakage the following day. There was also no silicone leakage in the rabbit eyes, although the eyes were always positioned perpendicularly. These findings suggest that there would be no leakage should a patient stand up immediately after the procedure. Leakage can occur when the accommodating IOL is forcibly pressed

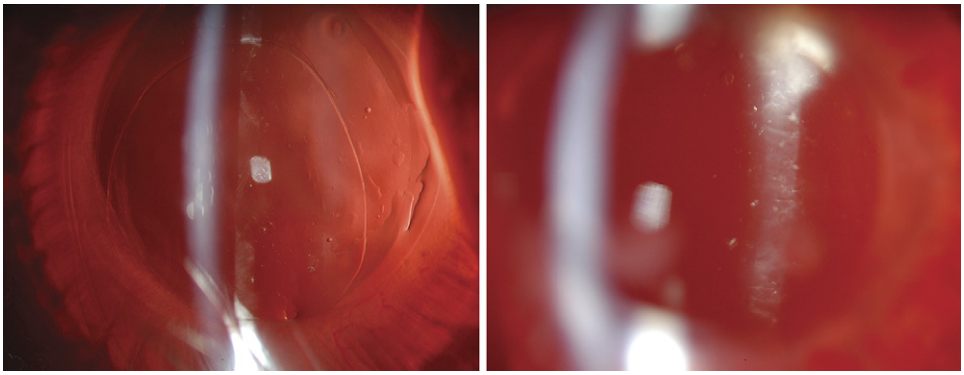


Figure 6. A refilled rabbit crystalline lens with 2 accommodating IOLs without CCC. Five weeks after surgery, the IOL was firmly and securely fixed. There was no leakage of the injected silicone compound. *Left*: Anterior CCC and anterior accommodating IOL. *Right*: Posterior accommodating IOL under the slitlamp. The posterior capsule is clear.

Table 1. Results in the rabbit eyes refilled with 2 accommodating IOLs and enucleated.

Rabbit	Postop Period (Wk)	Filling	Capsular Bend	PCO Degree*	PCO Within PCCC
R1					
Without PCCC	8	Well refilled, no leakage	Circumferential	–	NA
With PCCC		Poorly refilled, no leakage		+	–
R2					
Without PCCC	6	Well refilled, no leakage	Circumferential	–	NA
With PCCC		Well refilled, no leakage		+	–
R3					
Without PCCC	5	Well refilled, no leakage	Partial	+	NA
With PCCC		Well refilled, no leakage		+	–
R4					
Without PCCC	7	Well refilled, no leakage	Partial	+	NA
With PCCC		Well refilled, no leakage		+	–
R5					
Without PCCC	7	Well refilled, no leakage	No bend	++	NA
With PCCC		Well refilled, no leakage		++	–

NA = not applicable; PCCC = posterior continuous curvilinear capsulorhexis; PCO = posterior capsule opacification
*– = no PCO; + = slight PCO; ++ = moderate PCO; +++ = severe.

posteriorly, mimicking what happens when patients vigorously press or rub the eye.

When leakage did occur as a consequence of the silicone injection, it was a small amount that could be easily aspirated or irrigated. Postoperatively, no leakage was noted in any rabbit eye. Thus, this highly reproducible surgical technique using the accommodating IOL could successfully prevent leakage of injectable silicone polymers.

Our early studies[7,8] showed that silicone leakage can be successfully prevented through an upper mini-CCC (approximately 1.2 mm) when it was sealed by a single plate silicone plug slightly larger than the mini-CCC diameter. The principle of sealing the CCC should be the same, independent of CCC size. That the anterior accommodating IOL seals such a large CCC opening and thus prevents silicone leakage is consistent with our previous experience. Because the injected polymer presses the IOL from inside the capsular bag against the CCC and anterior capsule, and possibly as a result of the buoyancy of the silicone, the injected, very cohesive silicone polymer with its high molecular weight does not leak through the space between the anterior capsule and IOL unless the IOL is pushed very far posteriorly (Figure 11).

Similarly, the inversely implanted posterior accommodating IOL also sealed the PCCC, preventing silicone leakage. The operative principle may be the same as for the anterior CCC. This general principle should be recognized in future development of capsular bag refilling.

Historically, leakage of the injectable IOL was the main problem preventing clinical application of the lens-refilling procedure. Therefore, preventing

Figure 7. Posterior view of an enucleated rabbit lens refilled with 2 accommodating IOLs without PCCC 5 weeks after surgery. The arrows show the distinct posterior capsule bend created by the sharp edge of the posterior accommodating IOL. There is no PCO as the letters can be clearly seen.

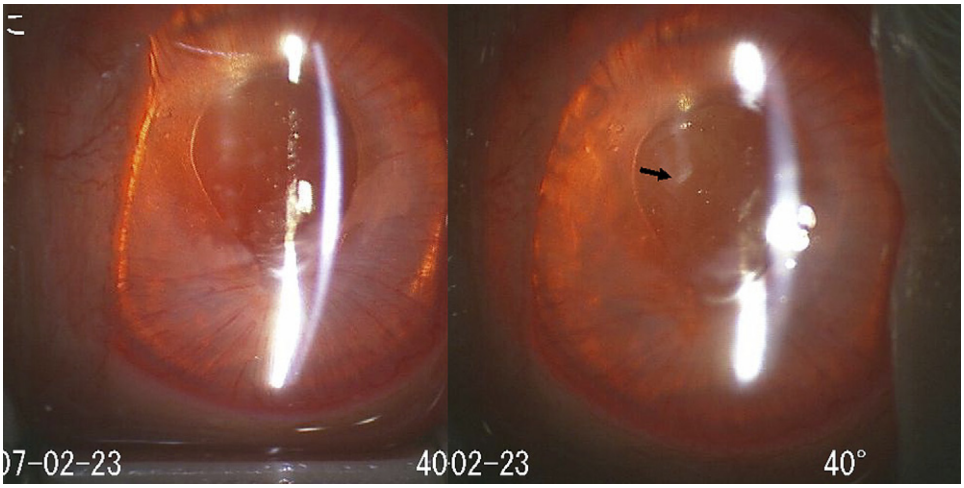


Figure 8. Slitlamp findings in a rabbit eye that was refilled with 2 types of accommodating IOLs and in which a PCCC was created. *Left*: The anterior capsule and anterior accommodating IOL. The capsule is refilled, and there is no leakage. *Right*: The posterior capsule and posterior accommodating IOL under the slitlamp. The arrow shows the apparently fibrotic PCCC edge in the slit.

the leakage is crucial for a lens-refilling procedure to be clinically useful. We think the present technique could be a breakthrough in the lens-refilling procedure and contribute to its future development.

Capsule opacification occurred in all rabbit's eyes with a few exceptions in which LECs were removed drastically.[10] Although neodymium:YAG laser posterior capsulotomy will not cause herniation or leakage of the injected silicone,[11] posterior capsulotomy may affect the accommodation attained.

In an attempt to prevent LEC migration, we implanted a posterior accommodating IOL with sharp edges. In the posterior view, there was a distinct capsular bend at the sharp edge of the IOL in some eyes. In the other eyes, however, the bend was not distinct and formed only partially throughout the circumference or did not form at all. In these eyes, there was significant migration of LECs. Bend formation may depend on the amount of silicone injected, which may in turn depend on the desired postoperative refraction. Further evaluation of whether this method can eliminate PCO is warranted.

No PCO, at least within the PCCC area, was observed in the eye with a PCCC at least 5 to 8 weeks after surgery. This was an expected outcome. No silicone leakage was seen in any of these eyes.

Under slitlamp examination and stereomicroscopic observation of the rabbit eyes, ACO in the form of capsule fibrosis was not seen, even 8 weeks after surgery. This may be due to characteristics of the IOL material. Posterior capsule opacification in the form of LEC migration was observed, but there was no fibrosis except what seemed to be fine fibrotic structures at the margin of the PCCC, although we did not perform a histologic examination.

The question is whether the opacification observed in the periphery as the cell mass of migrating LECs significantly affects the accommodating response. These cell masses can be regarded as lens regenerates, compared to the silicone, which might be expected not to

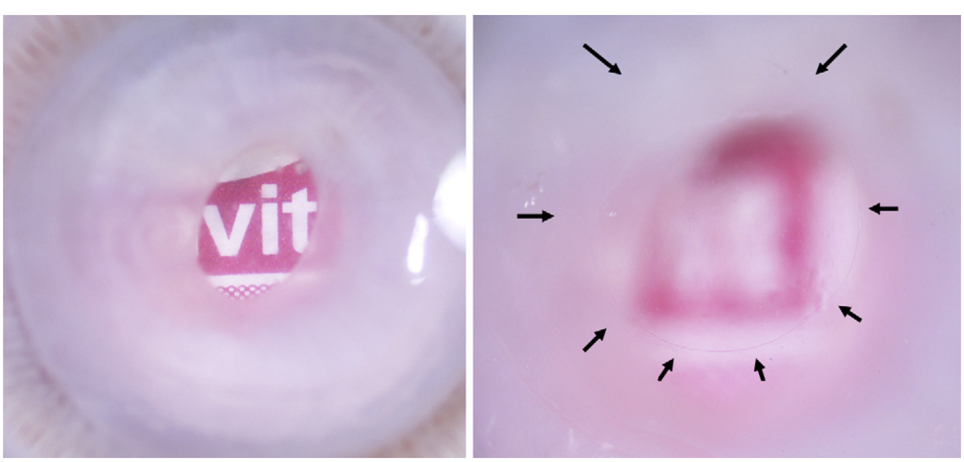


Figure 9. Posterior view of an enucleated rabbit lens refilled with 2 accommodating IOLs with PCCC 6 weeks after surgery. *Left*: The visual axis is PCO free as the letters can be clearly seen. *Right*: The arrows show the PCCC edge.

Figure 10. A refilled rabbit capsule with PCCC. The iris was removed. The visual axis is clear. The peripheral opacification was mainly caused by PCO, which apparently consisted of migrating LECs.

interfere with the elastic properties of the residual lens capsule. However, the physical properties of these masses, including the elastic property, may significantly differ from those in the physiological condition, possibly affecting the accommodating response. This is one of the numerous questions about lens refilling future studies may address.

The peripheral PCO may also affect visualization of the peripheral retina through a small PCCC. The only solution may be the prevention of PCO by eliminating the residual LECs, although in the past numerous methods have been developed, none of which have been proved to be easy, simple, safe, and effective as a routine clinical procedure. If an effective means is developed, the posterior accommodating IOL, as well as PCCC in our procedure, will become unnecessary, rendering the procedure even simpler.

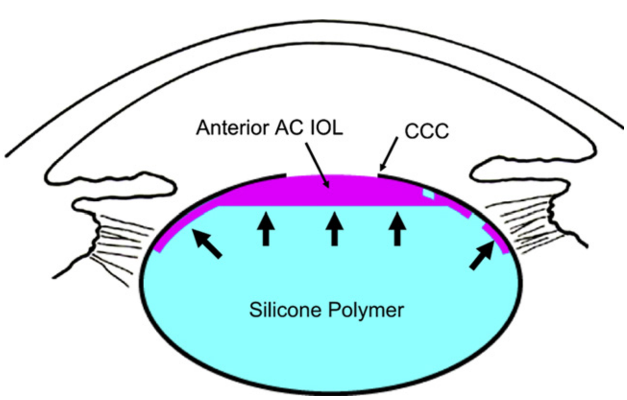


Figure 11. The principle of preventing leakage of injectable silicone. The injected silicone polymer presses the IOL from the inside of the capsular bag against the CCC and anterior capsule (*arrows*). The injected silicone polymer did not leak through the space between the anterior capsule and IOL unless the IOL was pushed very far posteriorly (AC IOL = accommodating intraocular lens; CCC = continuous curvilinear capsulorhexis).

Another advantage of the second IOL in addition to PCO prevention may be that it could enhance the accommodation-amplitude attained. The IOL can have a concave optic with minus dioptric power, which may give a greater power to the anterior accommodating optic, resulting in emmetropia. During accommodation, an anterior optic with a greater power when it moves forward may enhance the accommodation-amplitude attained.[12]

In this series, we observed ACO and PCO in the visual axis but no silicone leakage. Anterior CCCs and PCCCs, however, do not provide an optimum range of accommodation. A change in the anterior capsule curvature, including the fully preserved elasticity of the lens capsule, which may be the main factor for accommodation, may not occur. Therefore, the proposed mechanism of accommodation in this procedure may be a dual-optic shift of the accommodating IOLs and possibly steepening of the anterior curvature of the IOL when a very soft, very thin membranous accommodating IOL is used.

These problems and questions can be answered only in studies of primates. Because the present technique effectively solves the major setback to previous injectable IOL techniques (ie, leakage of the injectable silicone polymers) and is easy to perform and highly reproducible, we will soon perform a primate experiment and report the results.

In conclusion, restoration of accommodation by refilling the lens capsule is a goal of refractive cataract surgery. Technical feasibility has been repeatedly shown in primates by the creation of useful accommodation. Leakage of the injectable materials and formation of capsule opacification have hindered the development of the procedure in the past. The technique we describe may provide a future breakthrough for possible clinical application of lens capsule refilling.

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First author:
Okihiro Nishi, MD

Nishi Eye Hospital, Osaka, Japan