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ORIGINAL ARTICLE

The Optical Functional Advantages of an Intraocular Low-Vision Telescope

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ABSTRACT: An implantable miniaturized telescope (IMT) for low vision has recently been developed. Surgically inserted into only one eye of patients with bilateral central visual loss, the IMT provides a nominal magnification of 3.0× and a field-of-view of 6.6° (9.2° for the 2.2× magnification version). Theoretical concerns have been raised regarding the ability of patients to function with a large interocular magnification difference, the impact of the monocular restriction of the field-of-view, and the impact of this design on depth perception. This article addresses these concerns regarding the design of the IMT in comparison with spectacle-mounted telescopes and combined intraocular lens/spectacle (or combined contact lens/spectacle) telescopic systems. The effective field-of-view (as determined by the combination of both the field-of-view and the field-of-fixation), the effects of head motion and the vestibular reflex, and the disruption of stereo depth perception with a monocular device are considered here. Physiological optics considerations of these issues show that the IMT may have important advantages over other designs of magnification devices for patients with age-related macular degeneration. (Optom Vis Sci 2002;79:225–233)

Key Words: macular degeneration, adaptation, rehabilitation, binocular vision

The population profile of the U.S. and of other industrialized nations is aging. Low vision or vision disability affects mostly the elderly. Consequently, both the absolute number of people with visual impairment and the proportion of the population that is visually impaired are expected to increase rapidly in the next two decades. Prevent Blindness America[1] reported that approximately 2.5 million Americans over the age of 40 had moderate visual impairment and an additional one million had severe impairment, including roughly 300,000 who are blind. The most common cause of vision disability is age-related macular degeneration, which affects the fovea, the central retinal section used for high-resolution vision.[2] Age-related macular degeneration is the leading cause of visual impairment among persons aged 75 and older. It is the most common cause of new cases of visual impairment among those over age 65.[1] Diabetic retinopathy, optic neuropathy, central retinal vein occlusions, and other conditions also cause central field loss (CFL). Loss of central vision reduces the patient's resolution and contrast sensitivity and affects the ability to read, recognize faces, watch television, and drive.

A variety of magnifying devices have been used to aid patients with CFL perform vision tasks, most important, reading. Most magnifying devices have a restricted field-of-view and have to be manually scanned across the text, magnifying a small portion at a time. In some cases, the text is scanned in front of the magnifying device and is held at a very short, fixed viewing distance. In all cases, the scanning is slow and limits the usefulness of the device.

Spectacle-mounted telescopes have been used as low-vision aids for about 50 years. Magnification provided by the telescope effectively compensates for the loss of resolution suffered by patients with CFL. Thus, objects seen through the telescopes may be recognized from distances at which they would not be recognized with unaided vision. Near-vision telescopes provide magnification for reading and other nearpoint tasks at a more comfortable distance than microscopic spectacles. However, the field-of-view through the typical spectacle-mounted telescope is narrow and strongly dependent on the vertex distance. For a 4.0× Galilean telescope at a vertex distance of 10 mm from the cornea Nguyen et al.[3] reported a field of about 5° and about 11° for a 2.2× telescope. Bailey[4] reported for a 3.0× spectacle-mounted telescope a field-of-view of 11° for the Galilean design and 14° for the Keplerian design. With such a narrow field, navigation in the visual environment is difficult (and may be dangerous). In addition, the magnified visual motion of the environment seen through the telescope conflicts with the head movement information from the inner ear (vestibular), causing difficulties in adaptation to devices when worn centrally in the spectacle lens and used continuously.[5] Although low-vision telescopes are occasionally used in the central position for reading tasks, the most successful application of this technology is for distance vision and use as a bioptic telescope.

The bioptic telescope is mounted at the top of the spectacle lens, above the pupil, with a slight upward inclination. Most of the time, the patient views the environment through the regular spectacle lens (the carrier lens) enjoying the benefits of intact peripheral vision. When a distant object is detected and cannot be recognized due to reduced resolution (e.g., CFL), the patient tips his head slightly down, bringing the telescope in front of the eye and the object of interest into the field-of-view of the telescope. A short examination (1 to 2 s) of the target through the telescope provides the required high-detail information needed to recognize the target. This intermittent use, named Temporal Multiplexing,[6] makes the bioptic telescope an effective, comfortable, and safe device. Despite some adverse opinions,[7] low-vision telescopes are permitted as visual aids for driving in 34 states in the U.S.[8]

The use of a single bioptic telescope by a patient with two functional eyes represents another improvement (named Biocular Multiplexing[6]). When the patient views through the telescope, the magnification of the telescope creates a ring scotoma or visual field loss, as discussed below. However, when a single telescope is used, the fellow eye continues to see that part of the environment that is not seen by the eye with the telescope. This is an important safety feature because a threat or obstacle appearing at that field location during the telescopic glimpse will be detectable by a patient with a single telescope, but not by a patient with binocular bioptic telescopes.

Despite all these advantages, spectacle- and head-mounted telescopes have gained limited acceptance by patients with CFL as reading or distance vision aids. The reasons for this are presumed to be: the obvious and unattractive appearance of the devices,[9] the limited effective field-of-view resulting from the need to use slow head scanning movements rather than natural eye movements,[10] and the vestibular conflict caused by the increased motion that accompanies head-mounted magnification.[5] This last effect may cause discomfort or motion sickness. Although the vestibular system can adapt easily to low levels of magnification (i.e., a few percent) as created by spectacle lenses, the ability to adapt to the large magnification of a low-vision telescope has not been demonstrated.

In an attempt to overcome these limitations of spectacle- (head) mounted telescopes, two approaches using a combination of a spectacle lens as the objective with a second lens on the eye as the ocular of the telescope were developed. One approach combines a high-power positive spectacle lens with a high-negative-power contact lens.[11, 12] The second approach combines the spectacle lens with an implantable intraocular lens (IOL).[13, 14]

There are two varieties of the combined IOL/spectacle design, one with a single power IOL[14, 15] and the other with a bifocal IOL.[13, 16] In the former, a high-negative-power IOL is implanted in place of the crystalline lens and in combination with a high-positive-power spectacle lens, which provides magnification. In the latter, the outer segment of a concentric bifocal IOL provides standard power, and the central zone provides high negative power. This bifocal IOL may be used either with a high-power positive spectacle lens to provide magnification through the central zone or with a standard pseudophakic spectacle correction to provide a nonmagnified view. A similar bifocal design was previously suggested for the combined contact lens/spectacle telescopic systems.[17, 18] A bifocal IOL/spectacle system developed by Allergan underwent preliminary testing in the U.S. some years ago.[13] Despite the positive results reported, it was not brought to the market. A similar system is under testing currently in Europe by Morcher GmbH (Morcher IOL Type 59 "macular IOL").

The combined contact lens/spectacle telescope was described first in 1936 by Dallos,[11] and it was introduced as a low-vision device soon thereafter (see Ludlam[19] for a review of early results). There are also two varieties of the combined contact lens/spectacle design, one with a single-power contact lens and the other with a bifocal contact lens.[12] In the former design a high-negative-power contact lens in combination with a high-positive-power spectacle lens provides magnification. Moore[20] suggested that this device would be useful only for a patient with minimal need for peripheral vision, but suggested that the best use would be monocular with the other eye used for peripheral vision (biocular multiplexing). Moore also indicated that this design did not solve the cosmesis problem of the spectacle telescope; patients often rejected the device because of the thick unsightly spectacle lens. In the bifocal design, the contact lens is a concentric bifocal with the outer segment providing a standard contact lens power and the flat central zone of the anterior surface providing the high negative power.[12] Filderman[12] developed a bifocal spectacle lens to combine with the bifocal contact lens. The carrier plano lens used together with the outer segment of the contact lens is used for peripheral vision with no magnification, whereas the smaller concentric high-power inset lens when combined with the negative-power segment of the contact lens provides the magnification with a reduced field. Filderman[12, 17] recommended monocular use of his system to permit biocular multiplexing, and he felt that the cosmetic advantage of this design was substantial to justify its use in many cases.

A more recent approach to low-vision magnification uses an implantable miniaturized telescope (IMT) completely inside the eye.[21, 22] The IMT, developed by VisionCare Ophthalmic Technologies, is designed to provide magnification without an external lens and to be in focus at a nominal distance of 50 cm with the 3.0× IMT (2 to 2.5 m with the 2.2× device). Standard spectacles are used to adjust for other working distances and to correct for residual refractive error. Clinical trials in Europe resulted in the grant of a CE Mark, and further trials are underway in the U.S. Despite the favorable results from the early studies,[22, 23] (available on the web at: http://www.eri.harvard.edu/faculty/peli/posters/index.htm), theoretical concerns have been raised regarding possible difficulties and limitations of the IMT approach. After presentations made by the author and others, colleagues in the audiences raised questions about the ability of patients to function with a large interocular magnification difference, the restriction of the field-of-view, and the resulting impact on depth perception. The results of the clinical trials should provide the best answer to these questions, but it is also important to understand the theoretical reasons for the success or the failure of low-vision aids so these considerations may be applied in future designs.

This article analyzes the concerns raised regarding the design of the IMT in comparison with spectacle-mounted telescopes and combined IOL/spectacle (and contact lens/spectacle) telescopes for low-vision use. In addition to magnification and field-of-view (the frequently cited parameters of telescopic systems), it is important to consider differences in other parameters affecting the functionality of such a device. These considerations may prove as important in the acceptability of the devices. In particular, the effective field-of-view (as determined by the combination of both the field-of-view and the field-of-fixation[24]), the effects of head motion and vestibular reflex, and the disruption of stereo depth perception with a monocular device are addressed here. In considering these other physiological optics issues, it is argued that the IMT may have important advantages over other approaches to magnification for patients with age-related macular degeneration.

THE IMPLANTABLE MINIATURIZED TELESCOPE (IMT)

The IMT is a miniature Galilean telescope mounted on a polymethyl methacrylate carrier intraocular lens implant.[21] The IMT is implanted in the posterior chamber of the eye, in place of the crystalline lens ("in the bag"). It is held in position in the lens capsule by haptic loops, and the IMT bulges forward into the anterior chamber through the pupil (Fig. 1). The iris is used to support and center the IMT inside the eye near the optical axis and helps block nondirect light from reaching the retina, thus increasing the contrast. The IMT is implanted using a modified cataract extraction procedure in only one eye of a patient with symmetrical CFL.

The IMT is constructed from two glass lenses inside a glass tube. Two flat glass windows keep the lenses separated from the aqueous humor, increasing the effective power of the lenses relative to lenses immersed in the aqueous. The airtight tube also serves to float the telescope in the eye, so the effective weight of the 3.0× magnification device is only 46 mg, and its tube is 3.0 mm in diameter and 4.4 mm long. The front of the IMT is positioned about 2 mm behind the posterior surface of the cornea.

Together with the cornea, the IMT acts as a 3.0× nominal magnification telephoto lens in focus at a distance of 50 cm (or as a 2.2× telephoto lens in focus at 2.0 to 2.5 m), providing better resolution for many activities of daily living. With the use of spectacles, the IMT can focus at any distance. With the use of such additional lenses for reading at shorter distances, the relative effective magnification can be increased to 6.0× or more. Patients with refractive error before the surgery will need similar correction to their presurgical ametropia to achieve the same effect.

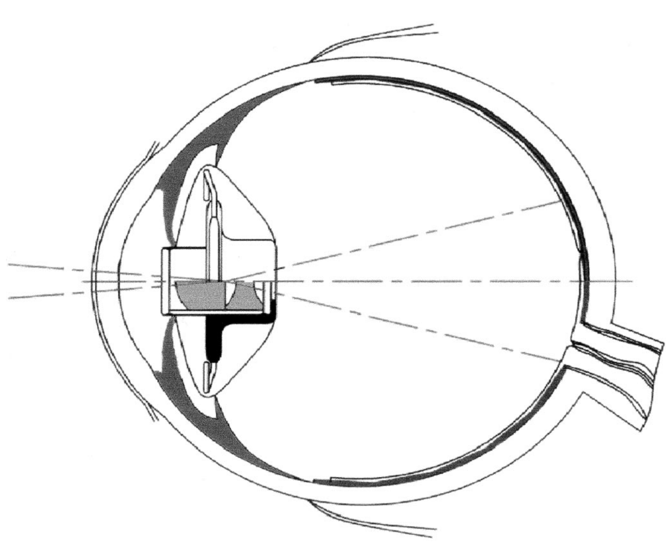

FIGURE 1.
Schematic of the implantable miniaturized telescope mounted in the lens capsule using a carrier lens similar to common intraocular lenses and supported anteriorly by the iris. The carrier structure is shown in black, and sections through the positive and negative lenses inside the telescope are shown in gray. Note the anterior and posterior flat windows that keep the lenses in air.

The instantaneous field-of-view through the telescope is 6.6° (with a wider extent of field available at low resolution and contrast) with the 3.0× IMT and 9.2° with the 2.2× device. For this reason, the telescope is implanted in one eye only to provide high-resolution central vision, whereas the fellow eye continues to be used for peripheral vision and safe mobility. Although the instantaneous field-of-view is small, the ability to scan using eye movements should provide much more comfort in reading and other activities than would be possible with a head-mounted telescope of similar field. As discussed below, the effective field-of-view is wider with the IMT than with the IOL/spectacle combination telescopic system.

EFFECTIVE FIELD-OF-VIEW AND EYE MOVEMENTS CONTROL

One of the main limitations of any magnifying device is the inherent restriction of the field-of-view that accompanies magnification. The magnified image occupies a larger angular span on the retina than the unmagnified object. This means that a ring scotoma must surround any magnified image irrespective of the magnification method or device. The inner diameter of the ring scotoma is equal to the diameter of the field-of-view of the telescope. The outer diameter is equal to the product of the field-of-view diameter and the magnification provided by the telescope. Thus, a 3.0× telescope with a field-of-view of 10° will have a ring scotoma extending from eccentricity of 5° to 15°.

Because scanning eye movements are necessary for proper function even with normal sight, the interaction of the magnification ring scotoma with eye movements can seriously impede the use of magnifiers. This is particularly true because the limited field-of-view seen through any of the telescopes discussed here requires scanning of the environment to function effectively. The effective field-of-view through a device is determined by a combination of both the instantaneous field-of-view and the range of the scanning permitted by the device. This range is measured by the field-of-fixation, the field to which eye movements can be made.[4] The field-of-fixation and the flexibility and convenience in scanning may be even more important than the instantaneous field-of-view. For example, patients with peripheral field loss (tunnel vision) due to retinitis pigmentosa or glaucoma can function quite effectively until their field-of-view is restricted to about 10° or less.[25] The main reason for this impressive ability is the large open field-of-fixation and the effective use of scanning eye movements by these patients. These patients frequently reject minifying devices that increase the field-of-view because such devices restrict their eye scanning, in addition to reducing resolution.[26]

As mentioned above, the field-of-view of spectacle-mounted telescopes is restrictive. To scan the environment, the user of such telescopes can use eye movements within that limited field. That field-of-fixation however is generally narrower,[27] computed by

Bailey to be only 6° for the 3.0× Galilean design telescope and 10° for the Keplerian design.[4] As a result, these patients must resort to head scanning to cover a wider angle of view through the telescope.

The limitations on the field-of-fixation are even more severe with the combined IOL/spectacle telescopic (or contact lens/spectacle) system.[4] With this device, the field-of-fixation was computed to be only between 1° and 5° depending on lens design and vertex distance.[4] The reason for this limitation, derived from computational ray tracings, is that this kind of system stabilizes the retinal image.[28, 29] Thus, even though a slightly wider field-of-view may be available with this device, eye movements will result in minimal image movement on the retina. Doesschate and De Vries[28] and Rushton and Cox[30] provided a simple intuitive explanation for the image stabilization properties of such systems. They showed that if a spectacle lens has its focal point at the eye's center of rotation it would stabilize retinal images against eye movements. To understand the effect, consider the chief ray from an object point on the optical axis. All other rays from that point after passing through the lens will intersect the globe radially toward the center of rotation. As the eye turns, it will always have one of these rays along the optical axis at its new position. Thus, that object will always appear along the optical axis at any eye position. A strong lens with such short focal distance should blur the retinal image, but that blur is counteracted by the high-minus IOL in the combined IOL/spectacle system. Doesschate and De Vries[28] attempted to use such a system to study the effect of image stabilization. Rushton and Cox[30] designed such stabilizing systems using high-power negative contact lenses as a treatment for nystagmus. The combined IOL/spectacle telescopic system as well as the combined contact lens/spectacle telescopic systems[31] are not designed specifically to have the spectacle lens focal point coincide with the center of rotation. However, in most cases, the focal point ends up not far from the center of rotation, resulting in substantial if not complete stabilization. This stabilization also means that the field-of-fixation is restricted because the eye movements fail to change the position of objects on the retina.[29]

The field-of-fixation with the IMT has no limitations at all. Any place in the field that may be fixated with the unaided eye may be fixated with the IMT eye. Although the field-of-view is restricted, any object seen within it can be fixated. Objects outside the field-of-view of the IMT may be seen with the fellow eye, and these objects can be fixated with the IMT eye using the same magnitude saccade as required for fixation by the fellow eye. Especially for reading, the eye with the IMT can continue to scan along the text line, whereas with all other systems, scanning head movements are required.

HEAD MOTION AND VESTIBULAR EFFECTS

Using any head-mounted magnifying device causes a disruption of image stability and perceived direction as a result of head motion.[32] In natural viewing without optical devices, if an observer fixates a target at primary position of gaze and then rotates his head while maintaining fixation on the same target (Fig. 2A), the required change in eye position in the orbit is equal in magnitude and opposite in direction to the head rotation. Such an eye movement is generated automatically by the vestibular ocular reflex (VOR) in response to the head rotation (Fig. 2B), and it serves to maintain a stable retinal image during head or body movements.

With the use of a head-mounted telescope, the required correcting eye movement is larger, as illustrated in Fig. 3A. For example, with 3.0× magnification, an eye movement three times as large as the head rotation is required. However, the vestibular system will rotate the eye only to compensate for the head rotation, leaving the fovea far away from the target image (Fig. 3B). Although an ability of the VOR system to adapt to large changes in magnification (up to 35%) that may occur (e.g., with diving goggles) has been demonstrated,[33] the ability to adapt to the high demand of a telescope (300% magnification) has not been demonstrated. Furthermore, it should be noted that when using a monocular telescope, as is commonly the case, the demand for adaptation is different between the two eyes (Fig. 3B). Some capacity to adapt the VOR of

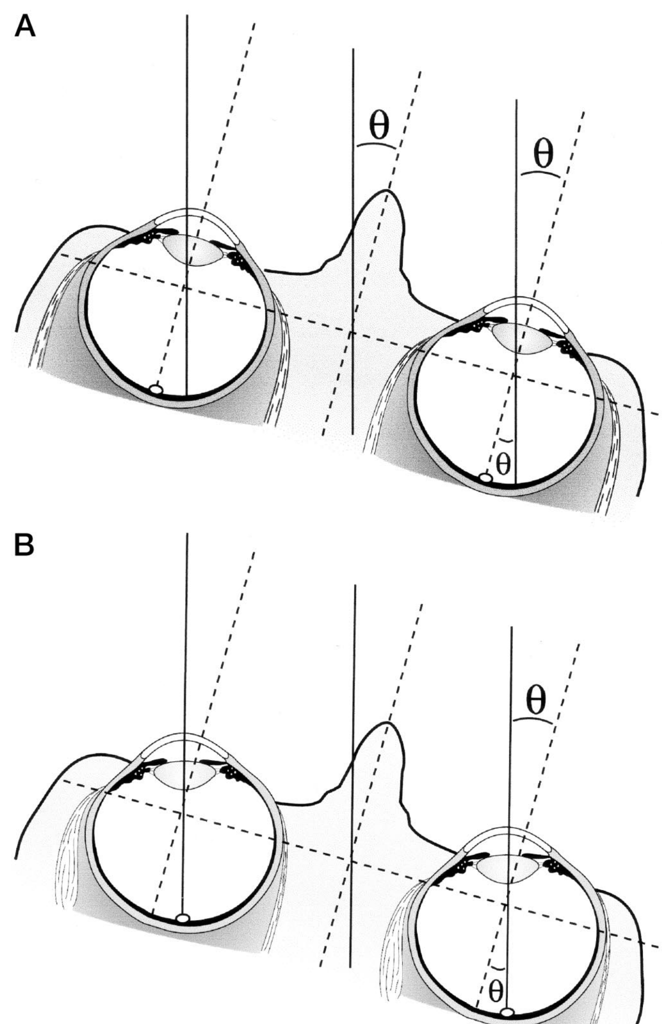

FIGURE 2.
The vestibular–visual interaction in unaided vision (i.e., without an optical device). Considering an observer who is maintaining fixation on a distant object straight ahead at the primary position of gaze. A: After a head rotation of angle θ° to the right, the image of the object is shifted by the same angle on the retina. B: The vestibular system, in the inner ear, generates a compensatory eye rotation of the same angle but in the opposite direction $-\theta$° through the vestibular ocular reflex. With such an eye rotation, both eyes return to fixation on the object straight ahead.

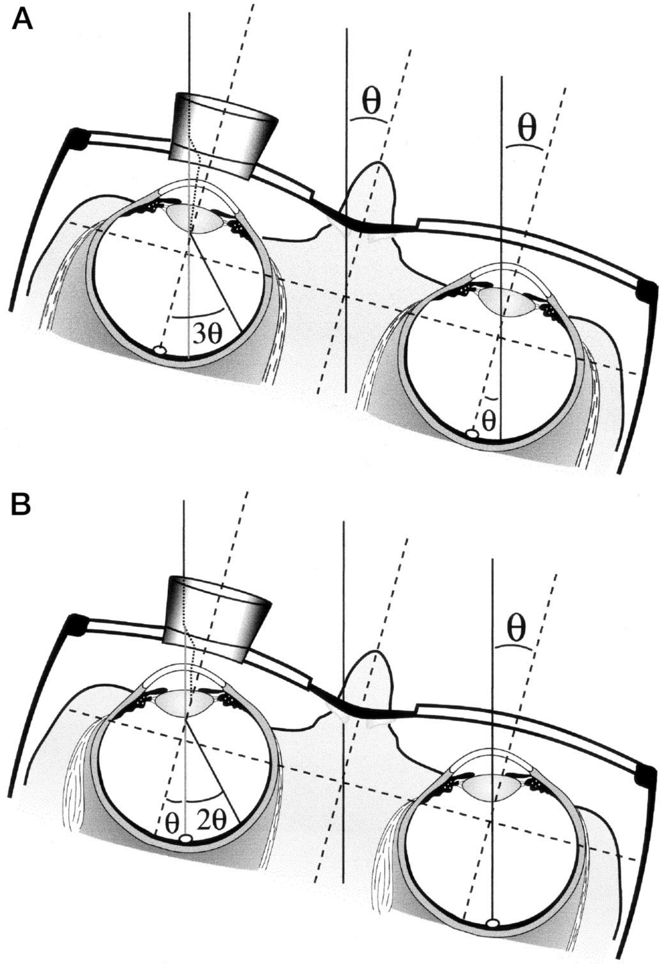

FIGURE 3.

A: When the observer is using a monocular spectacle-mounted telescope (with magnification of 3.0×, for example) a head rotation to the right, of angle $\theta°$, results in image shift of $3\theta°$ from the fovea in that eye. B: The vestibular ocular reflex generates a smaller eye rotation, $-\theta°$, leaving that eye off its target, causing a perception of object movement. Additional eye movement can bring the object of regard back onto the fovea through the telescope. Note also that in this case, the rotational demands for both eyes are not equal.

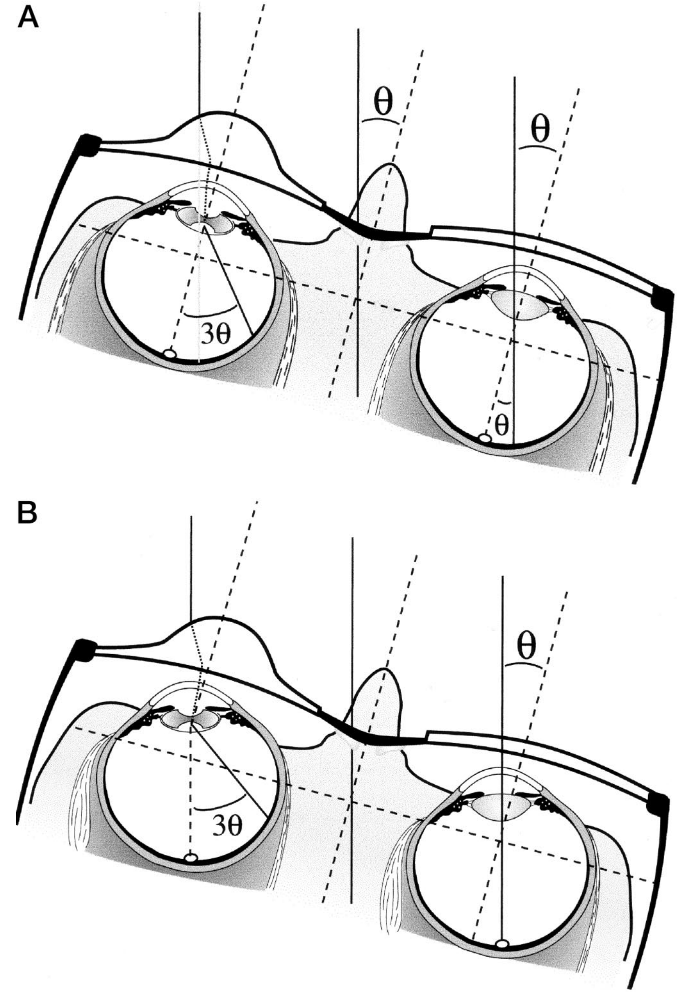

FIGURE 4.

A: When using a monocular combined intraocular lens/spectacle lens telescopic system, after a head rotation to the right of angle $\theta°$, here, too, the retinal image is shifted by $3\theta°$ from the fovea in that eye. B: The vestibular ocular reflex generates a smaller eye rotation, $-\theta°$, but that movement does not affect image position on the retina. The image stabilization nature of this system prevents a reacquisition of the target with this system until the head is rerotated toward the target.

each eye differentially has been demonstrated in monkeys,[34, 35] but again only small changes in VOR were demonstrated. If the VOR cannot adapt differentially between the eyes, every head movement with a head-mounted magnifying device will result in substantial image motion in one eye with the accompanying reduction in sensitivity.[36]

Using a combined IOL/spectacle telescope does not improve the situation; in fact, it makes it worse. With the combined IOL/spectacle system, a head rotation will result in magnified image motion on the retina (Fig. 4A), as it does with the head-mounted telescope. The disturbing effects of image motion due to head motion with all head-mounted telescopes as well as the combined contact lens/spectacle system was pointed out by Mandell.[18] Furthermore, due to the image-stabilizing effect of the combined IOL/spectacle system discussed above, eye movements will not be able to return the selected image to the fovea at all (Fig. 4B). In this regard, the impact of the combined IOL system is worse than that of the bioptic, especially because the combined system is used full time. Thus, it is exposed to head movements resulting from walking or being moved in vehicles, as well as intentional head rotations. The same problem will face patients wearing a telescope combined from a spectacle lens and a high-negative-power contact lens. These patients face a similar but more severe field restriction problem than that faced by patients corrected with spectacles after cataract extraction without IOL, commonly referred to as the "Jack in the Box" phenomenon.[37] The Jack in the Box effect is a result of head movement moving the object into the ring scotoma, whereas with a combined IOL/spectacle system, it cannot be refixated by eye movement alone.

Using the IMT resolves this problem completely. As illustrated in Fig. 5, with the IMT, a given head movement will require a compensatory eye movement of the same magnitude despite the magnification. Thus, a natural VOR gain of about 1.0 will suffice. In addition, no conflict will occur between the image motions in both eyes with a monocular IMT.

Although the discussion above was framed in terms of head

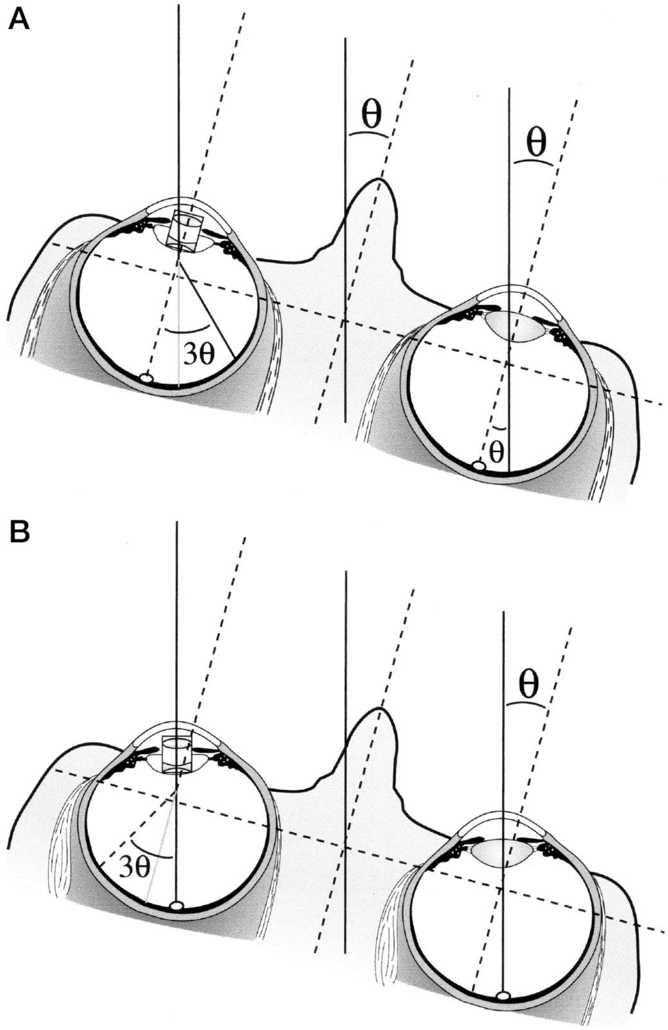

FIGURE 5.

A: When using the monocular implantable miniaturized telescope intraocular system, after a head rotation of angle $\theta°$ the image is shifted by $3\theta°$ from the fovea on the retina of that eye, as with the other telescopic systems. B: The vestibular ocular reflex-generated compensatory eye rotation of $-\theta°$ is sufficient to restore fixation. Note that here the rotational demands for both eyes are equal.

movement, it should be clear that the same arguments apply when the observer shifts fixation between two targets without any head movements. With the IMT, a target 3° from fixation will require only a 3° eye movement to be examined with an IMT but will require a 9° eye movement with a head-mounted telescope. The same target will require a 3° head movement with the combined IOL/spectacle system because eye movements will not change the positions of objects on the retina (or only minimally change them). The effect of such magnifying devices on the eye movement control and the fixation reflex was analyzed by Drasdo.[29] In particular Drasdo noted that even if the magnifying device is bound to the eye as is the integral contact lens telescope developed by Feinbloom,[38] it will result in disruption of the fixation reflex. The same would apply to the IMT. However, if a target is seen with the other eye to be at a certain angular distance from fixation, it may be acquired through the IMT with the corresponding magnitude eye movement. Thus the IMT offers distinct advantages in space and direction perception as well as clarity of vision in both eyes during eye movements, head movements, and tracking of moving targets.

MONOCULAR DEPTH PERCEPTION

All monocular telescopes prevent binocular disparity and stereovision and therefore limit depth perception when used. In addition to binocular disparity, there are many (monocular) depth cues that provide rich information about relative depth. Most of these monocular cues, including partial occlusion (interposition), relative sizes of known objects, linear perspective, foreshortening, shape from shading, and aerial perspective (or atmospheric effects), provide a useful sense of depth in the environment.[39] However, for some tasks that are conducted at arm's length, such as threading a needle, the fine depth perception provided by binocular disparity may be important, and the aforementioned monocular cues may not suffice. Another particularly strong and veridical monocular depth cue is motion parallax[40]; objects closer to the eye appear to move faster than objects moving at the same speed at a farther distance. For static objects, such relative movement between the eye and the objects can be caused by (lateral) movements of the eye (by moving the head). With such head movements, a closer object will move faster on the retina and will cover a larger retinal span than the farther object. The difference between these movements can be detected by the visual system and interpreted correctly as depth information. A number of animals (such as locusts) are known to use lateral head movements to derive depth information. It has also been shown that monocular patients (due to enucleation) produced larger and faster head movements than normal control subjects when tested at grasping objects.[41]

Rotational eye movements do not provide sufficient parallax cues because the center of rotation of the eye is close to the nodal point of the eye. Rotations about the nodal point provide no parallax at all. It was recently proposed that some animals, such as the chameleon and the sandlance fish, are able to use eye rotations to derive parallax and, from that, depth information needed for their survival.[42] They are able to do this because the optics of their eyes evolved in a way that shifts the nodal point anterior to the center of rotation (close to the cornea). With the nodal point separated from the center of rotation, eye rotations do provide the necessary parallax. As shown in Fig. 6, the IMT shifts the nodal points of the combined eye-telescope system substantially forward of the eye more than 4 cm in front of the cornea. With the nodal point at this position, even the slightest eye movements associated with normal fixation should provide sufficient parallax for fine depth perception. All magnifying devices necessarily move the nodal point of the combined eye-device system anteriorly. The effects of eye movements on nodal points positions are much more complex and are limited with the head-mounted telescope and with the combined IOL/spectacle system because of relative decentration of the components. Thus, these systems do not provide the same benefit as the IMT.

Monocular depth perception using motion parallax cannot be measured with any of the dichoptic stereo tests, but it can be measured with tests that provide real depth between targets such as the Frisby stereo test[43] (available from Clement Clarke International, Essex, UK). Incorporation of such assessment into future studies will enable us to verify whether the IMT indeed provides

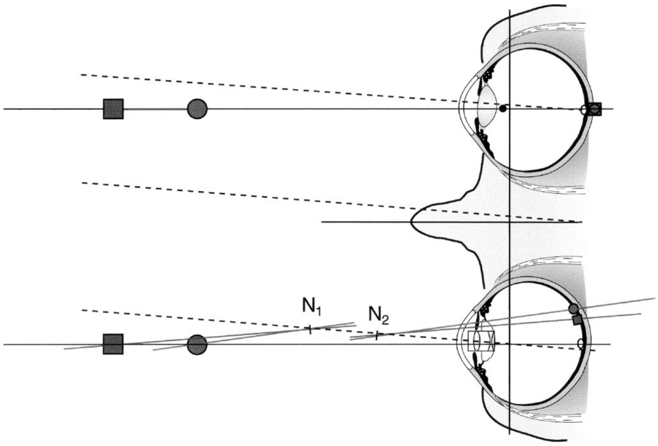

FIGURE 6.
An illustration of the way a single eye with implantable miniaturized telescope can determine depth by rotation. When the eye is in primary position, the two objects at two different distances (a square and a circle) are imaged on the same place on the retina in both eyes; the one with the implantable miniaturized telescope and the one without. When the eyes rotate, the two images shift together on the retina of the normal eye because the center of rotation is close to the eye's nodal point(s) (marked by a dot). In the eye with the implantable miniaturized telescope, the nodal points are far in front of the eye (as illustrated). This eye's rotation results in the image of the closer object (circle) moving faster and farther than the image of the farther object (square). This differential motion reveals that the circle is closer. Note, the diagram is not to scale.

the patients with a useful depth perception despite the lack of binocular fusion.

TRAINING ALTERNATE VISION WITH THE IMT

The biocular multiplexing[6] use of the IMT requires that the patient be able to switch easily between using the eye with the IMT for fine-detail, high-resolution vision and the fellow eye for a wide field needed in mobility and navigation tasks. Biocular use of a monocular contact lens/spectacle system requiring alternation of vision between the eyes was pointed out as an advantage by both Mandell[18] and Stone.[44] Such alternation may develop naturally in some patients.[18] For example, antimetropic patients are known to switch between the myopic eye used for reading or other near tasks and the fellow eye used for distance vision.[45] Even such patients with long-time adaptations may need to exert some special effort such as a blink to facilitate the transfer.[45] I have observed one patient with an IMT who similarly used winks to switch between the eyes at will. The wink was needed only to trigger the alternation, not to maintain it. Stone[44] remarked that low-vision patients are able to adapt easily to such biocular use with a combined contact lens/spectacle system in one eye.

The development of such adaptation strategies may be left to the patients, but it is clear that any adaptation and training is facilitated by feedback. Although it might appear that the difference in magnification will provide such feedback in the case of the IMT, discussions with two patients who successfully adapted to the IMT revealed that although they were aware of the resolution benefit of the IMT, they did not perceive the image through it as larger, just clearer. It therefore may be useful to provide additional feedback to the patients while they learn to alternate their attention between the eyes. As shown in Fig. 7, a simple polarized pair of spectacles used for stereo testing and a regular mirror may provide such feedback. When a patient wearing such glasses is looking at a mirror, each of his eyes can only see itself and not the fellow eye. An observer with good equal binocular vision will see both eyes in the mirror (each one seeing itself). If one eye is shut, the corresponding lens appears to darken, and the closed lid cannot be seen. Training with these glasses may start by closing one eye at a time, noting the appearance, and then trying to affect the same view by actively suppressing one of the eyes and then the other. The clear feedback provided by the device may facilitate the alternating vision that is essential for the successful functionality of the IMT. The same glasses may be used during presurgical evaluation to determine eye dominance and to assess the patient's ability to alternate between

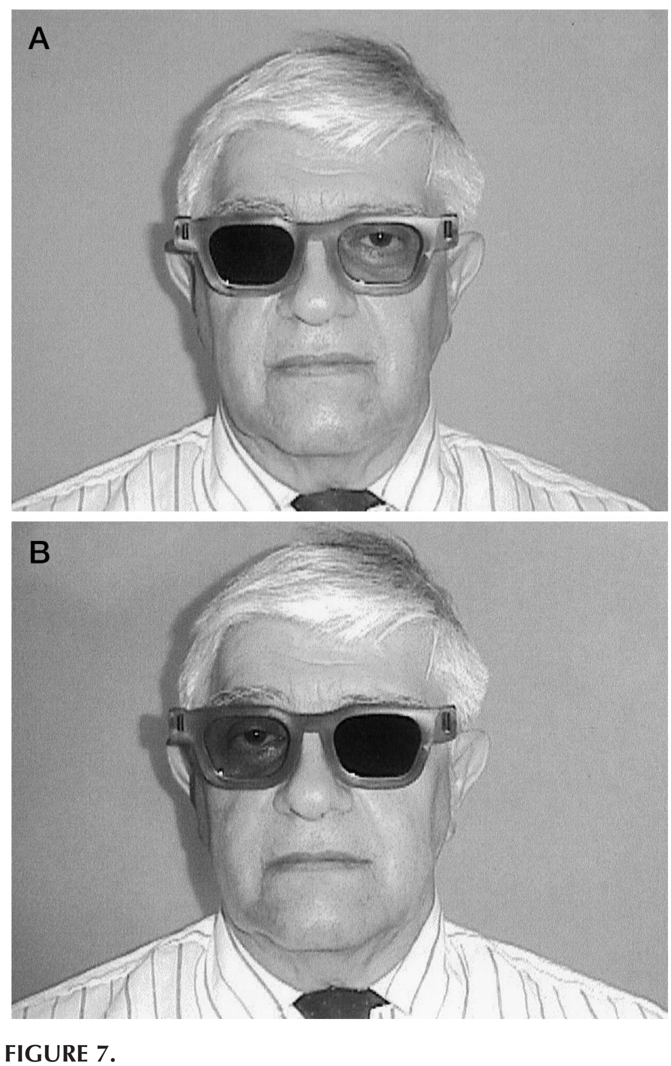

FIGURE 7.
Learning to alternate vision between the two eyes is important for successful use of a biocular multiplexing device such as the implantable miniaturized telescope. Patients may train in alternating suppression by wearing a pair of polarizing test spectacles in which each lens' polarization axis is oriented at right angle to the other. As shown here, when looking at a mirror with such glasses, the patient will be able to see each eye only through its own lens, not through the other. Thus, when the right eye is closed or suppressed (A), only the left eye will be seen. Similarly, when the left eye is closed or suppressed, only the right eye will be seen (B). The patient can use these views to provide feedback for training in volitional eye selection control.

the eyes. Such an assessment may facilitate determining which eye to operate on if the vision in both eyes is otherwise similar.

CONCLUSION

An implantable miniaturized telescopic device for low vision has been developed and tested. Preliminary results are encouraging because the implant procedure is feasible and no serious complications have been encountered. It is even more encouraging to find that the implant functions as it was designed, providing useful magnification and functional vision. The IMT has a number of advantages over other magnifying devices when considering the dynamic visual situation of a person walking and using eye movements to scan the environment. The successful alternating use of two eyes with widely differing magnifications and fields-of-view could be a challenge for the patients. Understanding this situation and the ways patients can adapt to it effectively is the biggest challenge facing this device in the marketplace. With a better understanding and good training techniques, such devices could be developed to assist the patients. If successful, the IMT will represent a new treatment option for patients with CFL and moderate loss of acuity that may be superior to all existing devices. Like other telescopic devices, the success of the IMT will also depend on its interactions with the preferred retinal locus used by the patient, and the effects of changes in the pathology with time, in progressive diseases.

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