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## ACCOMMODATING INTRAOCULAR LENSES

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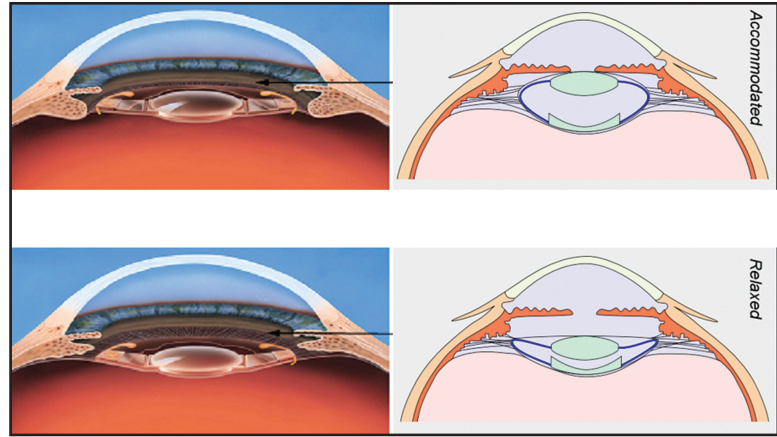
Surgical restoration of accommodation with accommodating intraocular lenses (A-IOLs) presents a complex set of problems involving functional mechanisms for accommodation, optical properties and aberrations, and interactions with binocular eye alignment (the near response). A variety of lens designs are currently used that translate the A-IOL toward the cornea along the sagittal axis, shear 2 lens components laterally, or deform lens shape to change dioptric power of the eye during attempts to accommodate. All of these designs attempt to alter the refractive power of the eye (pseudophakic accommodation). However, success of some of the designs can be attributed to dynamic increases in aberrations during attempted accommodation that extend the depth of focus (DOF) to include near vision stimuli (pseudoaccommodation). In all of these designs, the effective biomechanical properties (elasticity and viscosity) of these lenses depend on both material properties and the structural design of the A-IOL. Inevitable mismatches between the neuromuscular control of accommodation and the effective biomechanical properties of the prosthetic lens could lead to either unstable oscillations or sluggishness of dynamic accommodation; however, optimal dynamic

responses may possibly be restored by neural recalibration with training. Other neural adjustments that could contribute to success include changes in pupil size and neural deblurring. Additional design issues for A-IOLs include stability of optical properties and interactions of restored accommodation with binocular eye alignment (the near response).

### ACCOMMODATING INTRAOCULAR LENS DESIGNS

The natural crystalline lens with cataracts is usually replaced with a prosthetic IOL that has a fixed power to produce emmetropia or a dioptric power that is useful for near vision. Some of these static lenses are multifocal (see Chapter 18), and their added aberrations extend the DOF and clear vision range (pseudoaccommodation). Industry has embarked on a highly innovative endeavor to treat both presbyopia and cataract with a single surgical procedure. Instead of implanting a fixed-power IOL into the lens capsular bag, the new procedure implants an IOL that is designed to change the power or focal length of the

**Figure 19-1.** Accommodated (top) and disaccommodated (bottom) states of single- (left column) and dual-optic (right column) translating intraocular lenses. (Reprinted with permission from Schor C. Charles F. Prentice Award Lecture 2008: surgical correction of presbyopia with intraocular lenses designed to accommodate. *Optom Vis Sci.* 2009;86(9):E1028-E1041.)



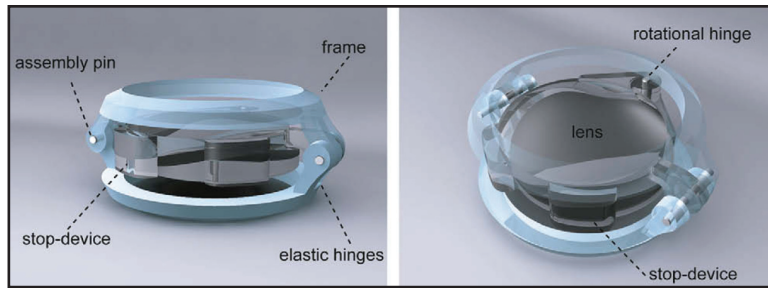
eye with natural efforts to accommodate. Several different lens designs are available for restoring dynamic accommodation, including injectable polymers that refill the lens capsule and change shape in much the same way as the natural lens does and sagittal-axial translating lenses that increase power of the eye by moving the lens anteriorly closer to the cornea (Optic-shift principle).<sup>1</sup> Both of these dynamic designs are referred to as accommodating A-IOLs. Success criteria for dynamic designs include retinal image quality, correction of refractive error, subjective behavioral measures of the amplitude, or total range of accommodation, as well as objective measures, with an aberrometer, of the response dynamics in terms of speed and stability.

### *Sagittal Translating Accommodating Intraocular Lenses: Single and Dual Optic*

Some of the dynamic A-IOL designs resemble the mechanisms of accommodation found in nonprimate vertebrates. For example, translating A-IOLs are designed to operate like the accommodation in the cat. This A-IOL is designed to translate fore-and-aft from the cornea with contraction and relaxation of the ciliary muscle, respectively, following the principle that the effective power of 2 plus lenses increases with their proximity. Single- and dual-optic applications of this design are shown in Figure 19-1, which illustrates the accommodated (top) and unaccommodated (bottom) states. The translating lens is positioned on the anterior surface or within the capsular bag with hinged haptics that flex the lens toward the cornea when the ciliary muscle constricts, much like a flexed playing card pinched across its edges. The amount of power change

depends on the magnitude of translation and the positive dioptric power of the lens. Theoretically, up to 1.50 D of accommodation could be achieved with the translating single-optic A-IOL, such as the Tetraflex IOL (Lenstec, St. Petersburg, FL) and Crystalens IOL (Bausch & Lomb, Rochester, NY).<sup>1</sup> Translation amplitude and corresponding optical power changes can be increased with springs and magnets.<sup>1</sup> The power change of the translating lens has been increased in a dual-optic design<sup>2</sup> that combines a more powerful positive lens with a negative lens, similar to the arrangement of a Galilean telescope (Synchrony IOL [Visogen, Irvine, CA]). The translating positive front optic is combined with a stationary negative rear optic and, because the front optic has a larger dioptric power than the single-optic design, the dual optic could theoretically achieve 3.00 D of accommodation with a large 1.5-mm translation.<sup>1,2</sup>

The single-optic Tetraflex and Crystalens IOL translating lens designs are currently being prescribed. Thus far, however, there is little empirical objective evidence to demonstrate their intended action in response to natural defocus stimuli to accommodation or during attempts to converge on near targets.<sup>1,3</sup> The dynamic response of the dual optic (Synchrony) is estimated to be 2.50 to 3.00 D for expected translations during attempted accommodation.<sup>2</sup> Failure to change power of the single-optic designs may be a consequence of postsurgical capsular fibrosis that stretches and immobilizes the capsule-IOL diaphragm. However, these translating A-IOLs extend the DOF in the same way as fixed-focus IOLs, by increasing the positive spherical aberration of the eye. This increased DOF is a consequence of the natural positive spherical aberration of the cornea that is normally negated by the negative spherical aberration of the crystalline lens.<sup>4</sup> Vaulting of the single-optic lens



**Figure 19-2.** Turtle lens design based on the Alvarez principle of sliding cubic surfaces to change dioptric power. (Reprinted from *J Cataract Refract Surg*, vol 34(12), Hermans EA, Terwee TT, Koopmans SA, Dubbelman M, van der Heijde RGL, Heethaar RM, Development of a ciliary muscle-driven accommodating intraocular lens, pp 2133-2138, Copyright 2008, with permission from Elsevier.)

during attempts to accommodate can introduce higher-order aberrations, such as coma, that also increase the DOF and the clear vision range. Both the standard static IOLs and translating dynamic A-IOLs have less negative spherical aberration than the natural lens; therefore, the positive spherical aberration of the cornea is no longer nulled by the IOL. The extended DOF in pseudophakic eyes is similar for fixed-focus IOLs and translating A-IOLs, and the DOF accounts for pseudoaccommodation, as measured with subjective methods, that quantify the clear vision range.<sup>4,5</sup> Finally, LiquiLens is a dual-liquid, gravity-dependent lens composed of a single optic with 2 immiscible fluids of a different refractive index. With downgaze, the liquids change position to produce increased power of up to 30 D.

### Lateral Translating (Shearing) Accommodating Intraocular Lenses

A recently developed dual-lens system (Turtle IOL [Abbott Medical Optics, Santa Ana, CA]; Figure 19-2) is based on the Alvarez lens principle that translates (shears) 2 lenses in opposite directions parallel to the plane of their contact. The lens surfaces have cubic profiles, one the reverse of the other, so that shearing them across one another varies their combined power. Shearing the lens surfaces across one another is achieved with the Turtle IOL by differential rotation of the dual lenses about an axis that is parallel to and decentered from their optical axes to achieve potential optical power changes of up to 8.00 D. The closest biological analog is the sliding nictitating membrane in the diving bird's eye (ducks, loons, auks), which was thought to assist accommodation underwater with a clear lens-like central window composed of highly refractive material that is capable of bending light rays under water. However, the nictitating membrane of some diving birds (double-crested cormorant, brown

pelican, black guillemot, and hooded merganser duck) has been shown to have a similar index of refraction as the cornea and is unlikely to serve as a refractive element in water in these species. The dual-lens Turtle IOL is inserted in the lens bag, and activation of the rotating hinge between the dual lens components is achieved by changing the separation between the 2 lenses during ciliary muscle contraction,<sup>6</sup> just as with the dual-lens translating Synchrony IOL described previously. The Turtle IOL prototype has been tested in an enucleated pig's eye. However, its ultimate success in humans depends on the amount that lens separation can be changed by attempts to accommodate and the postsurgical stability of elastic forces of the lens capsule.

### Refilled Lens Bag With Injectable Polymers

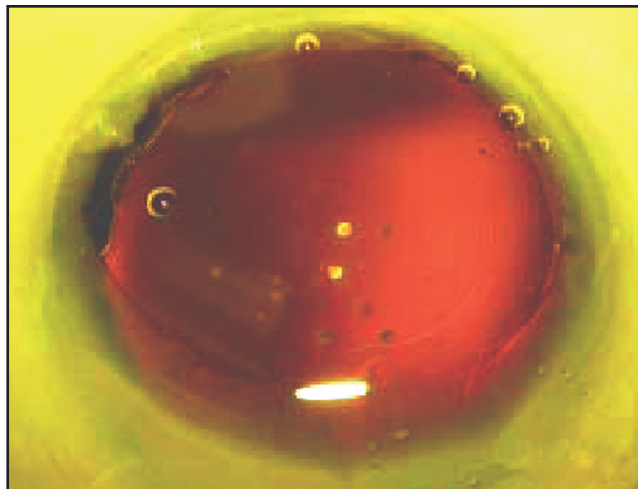
Another A-IOL design is a deformable lens that changes shape like the natural lens. It is produced by refilling the lens capsular bag with an elastic injectable polymer. An endocapsular balloon can also be inserted into the capsular bag and inflated with the polymer.<sup>7</sup> Alternatively, a small dehydrated rod (Smart Lens [Medennium Inc, Irvine CA]) may be inserted into the capsular bag, and, when hydrated, it takes up the shape of a full-size lens. The refillable lens designs have the most promise for producing large dioptric changes that would allow accommodation to near targets lying within arm's reach. However, unlike the gradient index of refraction of the natural lens that increases its effective power, these lenses have a uniform index of refraction, such that either they need a higher index of refraction than the natural lens or greater curvature to restore both emmetropia and a large range of accommodation. The lower refractive index needed to correct myopic refractive errors limits the amplitude of accommodation. Some efforts have been made to adjust the thickness and surface shape of an injected polymer after light-adjustable lens

implantation surgery to customize and correct spherical, cylindrical, and other higher-order aberrations with a cool-UV laser mounted on a slit lamp<sup>8</sup> (see Chapter 20). The concept is analogous to postoperative adjustable sutures in oculomotor surgery for strabismus. This technology would allow the surgeon to make fine postoperative adjustments of prosthetic lens power and aberrations.

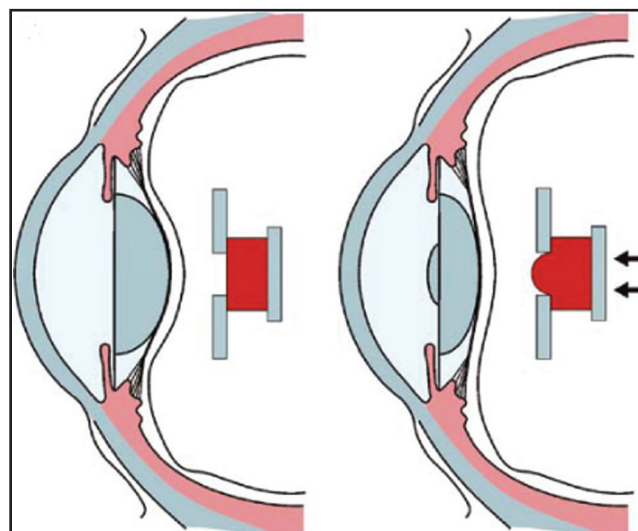
Several difficulties with surgical procedures currently prohibit the prescription of the deformable lenses based on refilling the lens capsular bag. These problems include leakage of the injected polymer from the capsule opening that is used to remove the natural lens; air bubbles, which can act as multiple Scheiner pupils (Figure 19-3) that could result in monocular diplopic or polyopic images of out-of-focus images; lens sag or shape changes in the deformable lens that could occur over time and degrade image quality by producing off-axis aberrations such as coma or astigmatism; and the formation of anterior and posterior capsular opacities, which are a problem for all IOLs. Capsular opacification is exacerbated with capsular stress produced by refillable lenses. Laser removal of opacified portions of the capsule near the optical pole of the lens is routinely performed for fixed-power static IOLs, but this could interfere with the stability of capsule elastic forces and deformable polymers and could result in polymer leakage or optical distortions. The anterior and posterior capsular opacification appears to be the biggest obstacle to the successful use of capsular-refilling deformable A-IOLs.<sup>2</sup>

### Posterior Piston Bulge

A fourth design works similarly to the accommodative system of diving birds, such as the cormorant. Because the refractive index of the cornea is similar to that of water, the refractive power of the diving bird's cornea is eliminated when it enters the water. These birds lose as much as 40.00 to 50.00 D of power that is restored by lenticular accommodation when submerged. Large amounts of accommodation are produced by pinching the front surface of the ocular lens with the iris muscle to produce a bulge of the lens into the natural pupil. The NuLens (NuLens Ltd, Herzeliya, Israel) is a prosthetic A-IOL that is based on this principle. It has a piston-like action that presses an elastic-pliable material against a small opening in the front surface of the piston chamber, causing an anterior bulge during accommodation (Figure 19-4). It operates like squeezing a tube of



**Figure 19-3.** Refilled lens capsule with air bubbles. (Reprinted with permission from Schor C. Charles F. Prentice Award Lecture 2008: surgical correction of presbyopia with intraocular lenses designed to accommodate. *Optom Vis Sci.* 2009;86(9):E1028-E1041.)



**Figure 19-4.** NuLens diagram illustrating the piston mechanism of accommodation that decreases dioptric power when the ciliary muscle is constricted. (Reprinted with permission from Menapace R, Findl O, Kriechbaum K, Leydolt-Koepl Ch. Accommodating intraocular lenses: a critical review of present and future concepts. *Graefes Arch Clin Exp Ophthalmol.* 2007;245(4):473-489.)

toothpaste or a caulking tube. The lens apparatus is placed in the sulcus and rests behind the iris against the anterior surface of the capsular diaphragm. This lens has the potential for larger changes in accommodation. However, the original design provides near focusing under conditions of ciliary muscle relaxation, which is opposite to the effects of ciliary muscle contraction on the natural lens. The capsule

presses forward on the lens when the ciliary ring is dilated. This could be problematic for binocular eye alignment that is influenced by the cross-coupling between accommodation and convergence. With the NuLens, efforts of accommodation would be associated with divergence, and efforts of disaccommodation would be associated with convergence, making clear, single binocular vision difficult if not impossible.

## PSEUDOPHAKIC RESPONSE DYNAMICS

All A-IOL designs have lower effective stiffness (higher compliance) than the natural older lens. The injectable-polymer designs can have either higher or lower effective viscosity than the natural lens. The viscoelastic properties of the axial translating lens designs are mainly structural and depend on the hinge-like mechanism of action and fluid drag of the translating lens enclosed in the chamber of the lens capsular bag. The issue of fluid drag applies to a capsule-filling, dual-lens translating system, and translation speed is modulated by the rate of fluid flow caused by lens displacement as well as by the intrinsic viscosity of the springs that link the 2 lenses. Evaluation of these devices has thus far been limited to the subjective measures of the amplitude of accommodation and near visual acuity, and these measures could be influenced by both DOF and changing optical power. Objective measures with aberrometers have yet to demonstrate any appreciable dynamic accommodation by any current A-IOL design under conditions of natural efforts to accommodate.<sup>1,3</sup> It is not known whether dynamic accommodation with these A-IOLs could eventually be restored with adaptive training.

Dynamic performance of an A-IOL is determined, in part, by how closely the biomechanics of the prosthetic lens are matched to the neuromuscular control of dynamic accommodation. Biomechanical properties of elasticity, viscosity, and mass of the A-IOL are determined by both material properties and structural design of the lens.<sup>2</sup> If the biomechanics of the A-IOL are mismatched to neural control, then accommodation could be overdamped and sluggish or underdamped and unstable.<sup>9</sup> Because the neural system controlling accommodation has adapted to slow down the decline of accommodation by compensating for the age-related biomechanical changes in the natural lens, a mismatch is inevitable when an

older biological lens is replaced with a “younger” more compliant prosthetic lens. The same effort used to control the older lens could be excessive for a more compliant prosthetic lens.

## AMPLITUDE OF PSEUDOPHAKIC ACCOMMODATION

What is the minimum amount of dynamic accommodation needed for functional restoration of accommodation with an A-IOL? The limited potential amplitude of accommodation in currently prescribed A-IOLs (less than 2.00 D) could present more problems than benefits. Accommodating IOLs that restore only a few diopters of accommodation are equivalent to producing the state of an incipient presbyope who can no longer accommodate within arm’s reach. Unless the DOF was also increased with additional aberrations to extend the range of clear vision to within arm’s reach, the patient would have symptoms of a functional presbyope and still would require optical aids for near vision tasks such as reading. Generally comfortable accommodation utilizes no more than half of the accommodative range (modified Sheard’s criterion).<sup>10</sup> Thus, to accommodate 2.50 D for a 40-cm viewing distance, there should be at least a 5.00-D amplitude of accommodation. If the range of dynamic accommodation is less than this, more useful near vision could be provided by increasing the DOF with aberrations, such as those afforded by the multifocal lenses, or by monovision designs that use one eye for distance and the other for near viewing distances<sup>6</sup> (see Chapter 16). Aberrations can increase with attempts to accommodate and produce dynamic pseudoaccommodation.

## OCULAR ABERRATIONS AND DEPTH OF FOCUS IN PSEUDOACCOMMODATION

What is the role of ocular aberrations in extending the DOF and range (amplitude) of useful accommodation? The natural lens normally has negative spherical aberration that reduces the positive spherical aberration of the cornea. The magnitude of negative spherical aberration increases with accommodation of the natural lens as a result of the aspheric-hyperbolic increase in the central curvature that is molded by

variations in lens capsule thickness. This has the effect of changing the overall positive spherical aberration of the eye in the unaccommodated state to a negative spherical aberration in the fully accommodated state. This transition from positive to negative spherical aberration with accommodation facilitates the useful DOF so that focusing at far leaves a large near-range of distances in focus, and focusing at near leaves a large far-range of distances in focus. When the natural lens is removed surgically and is replaced with a prosthetic IOL that does not have negative spherical aberration, there is an overall net increase in the positive spherical aberration of the eye that is present in the cornea. This has the consequence of extending the DOF (pseudoaccommodation).<sup>4</sup> This increase in spherical aberration is exaggerated in the multifocal IOL, which has increased aberrations.

Measures of the ocular wavefront in Crystalens patients can also increase during attempted accommodation, resulting in an increase in the DOF and reading performance,<sup>11</sup> even when the increase in DOF is associated with both a hyperopic shift in the conjugate focus and an equivalent defocus of the wavefront aberrations. Both increases and decreases in pupil size can interact with aberrations to determine the DOF. Increases in pupil size can increase higher-order aberrations, such as spherical aberration, resulting in improved retinal image quality of out-of-focus images and effectively increasing the DOF. Decreases in pupil size can limit rays entering the eye to the paraxial bundle and also increase the DOF. Pupil size can adapt to ocular aberrations to optimize retinal image quality of out-of-focus images. Indeed, the level of aberration present in an eye has an influence on pupil size. Sakai et al<sup>12</sup> found that a light-adapted pupil showed significant positive correlation with the image quality metric “neural sharpness.”

## BINOCULAR EYE ALIGNMENT

How might the limited range of dynamic accommodation provided by an A-IOL impact binocular eye alignment? Neural control issues for A-IOLs might require adaptation of the neural control of the near response when prosthetic lens materials are surgically implanted. For example, if surgical restoration of accommodation provides an insufficient amplitude of accommodation, the high efforts needed to fully accommodate could interfere with

binocular eye alignment by disrupting the normally balanced cross-coupled interactions between accommodation and convergence (see Chapter 12). The typically quoted 2.00- to 3.00-D maximum restoration of accommodation by A-IOLs<sup>1</sup> places most near tasks within arm’s reach in the upper soft-saturation region of the restored range of accommodation. This is similar to the effects of partial cycloplegia or the late stages of incipient presbyopia that result in excessive convergence (an elevation of the AC/A ratio). The limited accommodation amplitude of current A-IOL designs effectively reverts absolute presbyopia to a late stage of incipient or functional presbyopia. The small accommodative amplitudes could result in excessive accommodative effort and accommodative convergence in the upper saturation region and might then elevate the AC/A ratio.<sup>13</sup> Increased accommodative convergence could lead to an increase in esophoria (or esotropia) at near viewing distances and cause general discomfort from attempts to maintain binocular alignment with fusional divergence.

The interaction between accommodation and convergence cannot be suspended temporarily to allow the accommodation and convergence systems to operate independently. Conflicts between efforts for accommodation and convergence can be compensated on a short-term basis by disparity vergence and optical reflex accommodation over a limited range, as described by the width of the zone of clear and single binocular vision (ZCSBV); however, asthenopia is associated with combined responses of accommodation and convergence near the limits of the ZCSBV (Percival’s criterion), and conflicts between efforts of accommodation and convergence also degrade stereopsis by elevating stereo thresholds.<sup>14</sup> On a longer-term basis, it is possible to increase or decrease the strength of the cross-coupling interactions, either by fatigue or as a result of motor adaptation to stimulus conflicts to the 2 systems. However, adaptation ability is biased to produce greater increases than decreases in the strength of these interactions, and limited amplitudes of accommodation with the A-IOL would require the latter.

Given that older incipient presbyopes, whose AC/A ratios have become elevated, do not adapt to restore the normally lower AC/A ratio, it is not likely that patients with limited amplitudes of restored accommodation will adapt and have normal binocular eye alignment when accommodating on near targets. Thus, the current designs rely on an extended DOF to

obtain useful image quality for near targets. One way to extend the useful clear vision range and supplement restored dynamic accommodation is to provide 2 A-IOLs with different refractive biases for the 2 eyes (far and near), similar to a monovision contact lens correction but with some dynamic range of accommodation for each eye. This requires that the out-of-focus image of one eye be suppressed (monovision suppression). Fortunately, this suppression is not absolute, and binocular fusion and some degree of stereopsis is retained during the suppression.<sup>15</sup> However, not every individual is able to utilize this ability, and patients should be evaluated before this technique is applied.<sup>15</sup>

## TRAINING PSEUDOPHAKIC AND PSEUDOACCOMMODATION

Surgical restoration of accommodation with a prosthetic IOL can be facilitated by training the neuromuscular control of dynamic accommodation to match the biomechanical properties of the prosthetic lens. The training procedures are similar to the customary procedures for training accommodative insufficiency.<sup>16</sup> To avoid the soft-saturation range of accommodation with a limited range of accommodation, the amplitude should be restored to at least 5.00 D to leave approximately one-half of the accommodative range in reserve for most near-point activities. Although current lens designs provide a smaller dynamic amplitude (<3.00 D), training can result in increases in aberrations that extend the DOF (pseudoaccommodation). Accommodating IOLs can also be combined with other treatment techniques, such as an anisometropic (monovision) correction with some restored accommodation in each eye to minimize overtaxing the accommodative convergence response and convergence errors of binocular alignment. However, monovision suppression amplitude should be verified before adopting this procedure.

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