Extended Wearing Trial of Trifield Lens Device for "Tunnel Vision"

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Abstract

Severe visual field constriction (tunnel vision) impairs the ability to navigate and walk safely. We evaluated Trifield glasses as a low vision optical device for tunnel vision in an extended wearing trial. Thirteen patients with tunnel vision (5 to 21 degrees wide) from retinitis pigmentosa or choroideremia participated in the 5-visit study. To expand the horizontal visual field, one spectacle lens was fitted with two apex-to-apex prisms that vertically bisected the pupil on primary gaze. This provides visual field expansion at the expense of visual confusion (two objects with the same visual direction). Patients were asked to wear these spectacles as much as possible for the duration of the study (median 7 (range: 6 to 60) weeks). Clinical success (continued wear, indicating perceived overall benefit), visual field expansion, perceived direction and perceived quality of life were measured. Clinical Success: One patient did not complete the study for non-vision reasons. Of the remaining 12 patients, 9 chose to continue wearing the Trifield glasses at the end of the study. Of those 9 patients, at long-term follow-up (35 to 78 weeks), 3 reported still wearing the device. Visual Field Expansion: Median expansion of 19 degrees (range 9 to 38) was demonstrated for all patients. Perceived Direction: No patient demonstrated adaptation to the change in visual direction produced by the Trifield glasses (prisms). Quality of Life: For difficulty with obstacles, some differences between successful and non-successful wearers were found. Trifield glasses provided reported benefits in obstacle avoidance to 7 of the 12 patients completing the study. Crowded environments were particularly difficult for most wearers. Possible reasons for long-term discontinuation and lack of adaptation of perceived direction are discussed.

Introduction

A common definition (e.g. Social Security Administration in the USA) of legal blindness is a constriction of the visual field to less than or equal to 20º diameter as measured by Goldmann Perimetry using a III4e target size (tunnel vision). Tunnel vision is a debilitating symptom of retinitis pigmentosa (RP)and choroideremia. Retinitis pigmentosa, the most common cause of inherited blindness, has a prevalence of about 1 in 4000 people worldwide (Berson, 1993; Hartong *et al.*, 2006).

Patients with tunnel vision have difficulties with navigating, avoiding obstacles, and performing visual search (Marron and Bailey, 1982; Lovie-Kitchin *et al.*, 1990; Haymes *et al.*, 1996; Black *et al.*, 1997; Kuyk *et al.*, 1998; Turano *et al.*, 1999a; Turano *et al.*, 2001; Broman *et al.*, 2004; Luo and Peli, 2006; Apfelbaum *et al.*, 2007; Fortenbaugh *et al.*, 2007). The consequent loss of mobility and increased risk of falls (Felson *et al.*, 1989; Lord *et al.*, 1993; Tinetti and Williams, 1997; Lord and Dayhew, 2001; Biderman *et al.*, 2002; Freeman *et al.*, 2007) is detrimental to patients' independence and quality of life (Tinetti and Williams, 1997; Turano *et al.*, 1999b; Shinkai *et al.*, 2000; Biderman *et al.*, 2002; Melzer *et al.*, 2003; Cacciatore *et al.*, 2004). Visual field extent is a significant predictor of the mobility performance of people with tunnel vision (Marron and Bailey, 1982; Lovie-Kitchin *et al.*, 1990; Haymes *et al.*, 1996; Black *et al.*, 1997; Kuyk *et al.*, 1998; Turano *et al.*, 1999a; Broman *et al.*, 2004). Most people with tunnel vision receive orientation and mobility training, though the benefit of this training has not been proven (Soong, 2000; Soong *et al.*, 2001; Kuyk *et al.*, 2004; Virgili and Rubin, 2006).

Previously rehabilitation approaches for patients with tunnel vision included: training to scan (Cohen and Waiss, 1996); minifying devices (reversed telescopes, or hand held negative lenses) (Drasdo, 1976; Hoeft *et al.*, 1985; Weiss, 1992; Szlyk *et al.*, 1998) and various prism spectacle designs (Cohen, 1993; Onufryk, 1994). Most of these devices have not been commercially available and others have had limited clinical use due to their drawbacks. More recently augmented-vision head-mounted displays (Peli, 2001; Vargas-Martin and Peli, 2002) have shown some promise in early testing in visual search tasks (Luo and Peli, 2006) and obstacle avoidance (Luo *et al. in press*).

We are not aware of any publication explaining how to train patients to scan or showing that patients actually increase their scanning following training. We believe that in most cases the training simply consisted of instructing patients that they should scan more. In recording eye movements of patients with tunnel vision while walking, it has been reported that the distribution of eye movements while walking was not larger than that of normally-sighted subjects (Vargas-Martin and Peli, 2006) and saccadic amplitudes and directions were very similar to those of normally-sighted subjects (Luo *et al.*, 2008).

Minifying devices shrink the view of the scene so that a wider section of the world is available within the patient's residual visual field but have poor clinical acceptance primarily due to the reduction in resolution (visual acuity). The Amorphic lens reversed telescope (Designs for Vision, Inc., Ronkonkoma, NY) minified only the horizontal meridian in order to reduce the impact on acuity (Hoeft *et al.*, 1985) at a cost of image distortion. Despite some reports of success (Hoeft *et al.*, 1985; Szlyk *et al.*, 1998), they have been recently discontinued.

The use of prisms in treating peripheral visual field defects has been controversial, as previously proposed designs had significant limitations (Cohen, 1993). The best known binocular sector prism design (Onufryk, 1994), the so-called Channel lens, was based on a field-shifting principle (rather than field expanding). These prisms, commercialized briefly in 1998 and 1999 as the InWave™ lenses (InWave Inc., Janesville, WI), had a central prism free channel (corresponding to the width of the residual visual field of the patient). As a result they had no effect in primary position of gaze. When the patient made eye movements towards the surrounding prismatic areas the effect was to shift (relocate) the image more centrally, rather than expand, the residual visual field. Further, the prism powers available laterally (12Δ ≈6º - nasal and temporal base) and below the channel (8Δ ≈4º - base down) were too small to have an impact on mobility. Also, the prism apex scotomata could interfere with their functionality (Giorgi *et al.*, 2009; Ross *et al.*, 2009). Somani et al. (2006) implemented this design using stick-on Fresnel prisms and claimed small increases in visual fields and activities of daily living.

The use of the Channel lens (prisms), the Amorphic lens in a bioptic configuration (Szlyk *et al.*, 1998) or hand held negative lenses (Kozlowski *et al.*, 1984) requires that the user initiate a search action by spotting through the device in search of a previously unseen obstacle or threat. As such bioptic use is unlike the use of bioptics for magnification when the need for the device use is apparent to the user, it is not as effective as the use of bioptic magnification. Unlike magnification, visual field expansion devices need to provide expansion all the time to be effective.

Trifield prism glasses have been proposed that expand the visual field without minification, or prism scotoma (Peli, 2001). Trifield glasses consist of two apex-to-apex prisms mounted in front of one eye, and a conventional spectacle lens (e.g. single vision with prescription) in front of the other eye (Fig. 1). The patient retains the original residual visual field of the non-prism eye, while the prism lens provides a laterally shifted visual field. The combination of the original visual field and the shifted visual field provides an expansion. The prism lens is fitted so that the prism apices vertically bisect the pupil when the prism eye is in primary gaze. As the gaze is shifted to the left, the prism eye sees a part of the scene that is laterally farther to the left compared to that seen by the eye with the conventional lens. Similarly, when the gaze is directed to the right, the prism eye sees objects farther to the right than the non-prism eye. The combined percept is double vision (specifically visual confusion: two objects having the same visual direction). This is illustrated in Fig. 2. The direction of the lateral shift and expansion is dependent on the direction of gaze. As the patient looks left or right, the prism eye looks through the left or right prism, and areas the patient would not otherwise see are shifted into their visual field from the left or the right. If the patient looks directly forward so that the prism junction is over the pupil, three parts of scene are visible: one through the conventional lens before the non-prism eye and two parts, laterally shifted from opposite directions, through the two prisms of the Trifield lens before the prism eye. Thus, “tri-field” glasses make three possible pieces of the visual field available to the wearer, two of which would not be seen without the glasses, and increasing the available visual field extent up to three-fold. While the part (or side) of the field of view that is expanded varies with the gaze the area of the visual field that is visible is about double at all times. Prescribed prism strength varied for patients, with the nasal prism ranging 11 to 44 prism diopters (Δ) and the temporal prism ranging from 10 to 34 Δ.

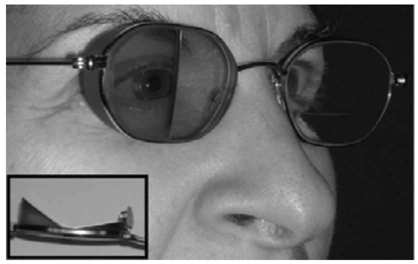

Figure 1. Trifield glasses correction for a patient with a restricted visual field. *Inset.* Top down view of the right lens showing the two prisms conjoined at each prism's apex (34 Δ temporal lens and 22 Δ nasal lens). The temporal prism is tinted red and the nasal prism is green in the hope that this would assist with determining the direction of objects. The fellow eye has a standard ophthalmic lens here shown with a bifocal.

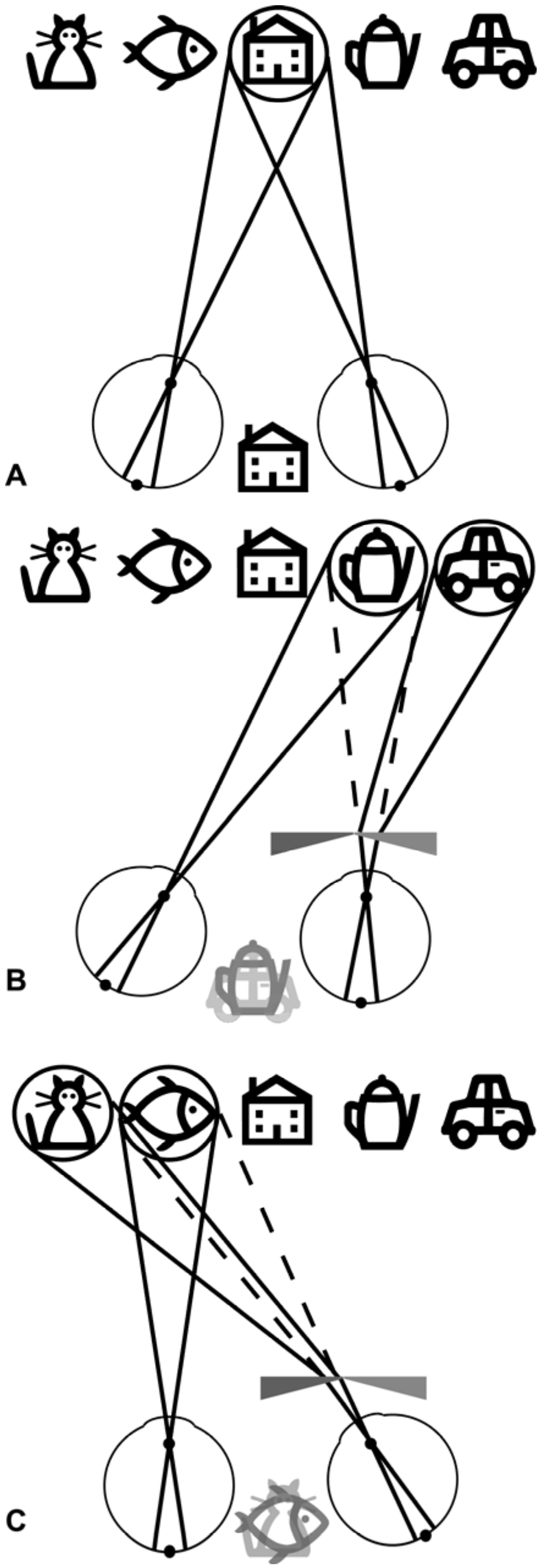

Figure 2. Schematic (not to scale) illustration of the visual field expansion effect of the Trifield glasses. (A) A person with severe bilateral visual field constriction ("tunnel vision") is only able to see one of the objects at a time when viewing with both eyes simultaneously (in primary gaze, the house). (B) The Trifield lens is placed over the right eye and the wearer looks to the right, here fixating the coffee pot with the non-prism left eye. The right Trifield prism segment shifts the view of the prism eye to the right, here to the car. Thus, the car, which would not have been visible without the Trifield glasses, is now visible to the wearer. However, the binocular percept is that of visual confusion, with the pot and the car both seen in the same apparent visual direction (See illustration between eyes). (C) Similarly, when the wearer looks to the left, here viewing the fish with the non-prism left eye, the left Trifield prism segment shifts the view of the prism eye farther to the left so that the prism eye sees the cat. Without the Trifield glasses, the cat would not have been visible, illustrating the visual field expansion. Again, the binocular percept is that of visual confusion, with the fish and the cat perceived in the same visual direction. Learning to interpret the double vision view induced by the prism is the most challenging aspect of the Trifield glasses. Note that in this illustration, we assume for simplicity that the person has normal binocular vision and no phoria. When the wearer looks through the junction between the two Trifield prism segments, the view is more complicated, with part of the prism-eye view coming from each prism segment. This view is illustrated in Fig. 9 of Peli (2001).

The lateral shift provided by the prisms is large enough to shift the extension outside the unchanged field of the non-prism eye, preventing the patient from experiencing diplopia (seeing one object twice in two different apparent directions). Diplopia occurs when the images of an object fall onto non-corresponding points of the two retinas. However, visual confusion does occur with the Trifield glasses. Visual confusion occurs when images of two different objects in the scene fall onto corresponding points of the two retinas and, therefore, appear to be in the same perceived direction. To help the patient differentiate the objects and their direction viewed through the prisms, the right prism was tinted red and the left was tinted green. While these cues are helpful, we expected that when wearers were first given the glasses, they would have difficulty interpreting what they saw. One of the two pieces of the field of view (the tinted one) brought into view by the prisms does not represent the objects in their true direction. However, we also expected that wearers adapt to this shift and eventually be able to determine the true direction of objects viewed through the prisms (Kohler, 1964; Pick *et al.*, 1969; Welch *et al.*, 1993).

In this study patients with restricted visual fields were fitted with the Trifield glasses for an extended period (nominally six weeks) during which their benefit as a mobility aid was evaluated.

Methods

Extended Wearing Trial

The Trifield glasses were evaluated during a prospective five-visit extended wearing trial planned for six-weeks duration (Fig. 3). At the initial visit, the patient received a full eye examination by one of us (ELB) at the Massachusetts Eye and Ear Infirmary (MEEI) and was then further screened for study eligibility at Schepens Eye Research Institute (SERI). If eligible (described below), the patient was measured for Trifield glasses. Typically, the Trifield glasses took 6 to 10 weeks to manufacture. The Trifield glasses were dispensed at visit 2. Follow-up visits were performed nominally one (visit 3), three (visit 4) and six (visit 5) weeks after delivery of the Trifield glasses at visit 2. The benefits (or otherwise) of the Trifield glasses were evaluated through measurements of clinical success, visual field expansion, change in perceived direction through the prisms, and perceived quality of life. At approximately one year following the end of the study, a long-term follow-up telephone interview was conducted with those patients who chose to continue to wear the Trifield glasses at the last visit of the study (Fig. 3).

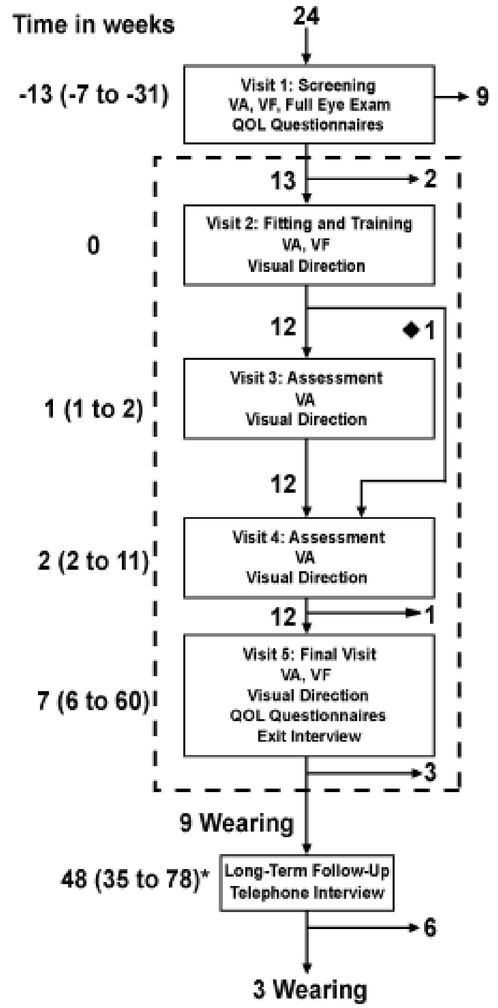

Figure 3. Study flow diagram showing the timing of visits, the main procedures at each visit and the number of patients attending each visit. Numbers on the left of the flow diagram are the median time in weeks (range in parentheses) relative to the Trifield glasses fitting and training visit (visit 2), except for the follow-up visit, which is relative to the study end (visit 5). Numbers next to the *down pointing* arrows indicate the number of patients moving to the next stage of the study. The numbers next to *right pointing* arrows indicate the number of patients who discontinued wear of the Trifield glasses at that stage. The solid *diamond* indicates a patient who did not have a visit 3, attended visit 4 and then discontinued wearing the Trifield glasses, so did not complete the study. The formal visits of the study are enclosed by the dashed rectangle. VA = visual acuity; VF = visual field as measured by computer perimetry. The * indicates that the reported times are relative to visit 5.

Eligibility Criteria

Eligibility requirements included best-corrected single-letter visual acuity of 6/60 or better in the each eye, a stable condition that caused tunnel vision, ability to understand verbal instructions in English, and age 18 years or older. The primary visual field criterion was a residual central visual field horizontal diameter of 3° to 20° in each eye as measured by our custom computerized perimeter using a white (340 cd/m^2), 12mm target, on a grey background (42 cd/m^2) viewed from 1 m. Patients with residual peripheral islands (as determined by Goldmann perimetry, target V4e) were considered for study inclusion if the islands seemed to be of little functional value in mobility situations. Four patients enrolled in the study demonstrated such peripheral islands. Lastly, patients were excluded if they had disruption of binocular visual function that could lead to suppression of one eye (e.g. strabismus, amblyopia).

Patients

Patients were recruited from patient databases at the Berman-Gund Laboratory and SERI and were also referred by the Foundation Fighting Blindness and the Choroideremia Foundation. Twenty-four patients (18 male) with tunnel vision, deemed potentially eligible based on a telephone interview, were screened for participation in the study (visit 1). Of those 24 patients, 15 were eligible and 13 agreed to participate in the study. For the 13 participating patients (8 male), the median age was 49 (range, 39 to 59) years, all 13 had severely restricted visual fields (median 9.5º, range 5.0º to 21.5º, wide) due to either retinitis pigmentosa (11 patients) or chorioderemia (2 patients), nine used a long cane to aid in mobility and eight of them previously had received orientation and mobility training, and median binocular visual acuity was 6/11 (range 6/5.5 to 6/60).

Of the 13 participating patients, 12 completed the study (Fig. 3). The visual status of those 12 patients remained stable during the study. Between visit 1 and visit 5, two patients had more than one line (0.1 logMAR) difference in visual acuity (0.12 and 0.14 logMAR) and two patients had improvements of more than one line in visual acuity (0.11 and 0.14 logMAR). The measurement error (95% confidence limits) of visual acuity in healthy eyes is about one line (Bailey *et al.*, 1991; Arditi and Cagenello, 1993), but is greater when vision is impaired (Reeves *et al.*, 1991; Woods, 1993; Kiser *et al.*, 2005). No patient showed a change in the horizontal diameter of the monocular visual fields of more than 1° measured when comparing visits 1 and visit 5.

The study protocol was approved by the Institutional Review Boards at MEEI and SERI. All patients read, or were read, the consent to participate forms, had any questions answered, and then signed the consent form.

Trifield Glasses Prescription, Fitting and Training

The Trifield glasses comprised a conventional single vision or bifocal lens placed over the dominant eye, and the prism lens over the fellow eye with both prism apices splitting the pupil (Fig. 1). Ocular dominance was determined using polarized goggles and a mirror (Peli, 2002) If no dominance was noted with the polarized goggle, it was determined by comparison of the blurring effect of a +1.50 diopter spherical trial lens placed over one or other eye (Benjamin and Borish, 1994; Siejas *et al.*, 2007). If no ocular dominance was found with either test, the conventional lens was placed over the eye with the significantly better visual acuity or larger visual field. If there was no clinically significant difference in the monocular visual acuities or visual field extents, conventional lens placement was based on patient preference.

As illustrated in Fig. 2, the field shift of the prism eye provided field expansion at the expense of visual confusion (two objects seen in the same direction). The prism powers used were calculated to be large enough to avoid diplopia (a single object having two apparent visual directions), as would happen with a prism power causing shift (in degrees) that was smaller than the residual field diameter. Since such separation eliminates all fusional clues, the eyes take up the phoria (resting) position with the Trifield glasses. Phoria measurements taken at near (3 feet) and far (15 feet) were used to adjust the prism powers to account for the effect of phoria. Prescribed powers for the Trifield glasses used in this study ranged from 11 to 44Δ for the nasal prism and 10 to 34Δ for the temporal prism. The right prism was tinted red with a transmission of about 37% and the left was tinted green with a transmission of about 46%.

To familiarize a patient in the use of the Trifield glasses the patient was escorted for a walk through SERI corridors and into uncluttered rooms. The patient was instructed to pay particular attention to doorframes and other potential obstacles. The patient was then escorted both up and down a flight of stairs, and instructed to make use of handrails whilst doing so.

In addition to this general instruction in the use of the Trifield glasses for obstacle detection a training exercise was demonstrated at the lab visit and was prescribed for home practice in an effort to improve adaptation to the image shift caused by the prisms. The exercise was a manual reaching exercise based on Kohler's observation that adaptation to prism induced field shifts was hastened by tactile and proprioceptive cues (Kohler, 1964). While the patients looked through one of the two prisms, an experimenter presented a finger into the prism field, and patients were instructed to quickly reach and touch the experimenter's finger with their own. This was repeated with both prisms monocularly and then binocularly until the patients' movements were swift and accurate. The patient was asked to repeat the reach and touch exercises at home for objects detected through the prisms as often as possible; initially through the prism eye only (i.e. monocularly) and then with both eyes open when the patient felt proficient with the prism-eye only exercise.

Clinical Success

Clinical success was measured as the percent of patients who chose to continue to wear the Trifield glasses after the wearing trial concluded (visit 5). At visit 5 and long term follow-up (Fig. 3), the investigators recorded responses to questions covering use, benefits, and difficulties attributed to the glasses and whether the patient found the Trifield glasses of sufficient perceived benefit as to pay $1000.00 to use as a device in their everyday mobility situations. At the visit 5 interview, a joint (patient and clinician) decision was made based upon the patient's perceived benefit from the Trifield glasses and the clinician's opinion, as to whether the patient should continue to wear them.

We asked patients to wear the Trifield glasses as much as possible during the course of the study. The glasses were designed as mobility devices so they were only meant to be used when walking, not when working at a desk or when watching TV etc. Following fitting of the Trifield glasses (visit 2) patients were given a take-home wearing diary to record the number of hours per day that the glasses were worn. The form also had an open-ended comments section in which patients could record any difficulties or benefits experienced with the Trifield glasses. Patients were asked to return the diary to us at the subsequent visit and were given a new diary at visit 3 and visit 4 with the same instruction. During the interview at each visit, the investigator asked the patient for an estimate of the hours worn per day since the last visit.

Visual Field Expansion

Extent of monocular visual fields was defined as the width from the farthest lateral edges of the residual central visual field (Fig. 4a). The binocular visual field without the prism was defined as the width of the horizontal extent that would be covered by either eye (Fig 4a).

The visual field with Trifield glasses (Fig 4b) was measured in two steps. First, the patient fixated with the non-prism eye (left eye in Fig 4b) and tilted his head slightly to the right. That head shift brought the left prism in front of his right eye. The visual field of the left eye was measured under this condition (using standard kinetic perimetry) followed by the measurement of the visual field of the right eye that covered a field of view to the left of the fixation target. The patient then turned his head a little to the left to bring the right prism in front of his right eye. The visual field expansion to the right of fixation was then measured. While the patient had at any instant only one of the two peripheral extension areas, we defined the full extent of the visual field as the width covered with these three areas (double arrow in Fig 4b) as they represent potential field of view coverage at different times and available through scanning eye and head movements. As shown in Fig. 4b this sometimes significantly overestimated the amount of visual field afforded by the Trifield glasses. This was especially true in the case illustrated where, apparently, the phoria at the time of testing was larger than that determined during the fitting process (visit 1).

The enrollment criterion of no more than 20º residual visual field was selected because the prism powers of much above 20º (36Δ) would impact visual acuity and are so thick that the prisms could impinge on the face and be uncomfortable or cause injury.

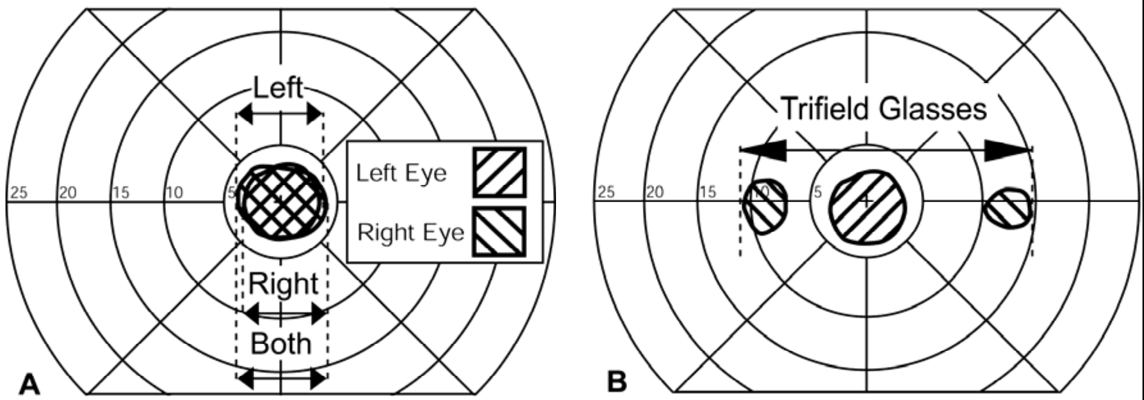

Figure 4. Visual field expansion measured using a computerized perimeter for one patient. (A) Left and right eye monocular visual fields. (B) The visual fields of the same patient when wearing Trifield glasses with the prisms over the right eye. Visual field expansion by the prisms is indicated by the two hatched areas to the left and right of fixation. Only one of these is available for the patient at any instant depending on the direction of gaze at that moment. The distance between the left most edge of the left expanded area and the rightmost edge of the right expanded area (shown by the arrow) was defined as the expanded visual field.

Perceived Direction

Initially the perceived direction of an object seen through a prism is not veridical (correct). People can adapt the perceived direction of objects seen through a prism (Kohler, 1964; Pick *et al.*, 1969). Kohler (1964) reported a "dual" adaptation after full time wearing a binocular half-prism for 10 days. Initially, he reported adaptation to the directional change and visual distortions affected by the prisms. However, when looking through the clear portion of the spectacles, aftereffects of adaptation to the prism were perceived (i.e., he perceived distortions and inversed directional change). After additional wearing time, these aftereffects dissipated as well, and a "dual" adaptation was noted so that perception was correct both through the prism and through the prism-free segment of the lenses. We hypothesized that patients wearing the Trifield glasses may adapt to the directional change through the monocular prism in a similar manner.

To measure adaptation to perceived direction we used a pointing task at visits 2, 3, 4 and 5. Patients were seated 1m from a 64° by 81° rear-projection screen. Large head movements were restricted by a chin rest and a tight fitting headband from a binocular indirect ophthalmoscope that was connected to the head rest. This experimental set-up is illustrated in Fig. 5 of Giorgi et al. (2009). Patients indicated the perceived lateral direction of stimuli on the screen using a large graphic bitpad tablet (90 by 120 cm) and a computer mouse held in the hand. Patients wore a brace to limit flexion of the elbow and were asked not to flex the elbow or the wrist, so that pointing was from the shoulder. Pointing was open-loop with no visual feedback, as a wooden box over the bitpad prevented a view of the arm, hand or mouse. Using small counter-rotations of the head, as used in visual field testing, the left and right extended areas were tested separately in consecutive sessions. In each session, stimuli were presented one at a time to the visual field of the non-prism eye or the prism eye. The fixation cross was always viewed with the non-prism eye.

A calibration step conducted without the prism glasses adjusted for individual differences in pointing responses. During calibration the patient turned his eyes (but not head) towards each approximately eye-level target. During perceived direction testing the non-prism eye fixated a central target.

The difference in the perceived visual direction for targets presented in the prism field of view and those presented in the visual field of the non-prism eye was used as the outcome measure. Adaptation of perceived visual direction would appear as no difference in these two directions. Lack of adaptation would appear as a persistent difference in reported direction, with the expected separation being the prism power.

Quality of Life

Patients were administered two questionnaires during the first and last visits of the study. Both questionnaires; National Eye Institute Visual Functioning Questionnaire-25 (NEI-VFQ: Mangione *et al.*, 2001) and the Independent Mobility Questionnaire (IMQ: Turano *et al.*, 1999a) contained items relating to mobility. The patients reported their perceived levels of difficulty for each item. Patients completed each questionnaire, but we only analyzed responses to subsets of questions that we hypothesized would be related to mobility and obstacle avoidance and thus could be sensitive to the effects of the Trifield glasses. The chosen questions from the NEI-VFQ were 7, 10, 14, 20, 24, A7, A11a & b, and A13 and from the IMQ were 2, 4, 6-8, 10, 18, and 24-35 (the text of those questions is reported in the Appendix).

A modified Rasch analysis, which estimates interval scales for questionnaires ordinal data, was used to transform the raw scores of responses to the items of each questionnaire (Massof, 1998). Non-parametric tests were used in the data analysis. The Wilcoxon test was used for paired comparisons and the Mann-Whitney test for unpaired comparisons. We report test results as statistically significant when $p \leq 0.05$. However, because of our small sample size, we have reported test results as "approaching" significance when $0.05 < p \leq 0.10$. A Bonferroni correction for the number of NEI-VFQ and IMQ questions tested (28 in total) would have required $p < 0.002$ for significance.

Results

Clinical Success

As shown in Fig. 3, of the fifteen patients who met the eligibility criteria at visit 1, two patients declined to participate, thirteen were dispensed a pair of Trifield glasses at visit 2, and one of that 12 did not complete the study due to non-vision related reasons. That patient who did not complete the study did not attend visit 3, did have a visit 4 and then did not attend the final visit (visit 5). Thus, 12 of the 13 patients who participated in the study completed all visits (Fig. 3). Unless otherwise noted, analyses of data on outcome measures were restricted to the 12 patients who completed the study.

Of the 12 patients who completed the study, 9 were wearing the Trifield glasses when interviewed at visit 5, and all 9 (75% of those completing the study) chose to continue to wear following the study (visit 5). Patients not wishing to continue to wear the Trifield glasses returned their glasses at the final visit. At the long-term telephone follow-up (median = 48 weeks, range 35 to 78), 3 of the 9 patients reported still wearing Trifield glasses.

At the visit 5 interview 6 of 9 (67%) successful wearers reported benefits of the Trifield glasses as useful in avoiding collision with objects and passersby, as did one of the three non-successful wearers. At the same time, 5 of the 9 (56%) successful wearers reported some difficulties associated with the Trifield glasses in “street crossing”, 6 of 9 with “crowds”, with one patient describing crowded environments as “visual noise”. All

3 non-successful patients cited “crowds” as a difficulty, and these 3 patients reported insufficient observed benefit using the device as the reason to discontinued use.

Visual Field Expansion

Visual field expansion was recorded for all patients completing the study, as illustrated in Fig. 4. The median absolute difference between the expanded visual field and the normal visual field was 18° (range 9 to 38) for the 12 patients completing the study. The median ratio of visual field with-to-without the Trifield glasses was 2.7 (range 1.6 to 4.0).

Perceived Direction

No patient in the study demonstrated adaptation to the prismatic image displacement. Possible reasons for the lack of adaptation are addressed in the discussion.

Quality of Life

We hypothesized that Trifield glasses would affect the perceived quality of life of the patients, either benefiting or hindering them in their daily mobility situations. Analyses were performed for the 12 patients who completed the 5-visit study. One of those 12 patients did not complete the visit 5 questionnaires for health reasons. Planned analyses were performed on specific questions (Appendix) considered pertinent to mobility. No significant change in responses to the nine NEI-VFQ or nineteen IMQ questions were found between study start (visit 1) and end (visit 5) for all 12 patients completing the study, nor for the 9 successful patients. For NEI-VFQ questions, no significant differences were found between successful and non-successful patients at study start or at study end. For the IMQ questions, at study start, successful-wearers reported greater difficulty in *moving about at work* (Mann-Whitney $Z_{11} = -2.16$, $p = 0.06$), *avoiding bumping into walls* (Mann-Whitney $Z_{11} = -1.79$, $p = 0.10$) and *avoiding shoulder height* *objects* (Mann-Whitney $Z_{11} = -2.06$, $p = 0.06$) than non-successful patients. At study end , non-successful patients reported more difficulty *being aware of another person's presence* (Mann-Whitney $Z_{10} = -2.13$, $p = 0.04$) and *avoiding bumping into knee-high objects* (Mann-Whitney $Z_{10} = -1.97$, $p = 0.07$) than successful patients.

No difference was observed between the wearing times of the successful wearers (median 1.2, range 0.6 to 3.8 hours/day) and the non-successful wearers (median 0.99, range 0.57 to 2.29 hours/day)(Mann-Whitney $Z_{11} = 11.0$, $p = .73$).

Discussion

Initial success with the Trifield glasses appeared to be very high as 75% (9 of 12 patients who completed the study) felt that they benefited from the device and wanted to continue to wear the device following about 2 months of experience. However, after about a year only 25% (3 of the 12 who completed the 6-week study) continued to wear the Trifield glasses. Even that reduced success rate (25%) may be considered high in view of the lack of effective visual aids for patients with tunnel vision. Yet, it is relatively low when compared to about 47% (Bowers *et al.*, 2008) and 42% (Giorgi *et al.*, 2009) found for long term retention rate of the prismatic correction for hemianopia. The decline in use with time suggests that the perceived benefits were either eliminated or were overcome by the perceived limitations and difficulties of the device. We believe that it is the latter. While the patients with tunnel vision have greater impairment of mobility than those with hemianopia and thus would be expected to benefit more from a visual aid, the Trifield glasses are more difficult to use and may present more difficulties than the peripheral prism correction for hemianopia. The peripheral prisms do not interfere with central vision and thus do not affect visual acuity. Trifield glasses affect central vision and, at least in one eye, the relatively high power prisms may reduce visual acuity and cause spatial distortions. While the peripheral prism glasses use higher-power, lower-image-quality Fresnel prisms, their placement out of central vision makes these limitations less apparent and easier to deal with. However, it appears that the greatest difficulty in adapting to the Trifield glasses was the central double vision experienced as visual confusion. The visual field expansion of the Trifield glasses (as that of the monocular peripheral prism for hemianopia) is provided by visual confusion, as the objects (potential obstacles) that would not be detected without the device can be detected, but they appear to be in a different (prism shifted) direction, superimposed on another object in the environment seen by the other eye. This double vision is known to be uncomfortable, annoying and disturbing in central vision. Peripheral double vision as represented by physiological diplopia (Peli, 2000) is common and thus easier to accept. It is interesting to note, however, that double vision (i.e. visual confusion) was not reported in patient diaries or in responses to questions as perceived difficulties in using the Trifield glasses.

Based on the findings of Kohler (1964) we hypothesized that at least some patients would obtain veridical perceived direction of objects seen through the prism segments. This did not happen. The reason for the lack of adaptation of the type described by Kohler may include the short and intermittent wearing times (0.6 to 3.8 hours/day even for successful patients) as compared to full time wear by Kohler and his subjects, and that our Trifield prisms were fitted monocularly and not binocularly as did Kohler, and the higher power of the prisms we fitted, at least for some of the patients.

Patients with tunnel vision at the level enrolled in our study have had many years of slow progression of their visual field loss. It appears that many of them have slowly adapted to the situation by gradually changing their life style to reduce the challenges of pedestrian mobility as much as possible. As a result, these patients have reduced opportunities to walk and to gain experience with the Trifield glasses. Most of these patients also suffer from night blindness and that reduces their mobility further. This is particularly true in a place like Boston when the light hours after work hours are limited for most of the year (Bowers *et al.*, 2003). Thus, our patients had fewer opportunities to walk with the Trifield glasses and to learn to benefit from them. Our patients wore the glasses for a median of 1.2 hours per day (range 0.6 to 3.8), whereas, patients with hemianopia in comparable studies wore their peripheral prism glasses for a median of 3.0 hours per day (range 1.0 to 13.4: Giorgi *et al.*, 2009) to 8.0 hours per day (range 1.0 to 16: Bowers *et al.*, 2008).

Using the Trifield glasses when reading may be possible, but is certainly uncomfortable due to the visual confusion. Thus, the user has to remove the glasses or shut his prism eye even for spot reading (e.g. reading labels or price tags in stores) or reading distance text such as street signs. This additional limitation may have contributed to the eventual rejection of the device by some patients. In comparison the peripheral prisms for hemianopia may be used with a small bifocal segment and permit spot reading at near and distance with little difficulty.

Another possible reason for the long-term discontinuation is the lack of follow up during the year following the end of the formal (5 visit) study. RP patients of many years usually realize that no significant help is provided and tend to avoid follow-ups. In the study they were instructed to continue care with their referring doctor. We do not know if they indeed had any follow-up visits during the year, and even if they did, they would not have received advice on this experimental device. It is possible that follow up care at shorter interval with further instruction on the use might have resulted in higher retention rate.

The Trifield lenses expand the field only laterally, which may be important in avoiding collisions with other pedestrians and some obstacles. However, the lower visual field is known to be of more importance for mobility (Lovie-Kitchin *et al.*, 1990) and was not expanded at all by the Trified glasses. An earlier design included a lower base-down prism segment for that purpose. This was eliminated when it became apparent that the prism powers practical in our design provided a lower visual field expansion that was too small to be meaningful. This aspect needs to be reconsidered in future designs of devices for tunnel vision.

Trifield glasses are suitable only for patients with two functional eyes with similar residual visual fields. While in RP this is not rare, it is a restrictive criterion. We have developed (Vargas-Martin and Peli, 2002) and tested (Vargas-Martin and Peli, 2001; Peli *et al.*, 2007; Luo *et al.*) an augmented-vision system using a head-mounted display which can be used by patients with one or two eyes. The electronic system is much more complicated to maintain and much more expensive and thus, although it may be an attractive option, we still consider the Trifield glasses as a potentially useful design perhaps with some modifications of the design, the fitting procedures and training in its use.

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Appendix

The text of questions in the two Quality of Life questionnaires that we hypothesized would be affected by the Trifield glasses. Patients rated all of the following questions in terms of degree of perceived difficulty.

National Eye Institute Visual Functioning Questionnaire (NEI-VFQ-25) (Mangione *et al.*, 2001)

7	Because of your eyesight, how much difficulty do you have finding something on a crowded shelf?
10	Because of your eyesight, how much difficulty do you have noticing objects off to the side?
14	Because of your eyesight, how much difficulty do you have going out to see movies, plays or sports events?
20	I stay at home most of the time because of my eyesight?
24	I need a lot of help from others because of my eyesight?
A7	Because of your eyesight, how much difficulty do you have taking part in active sports or other outdoor activities that you enjoy (like golf, bowling, jogging or walking)?
A11a	Do you have more help from others because of your vision?
A11b	Are you limited in the kinds of things you can do because of your vision?
A13	I don’t go out of my home alone, because of my eyesight?

Independent Mobility Questionnaire (IMQ) (Turano *et al.*, 1999a)

2	Walking in unfamiliar areas?
4	Moving about at work?
6	Moving about in stores?
7	Moving about outdoors?
8	Moving about in crowded situations?
10	Moving about using public transportation?
18	Walking in high-glare areas?
24	Being aware of another person's presence?
25	Avoiding bumping into people?
26	Avoiding bumping into walls?
27	Avoiding bumping into head height objects?
28	Avoiding bumping into shoulder height objects?
29	Avoiding bumping into waist height objects?
30	Avoiding bumping into knee height objects
31	Avoiding bumping into low lying objects?
32	Avoiding tripping over uneven travel surfaces?
33	Moving around in social gatherings?
34	Finding restrooms in public places?
35	Seeing cars at intersections?

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