2017 Charles F. Prentice Award Lecture: Peripheral Prisms for Visual Field Expansion: A Translational Journey

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ABSTRACT: On the occasion of being awarded the Prentice Medal, I was asked to summarize my translational journey. Here I describe the process of becoming a low-vision rehabilitation clinician and researcher, frustrated by the unavailability of effective treatments for some conditions. This led to decades of working to understand patients' needs and the complexities and subtleties of their visual systems and conditions. It was followed by many iterations of developing vision aids and the techniques needed to objectively evaluate their benefit. I specifically address one path: the invention and development of peripheral prisms to expand the visual fields of patients with homonymous hemianopia, leading to our latest multiperiscopic prism (mirror-based design) with its clear 45° field-of-view image shift.

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It is natural, on the occasion of receiving a great award and recognition, to reflect on the path that led to this time and place. I expressed some of this in the preamble to my scientific presentation at the award ceremony. I was then encouraged by Dr. Michael Twa, the *Optometry and Vision Science* chief editor, in his letter requesting this article, to make it more autobiographical. It did not require very much persuasion; as my dear wife Kathleen Carroll will tell you, I am not bashful in talking about myself. She frequently reminds me of our first date, when she found my biography on her dinner seat, as I provided the post-dessert lecture.

In 1964, perhaps to mark my bar mitzvah, the National Institutes of Health announced an artificial heart program aimed to put a man-made heart into a human by the end of the decade.[1] The media followed that program with much attention for the next 20 years to its success in the early 1980s. I was inspired and expressed my wish to become a biomedical engineer and to work on the artificial heart in my elementary school matriculation paper. For some reason, I kept that idea alive for more than a decade. When I graduated as an electrical engineer in 1976 from the Technion–Israel Institute of Technology, there were no jobs for electrical engineers. I was interested in continuing my studies, so I enrolled in a master's program under Dr. Josh Zeevi, who was involved in cardiology-related biomedical engineering. Dr. Zeevi also worked in eye movements and image processing. I started my research in cardiology, even attending open-heart surgery practice runs that the surgeons conducted on dogs in those early days when patients were not available to operate on every day. While helping a colleague in the laboratory calibrate our eye-tracking system, I made a chance observation that led me to switch my research project to the control of eye movements with peripheral vision. Dr. Jake Sivak, in his Prentice award lecture,[2] called it serendipity. Jake had arrived for a sabbatical at a laboratory across the hall from mine, at the newly formed Silver Institute of Biomedical Engineering at the Technion in Haifa, Israel. We became close friends, and among other things, Jake asked me to help him refract a Mongoose at the Haifa Zoo. He taught me how to use the retinoscope while he held the angry animal (using large and heavy gloves). We were trying to determine the predator's accommodation. I got the optometry bug, and Jake talked me into applying to optometry school after my master's degree. As a student at New England College of Optometry, I continued my eye movement research with great support from Drs. Glen McCormack, Frank Thorn, Jim Comerford, and Mitch Scheiman. All of them encouraged me to pursue any direction that caught my attention—from ophthalmic optics through binocular vision to light polarization and its applications.

The Introduction to Low Vision course refocused my attention. I realized that low vision was an excellent fit for my engineering inclinations, interests, and skills. I also saw it as a great challenge, and I was looking for one. I initiated a project to apply digital image processing to enhance images for the visually impaired. This was in 1982, when very few places had digital image processing capabilities. Boston was one of the best places in the world to find such capabilities. Upon graduation, I looked for post-doctoral training opportunities and sent letters that went unanswered. Determined, I walked into the Schepens Eye Research Institute in person. I had read in *Optometry Times* about the scanning laser ophthalmoscope that was invented there and realized that it could be a great tool to implement the ideas that emerged from my master's thesis. I

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also learned that the ideas I had were relevant for studying eye movement control in macular degeneration, a condition I never heard about while doing my master's research. I showed up at the door and asked to see Dr. Timberlake, who was mentioned in the article, and left with a half-time position (working on the scanning laser ophthalmoscope). I was also encouraged by Drs. George Timberlake and Larry Arend to pursue my interest in image enhancement over the eye movement research.

I still needed another half-time position. I cornered Prof. Bernard Schwartz, the chair of Ophthalmology at Tufts Medical School, at the end of a talk he delivered to the regional optometry conference. I introduced myself and gave him my resume. Luckily, he knew about the Technion and immediately invited me for an interview. His department was one of the first places in the world to apply image processing to retinal images (serendipity!). With this second half-time position, I gained access to a most advanced image processing laboratory and a clinical appointment providing low-vision and contact lens services. As much as I liked my new exciting research career, I greatly enjoyed my clinical low-vision practice. In addition to the opportunity to apply the more complex low-vision devices (optical and electronic: CCTV) and deal with difficult clinical cases, I really enjoyed the personal interactions with the (mostly elderly) patients. It gave me the opportunity to implement much of my training in psychology, acquired during my doctor of optometry education, and allowed me to connect with the patients in ways that facilitated solving their vision problems effectively.

At least 80% of the low-vision patients I cared for during these early years were elderly with macular degeneration. It was possible to help most of them with a variety of aids for reading. I also started fitting bioptic telescopes. In many cases, these enabled patients to resume driving or, for young patients, to gain their first driving license. This service was extremely rewarding, as most people I saw from eastern Massachusetts, southern New Hampshire, and Rhode Island had limited other transportation options. The same macular degeneration patients were also the focus of our scanning laser ophthalmoscope, image enhancement, and reading with electronic displays research projects at Schepens.

The bliss of successful vision rehabilitation care was only rarely interrupted. On occasion, patients with macular degeneration were so severely impaired that it was not possible to enable them to function the way that they wanted. Even in these cases, it was frequently possible to provide the patients with explanations of their situation, encouragement about the low likelihood of further vision loss or total blindness, and other expressions of empathy. In many cases, these approaches were sufficient to provide significant and meaningful relief for the patients.

The most difficult patients to care for were those with visual field loss. Whenever patients with homonymous hemianopia or tunnel vision due to retinitis pigmentosa or glaucoma would show up at the door, I knew it was not likely to end well. Although the textbooks and scientific literature offered a few solutions, most were not sensible based on my understanding of the optics and physiology. Trials of these approaches were not very successful in the clinical setting. For example, fitting homonymous hemianopia patients with unilateral (or bilateral) sector prisms (using Fresnel Press-On prisms from 3M Corp., St. Paul, MN) regularly received a very positive initial response. However, when I purposely switched the prism base direction from the field loss side to the seeing side and reapplied the glasses, the patient would frequently respond with even more enthusiasm, indicating that the effect elicited was not an optical one. Fortunately, very few patients with peripheral field loss were referred to my service. However, the frustration accumulated, and it became obvious that this area needed better solutions than those available to us then.

In 1994, I was invited to present a talk at an Association of Research in Vision and Ophthalmology Special Sunday Symposium during the Annual Meeting in Sarasota, FL. I offered the title "Enhancement of Retinal Images: A Critical Evaluation." By that time, I had been working in that area for more than a decade. I had leveraged this applied investigation into basic research in contrast perception, which is considered my most impactful pursuit (based on citation counts).[3] Now, 25 years later, we are seeing multiple implementations of image enhancement technology for low vision in the marketplace, some using head-mounted displays. The interplay of applied and basic research has been a central feature of my research. I truly believe that this interplay is crucial for success in both areas. Advancement in clinical applied research needs access to new answers from basic research. Occasionally, such answers may be found in the literature, when they were explored unrelated to the clinical problem. However, the chances of getting to these answers by pursuing them when they arise from clinical research needs are much greater and a more direct path. At the Association of Research in Vision and Ophthalmology Sunday Symposium, instead of talking about my advertised title, I decided to take the opportunity that I had to reach the ears of about 300 of the best and brightest of our colleagues, who specialized in physiological optics and psychophysics, and call on them to find more helpful solutions for patients with field loss. I explained the problems of field loss, as best I understood them at the time, the severity of their impact and the lack of any effective rehabilitation treatment. I then asked for anyone with ideas to address these difficulties to come and talk to me during the coming week so we could try to change the situation. No one approached me to discuss the matter at all. As the week progressed, I fumed with anger that no one was interested enough in this problem to even strike up a small-talk conversation about it. On the flight on my way back home, with a piece of paper and my mechanical pencil, I came up with the idea of peripheral prisms for homonymous hemianopia.

I have been working on developing and implementing the peripheral prism concept for the past 25 years. In the process, we have developed a much-refined understanding of visual field loss, its impact, and the consequences of applying prisms and other approaches for field expansion. During that time, we addressed various types of field loss, such as tunnel vision,[4–6] bitemporal hemianopia,[7,8] and the loss of the temporal crescent that comes with the loss of vision in one eye.[8,9] However, here I will focus on the development and evaluation of the peripheral prisms for homonymous hemianopia.

HISTORICAL BACKGROUND WITH CURRENT PERSPECTIVE

Patients with homonymous hemianopic field loss due to post-chiasmal lesions from stroke, tumors, or trauma experience difficulties with navigating and avoiding obstacles.[10,11] The consequent loss of mobility, increased risk of collision with other pedestrians, falls due to tripping obstacles,[12] and unsafe driving[13] can be detrimental to patients' independence and quality of life.[11,14,15] Although the impact of homonymous hemianopia is less debilitating than some of the other conditions resulting in peripheral field loss such as advanced retinitis pigmentosa or end-stage glaucoma, the condition is far more prevalent,[16] and the field loss is sudden, unlike the slow progression of the other conditions.

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From the early 20th century, spectacles-mounted prisms have been proposed for field expansion, as they were believed to shift portions of a scene from the blind field of view to the residual seeing field.[17] The use of prisms for field expansion became more popular in the 1970s with the introduction of the Fresnel Press-On prisms.[18] Full-field yoked prisms that fill the entire spectacles eye wire (Fig. 1A) have been considered as field-expansion devices for homonymous hemianopia (Fig. 1A).[17,19–21] However, to fixate an object of interest, users need to turn their head and/or eyes away from the blind side (toward the prism apex), which negates the field shift into the blind side.[22,23] We have recently shown that there was no difference in the perimetry results on the blind side with or without yoked prisms.[23] The reason for the misapplication of full-field yoked prisms for field expansion is the lack of consideration of eye movements and the fixation reflex. To make this point, I have frequently joked that yoked prisms may work as a field-of-view expansion device for a patient with homonymous hemianopia who also lost all lateral eye movements. Unfortunately, even such a patient will not benefit from the full-field yoked prisms because of head movements that will redirect the gaze to an object of interest through the prisms, nulling the "field-expansion" prism effect. The introduction of prisms into central foveal vision also results in reduced acuity[24] and contrast sensitivity.[25] The impact is worse with Fresnel prisms than with ophthalmic prism lenses.[26] For both, however, if the prisms are applied centrally, the impact of color dispersion on image contrast is sufficient to limit prisms to moderate power (<10°). This results in a shift of only a few degrees of visual angle, which, nevertheless, does not expand the field of view even a little. The power of the yoked ophthalmic prisms used is limited not only by the optical quality but also by the thickness and weight of the prisms. In higher powers, the prism thickness becomes impractical, even with very narrow frames. Although Fresnel prisms overcome these limitations, their poorer optical quality similarly limits power to about 20 prism diopters (Δ) in most of these designs and frequently to much lower power. To address the central vision limitation, bilateral sector (partial) prisms have become an alternative to the full-field yoked prisms.[19–21] In these designs, the prism is limited to the blind-side part of the carrier lenses (Figs. 1B, C), leaving the line of sight at the primary position of gaze free of prisms.[27] Bilateral sector prisms have no effect at primary gaze or when the gaze is directed toward the seeing hemifield. As a result, they do not show any effect on perimetry. If and when the gaze is shifted toward the blind side and into the prism, the foveation reflex eliminates the field expansion, as it does for full-field yoked prisms.[23] Furthermore, they introduce pericentral field loss (an optical scotoma, which we named apical scotoma[22]).

If a sector prism is fitted unilaterally (usually mounted on the carrier lens on the blind side; Fig. 1D),[27–29] it also affects the field of view only when the gaze is directed into the prism. Although some field expansion may take place with a unilateral sector prism, the benefit may be limited by the presence of a pericentral apical scotoma (Fig. 2) and/or central diplopia (Fig. 3C). The exact effect depends on the interaction between the prism power and the magnitude of the eye movement (Fig. 3).[22,30]

There seems to be a widespread lack of intuitive appreciation, in the literature[31,32] and in clinics, for the relationship between prism diopters and visual angle, even though an approximation that 1Δ ≈ ½° would suffice. As a result, there is little sense of how ineffective low-power prisms are, even if they were to work as expected. This is a major impediment to any development work in this area. An easy way to avoid many of the pitfalls is to actually carry out perimetry with the proposed field-expansion devices, preferably with the type of patients for whom they are proposed. Some sanity checks may be obtained by measuring normally sighted subjects, and in some cases, mapping the blind spot can be very helpful. Apfelbaum and Peli[5] strongly recommended perimetry as a needed validation of the field-expansion effects of proposed prism designs. However, they pointed to numerous articles that reported impossible or improbable results, even with (reported, although not shown) perimetry. We further recommended calculations of the expected effects to ensure that the measurement results are not due to artifacts or errors. We specifically pointed to a case where perimetry conducted with 40Δ prisms led us to incorrectly conclude a similar qualitative effect of eye scanning to the blind side for the higher power such as 57Δ prisms,[22] which we later realized was not the case.[33] Repeating the perimetry with the higher-power prism would have revealed the difference.

The relationship between linear distance in millimeters on the spectacles lens and visual angle (about 3° for every millimeter) is another important but infrequently considered numerical relationship. The utility of sector prisms is brought into question when considering this relationship. Because the patient needs to scan in the

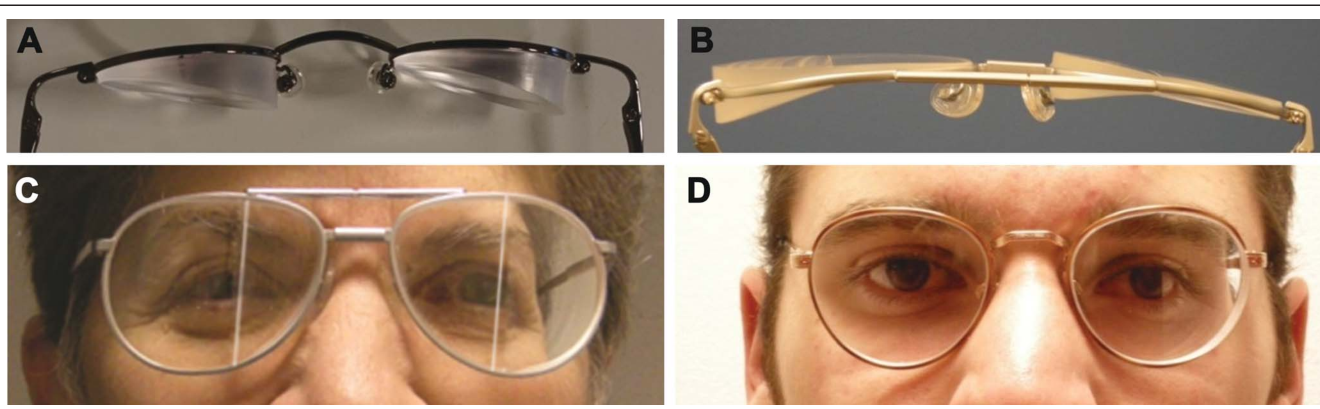

FIGURE 1. Yoked prisms fitted as field-expansion devices for homonymous hemianopia (HH). (A) Base-right 20Δ full-field yoked prisms, for a patient with right HH, shown mounted in a very narrow frame designed to reduce the prism edge thickness. Even with this frame, the left lens thickness at the nasal edge is too thick for a comfortable fit. (B) Base-left 20Δ sector prisms for a patient with left HH viewed from above. (C) The spectacles shown in panel B shown fitted on a person. (D) Unilateral sector prism glasses, for a patient with left HH. The base-left prism sector is mounted on the left lens only. Note the apical scotoma appearing to cut the left iris on the left side.

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FIGURE 2. The apical scotoma (an optical scotoma) caused by a sector prism depicted photographically. (A) The street scene without a prism. (B) The same scene photographed through a base-left sector prism, demonstrating the impact of the apical scotoma, eliminating the doorway and the front of the red car (seen at the center of panel A). At the same time, the next door farther to the left and the rear of the red car are shifted into view. This same field-substitution effect also occurs with the bilateral fitting of sector prisms. The monocular sector prism does result in field expansion, but a paracentral scotoma and diplopia may also occur, depending on the prism power. Note the reduced image quality and distortion (curvature) through the prism on the left part of panel B.

direction of the sector prism to benefit from the effect, the patient may as well scan a little farther and get the same access to the unseen field without the limitations of diplopia, confusion, and apical scotoma that comes with the sector prisms. The sector prism's apex is fitted as close as 1.5 mm from the lens optical center,[21] or much farther,[29] and the prism power is typically no more than 20Δ (10°).[29,34] An eye scanning of more than 6° is needed to reach into a prism that is 2 mm from the optical center. A larger but still practical saccade of 16°[35] will achieve the same limited "field-expansion" effect without the prism. To understand and design effective field-expansion devices, all these issues illustrate the need to consider the interaction between magnitude and effects of the prism power and eye movements. Using a sector design, an expansion of just 10° is available but only when scanning into the prisms and is of limited use, given the imposition of central double vision (confusion and diplopia) or loss of pericentral field to an apical scotoma.

DEVELOPMENT OF A NOVEL PRISM TREATMENT FOR HOMONYMOUS HEMIANOPIA

On the flight back from the Association of Research in Vision and Ophthalmology 1994 symposium, I came up with the concept of peripheral prisms for homonymous hemianopia, placing prism segments peripherally above and below the clear central portion of the carrier lenses. The initial design[36] addressed the main limitations of the prior approaches: first, eliminating central double vision and the pericentral apical scotoma:[22] second, with 40Δ, the highest prism power available at the time, it also extended the field-expansion effect farther into the blind side upon scanning into that side, as well as when the patient scanned away from the blind side (which works with any power prism). All these effects could be demonstrated with perimetry,[22,33] including field expansion while at the primary position of gaze, where the patient's eyes are most of the time (Vargas-Martin F, Peli E. IOVS 2002;43:ARVO Abstract S3809), thanks to the fixation through the prism-free section of the lens. The field-expansion effects occurred in the upper and lower peripheral fields. Of course, the diplopia and confusion were not eliminated; they were just moved vertically to peripheral locations. However, because of the common, almost constant, presence of peripheral double vision (physiological diplopia),[37] it is easy for patients to accept and get used to these effects in the periphery. Moreover, with proper design of the prism segments' width and position, the diplopia can be eliminated at the primary position of gaze.[22,33]

The main concept behind the peripheral prisms—splitting the visual field vertically, using the central section for the critical single clear central binocular vision, allocating the peripheral eccentricities to provide the field expansion by prism shifting, and further using the prism-free eye to compensate for the optical (apical) scotomas of the prisms—quickly evolved into the more general concept of vision multiplexing.[38] In engineering (and in my service in the Israeli Signal Corps), multiplexing refers to the transmission of two or more messages/signals simultaneously over the same communication channel, in a way that enables them to be separated and used at the receiving end. Vision multiplexing aims to

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FIGURE 3. Illustrations of binocular perception of a patient with left homonymous hemianopia (HH) with a unilateral sector prism. An illustration is used here, as currently we have no way to present *binocular* perception photographically. (A) An airport terminal scene as it may be perceived by a patient with left HH with the eyes in primary position of gaze, looking forward and fixating at the position of the red X. In the full panoramic scene (not shown here), a man walking to the left of the group in the center is not seen by the patient with HH. The use of a cartoon-like edge images facilitates illustrating the lack of vision, as over most of the transitions, from the right seeing side to the left blind side, there is no demarcation of the border. (B) Illustration of the view with a 20Δ (10°) sector prism placed about 2 mm (6°) to the left of the optical center of the carrier lens and with the patient's eye shifted 11° to the left, which brings the left eye line of sight 5° into the prism and the right eye fixating the red X. With this realistic eye movement, the right eye does not reach as far as the man on the left, but because of the prism effect, the left eye can see the right side of the man through the sector prism, marked with a red highlight (*binocular confusion*). There is no diplopia, and the apical scotoma is apparent as the missing right arm of the man. (C) Illustration of the same situation, but with the patient's eye shifted farther, 26° to the left, bringing the left eye line of sight 20° into the prism. This is a large, possible but not common, eye movement. The gaze shift alone enables the patient to see the right side of the man with his right (no prism) eye. The prism on the left lens shifts a second image of that man rightward by 10°. The diplopic image of the right side of the man seen by the left eye, highlighted in yellow (*diplopia*), is not helpful, as it is already seen by the right eye. However, the prism on the left lens also brings the left side of the man (holding a briefcase) into view by the left eye. That left side of the man, highlighted in red (binocular *visual confusion*), represents an actual expansion of the field of view, not diplopic, as only one copy is seen. Careful observers may note the effect of the apical scotoma on reducing the extent of the diplopia. Note also the loss of field on the right side due to the gaze shift to the left.

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provide two different visual functionalities together (e.g., a see-through display). The peripheral prisms apply vision multiplexing by shifting in combination with binocular multiplexing (binocular visual confusion) so that both the central and peripheral visual functionalities together can be provided through the one residual channel.

The general concept of vision multiplexing then guided us in designing numerous novel vision rehabilitation devices, all based on the same principle. These included, among others,[38] an in-the-spectacles-lens bioptic telescope[39] that enabled both a peripheral view of the central magnified (up shifted) and, simultaneously, the unmagnified primary view below it (including the region that would otherwise be lost to the telescope's ring scotoma). A small head tilt switches the central and peripheral roles. This arrangement supports easier navigation and reduces the risks associated with the bioptic ring scotoma.[40,41] In an augmented-reality head-mounted display, a field expander for patients with tunnel vision provides a minified cartooned field of view superimposed over the natural full resolution and color see-through view.[38,42–46]

The first benefit of the peripheral prisms to be realized and appreciated was the ability to use 40Δ high-power prisms, the highest power available in the press-on format. These provided 20° of field expansion, as documented by perimetry. This all but doubled the field expansion of all prior designs; it provided the same field expansion in practically all positions of gaze and without any requirement for scanning. With a principal solution at hand and with various other vision-multiplexing device ideas, we were awarded one of the early National Institutes of Health Bioengineering Partnership grants. In collaboration with Karen Keeney, then President of Chadwick Optical (now in Souderton, PA), we turned our attention to improving the basic device. Although the press-on prisms were an excellent option for introducing the prisms to potential users, they were rightly known as a temporary prism. We needed long-term devices. The soft plastic of the press-on material had relatively poor optical quality, especially at the higher power we used. The prisms also lost quality further with time because of various environmental effects from UV radiation, dust, hand and facial skin oil, and more. In collaboration with Chadwick Optical, we developed a PMMA solid Fresnel prism inset, embedded into the lens, which we called the permanent peripheral prisms. These prisms provided higher optical quality than did the press-on when new and maintained this quality for years. Although the 40Δ prisms were a great advantage over prior options, and the expansion of the field into the pericentral 20° was very helpful, we continued to pursue higher-power prisms. With the loss of 90° due to homonymous hemianopia, any additional power to expand the reach of the field-expansion prisms would be of value. Supported by a large Small-Business Innovation Research grant to Chadwick Optical, we were able to continue our collaboration and to develop and bring to the market a permanent PMMA 57Δ prism that provides a substantially wider-field expansion of 30°. The use of such higher-power prisms prevented the use of small-angle approximations typically applied in ophthalmic prism designs.[33,47] These issues will be addressed further hereinafter.

Various other considerations went into the design of the prism segment insets. For safety, the pocket in the carrier lens and the inset were cut as conical surfaces, with the wider opening toward the front of the carrier to prevent pushing of the prism through the lens and injuring the eye. The vertical positions, and particularly the inter prism separation of the upper and lower segments, were determined as part of a multicenter clinical trial.[48] These dimensions were also constrained by the mechanical requirement for a safe

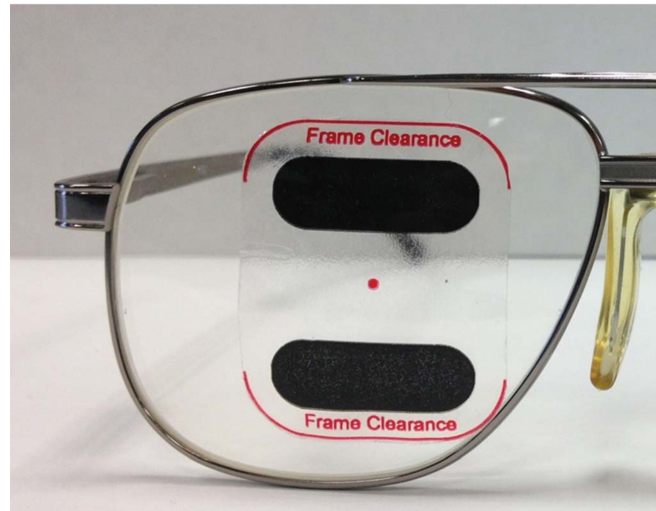

FIGURE 4. The fitting template for peripheral prisms. A seemingly simple device that highly simplifies the fitting procedure by setting the prism position, simultaneously ensuring that the permanent prisms can be safely embedded into the carrier lens and marking a 3-mm safety margin around the prism. Note the crucial tangential point at the nasal edge of the lower segment. This helpful template was developed by Charlie Saccarelli, President of Chadwick Optical.

margin around the segment to ensure the integrity of the carrier lens. Including this safety margin in the clinical fitting of the prisms was made much easier by the smart design of a cling-on plastic template (Fig. 4) that was developed by Charlie Saccarelli, Karen's son, who took over Chadwick Optical upon her retirement. The width of the prism segments was also considered in a number of ways. The horizontal size of the permanent prism segments was affected by the optical effect of the apical scotoma.[22,33] The angular magnitude of the apical scotoma is equal to the effective prism power at the apex of the prism. Our analyses revealed that the optimal distance of the apex from the optical center of the carrier lens is achieved when that portion of the prism spans the same visual angle as the angular shifting power of the prism at the apex. In fulfilling this condition, the apical scotoma is fully compensated by the other eye, when the patient's eyes are at the primary position of gaze, which is their most common location. A longer distance (wider prism segment) would result in diplopia near the vertical meridian, which is not helpful at all. A shorter distance (narrower prism segment) would result in a *binocular* apical scotoma near the vertical meridian, an undesirable effect.[22] The extent of the prism segment nasally (apex direction) is limited by the frame dimensions, and the lower segment is especially limited where the flare of the nose dictates the frame shape.

We realized that the peripheral prism design that shifted the image laterally was suboptimal in aiding driving. The lateral peripheral field expanded by the original design (called the horizontal design) was vertically situated about 20° below and about 20° above the center of the spectacles lens, viewing areas that fall outside the field of view through a standard car windshield. A new oblique prism design was invented[49] to enable the prism to cover the field through the car's windshield. These prisms were positioned at the same locations in the carrier lens as the horizontal peripheral prisms, but the prism bases were rotated toward the horizontal midline (Fig. 5). With this design, the shifted view from the blind side

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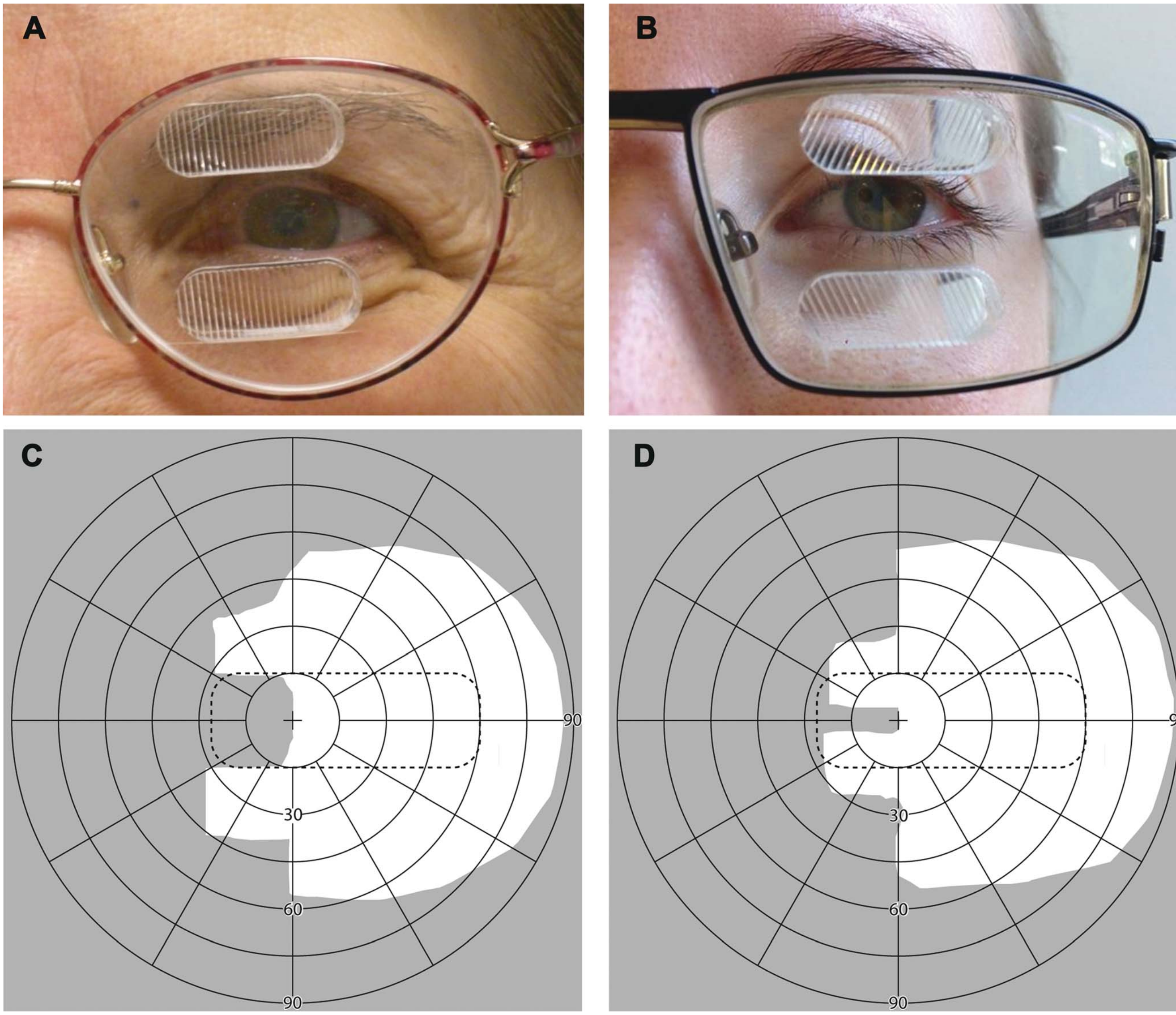

FIGURE 5. Permanent rigid PMMA-embedded peripheral prisms. (A) Horizontal design of 57Δ power placed base left (base out) for left homonymous hemianopia (HH). (B) Oblique design in 57Δ for a patient with left HH. The upper segment is placed base out (base left) and base down. The lower segment is placed base out (base left) and base up. Note the upper-lid image shifted up and left (in the image) in the upper prism and the shift of the small piece of the temple (and the lower lid) to the left and down in the lower segment. This design was developed specifically to aid in driving. (C) Binocular field plot measured in a Goldmann perimeter of a patient with left HH wearing the horizontal design peripheral prisms (57Δ), as shown in panel A. (D) The binocular visual field of the same patient while wearing the oblique design peripheral prisms, as shown in panel B, reducing the gap between the top and bottom expanded field sections to enable view through a car windshield (the field of view through the windshield is marked with dashed lines in panels C and D). In both cases, the prism position in the carrier lenses is the same.

through the windshield was shifted up (through the upper segment) and down (through the lower segment) while at the same time leaving the seeing-side view through the windshield unobstructed.[47]

EVALUATION OF PERIPHERAL PRISM TREATMENT FOR HOMONYMOUS HEMIANOPIA

Evaluation of the Peripheral Prism as a Walking Mobility Aid

Once one develops a new device that seems to be effective, it has to be formally evaluated. The original horizontal design of the peripheral prisms was evaluated first by us in a case series[36] and then in a laboratory-based extended wear study,[30] both using the press-on prisms and showing promise for the new design. An independent trial reported significant improvements in quality of life, and 83% of the subjects continued to use at 1 year.[15] We then conducted an open-label, community-based, multicenter clinical trial.[48] Two-thirds of the patients in the multicenter study perceived the peripheral prism glasses to be beneficial, usually reported as better ability to avoid obstacles on the hemianopic side, and 50% were still using the peripheral prism glasses after 6 to 12 months.[48]

These days, such open-label studies are insufficient to attest to the value of treatment; a randomized controlled clinical trial (preferably

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multicenter) is required. Some may think that one can learn how to conduct such a trial by reading a few articles reporting such studies. Unfortunately, it is difficult to master anything by just reading a few articles. Luckily, in 1992, I had a great opportunity to be invited to participate in the Third Clinical Research Workshop, Forest Grove, OR, cosponsored by the American Academy of Optometry and the American Optometric Association. This series of workshops takes place every other year under the outstanding leadership of Dr. Karla Zadnik. At these wonderful training courses, experts on all aspects of clinical trial design and analyses provided many of us, over the decades, with the basic understanding, tools, and perspectives that helped us carry out effective clinical trials. For me, the knowledge acquired in this course enabled many of the projects that I conducted while consulting for industry, as well as my academic work at the laboratory. I was so impressed with the quality of this course that I sent each and every optometric research fellow of mine to participate in the course, and I readily agreed to be on the faculty when asked in 2013. Sending my fellows to participate in the course turned out to be a great investment, as Dr. Alex Bowers was then ready to lead the clinical trials we needed to conduct with the peripheral prisms. In two multicenter clinical trials,[48,50] the long-term continued uses of peripheral prism glasses after 6 months were 49 and 41%, respectively, an impressive success rate for a low-vision aid. Patients continuing to use the prisms reported that they helped them detect and avoid obstacles when walking. In the randomized controlled trial, 26% of the patients chose the sham prism, accounting almost exactly for the difference between the 74% selection of the prism in the open-label trial[48] and the 49% selection in the randomized controlled trial,[50] demonstrating the importance and value of a controlled clinical trial.

Evaluation of the Peripheral Prism as a Driving Aid

Patients with homonymous hemianopia may drive legally in about a third of the states, where the field requirement is less than 90°.[51] For many patients, the most severe impact of hemianopic field loss is the loss of driving privileges. Resuming driving after the onset of homonymous hemianopia is an important rehabilitation goal. We have studied the impact of homonymous hemianopia on driving performance in a driving simulator over two decades. In a series of studies, we investigated the ability of drivers with homonymous hemianopia to detect and respond in time to pedestrians standing on the side of the road[52] or approaching the road on a collision course with the driver's car,[53,54] and on their ability to control the car in the lane.[55] In other studies, we evaluated the impact of homonymous hemianopia on hazard detection at intersections.[56,57] We found wide variability in individual ability to compensate for the field loss in driving on a straight road. Although some performed well, many drivers with homonymous hemianopia do not adequately compensate for the field loss and fail to detect potential hazards approaching from the blind side, in both simulated[53,54] and real-world driving.[58] We also documented an impact on hazard detection performance at intersections due to insufficient gaze shifts to the blind side.[57]

Further studies showed that oblique peripheral prisms can help with the detection of roadside hazards on the blind side when driving. Responses to unexpected blind-side hazards were better with real oblique peripheral prisms than sham prisms in our on-road randomized clinical trial.[58] Detection of blind-side pedestrians at 14° eccentricity in the driving simulator improved from 20 to 60% with the oblique prisms.[59] However, in all these studies, although the oblique prisms improved performance significantly and substantially, the prisms did not fully ameliorate the detection deficits, as they did not restore the performance on the blind side to the level of performance on the seeing side (where detection rates were 100%). This may in part be due to the poor image quality of Fresnel prisms (as we have shown that roadside hazard detection is affected by pedestrian visibility[60]) and in part due to peripheral binocular rivalry with the unilateral prisms.[61,62] These results, although encouraging, suggest that our work is not yet done.

Intersections are especially challenging for drivers with homonymous hemianopia because a wide field (~180°) has to be scanned, requiring a gaze scan of ~90° to the blind side, comprising a 50° head scan with an additional 40° eye scan,[57] which is well beyond the normal 15° eye-scanning range.[35] In our driving simulator studies,[57,63] hemianopic drivers had very low detection rates for pedestrians who appeared on their blind side at ~90° eccentricity, which represented a potential hazard when entering the intersection. Detection failures were mainly a result of insufficient scanning into the far blind side,[63] with the gaze scan ending, on average, 30° away from the pedestrian.[57] These results suggest that a minimum of 30° field expansion would be necessary, which is at the very limit of the expansion with conventional 57Δ Fresnel prism spectacles. Thus, higher-power prisms are needed to cover the full extent of the intersection on the side of the hemianopia.

IMPROVING COSMETICS, UTILITY, AND IMAGE QUALITY THROUGH THE PRISMS

Higher-power prisms were needed to provide wider-field expansion than that afforded with earlier designs. Because higher prism powers, especially in Fresnel, reduce the image quality through the prism, we first tried to use ophthalmic prism segments embedded in the carrier lens (Fig. 6A). However, even with the narrow width of the segments, a very thick prism edge results in a dangerously sharp edge near the eye when embedded into the carrier (Fig. 6A). To overcome the overall size and weight, Chadwick Optical split the prism into two (Fresnel-like) sections and, to reduce the sharp edge injury risk, we rounded that edge, as seen in Fig. 6B. This design was still large, heavy, and very expensive to manufacture. In collaboration with Chadwick Optical, we then developed the permanent prism segment described previously and shown in Fig. 5. A similar design was later implemented by Multi Optical in Sweden, shown in Fig. 6C. This is essentially the same design, although the contours of the segments better match the frame curvature above and below, enabling taller segments centrally, where it is more important. Although the permanent peripheral prisms are not very visible, some patients consider them objectionable. In fact, many people with visual impairment prefer to avoid any devices that might draw attention. The issue of acceptable cosmetics is a major consideration in the success of low-vision aids. Therefore, we always paid much attention to cosmetics in any of the technologies we were developing or evaluating and looked for any possible improvements. We were able to implement one simple solution, fitting the patient with a dark sunshade clip-on over the prism glasses. With these clip-ons (Fig. 6D), the prisms are completely invisible.

The peripheral prism glasses are a mobility device. Most patients with homonymous hemianopia (or for that matter most of us) are walking for only a small portion of their day. The peripheral prisms may not interfere with many activities, such as watching TV and talking to others, but the lower-segment prism is sure to interfere with reading or any other tasks that are carried out when

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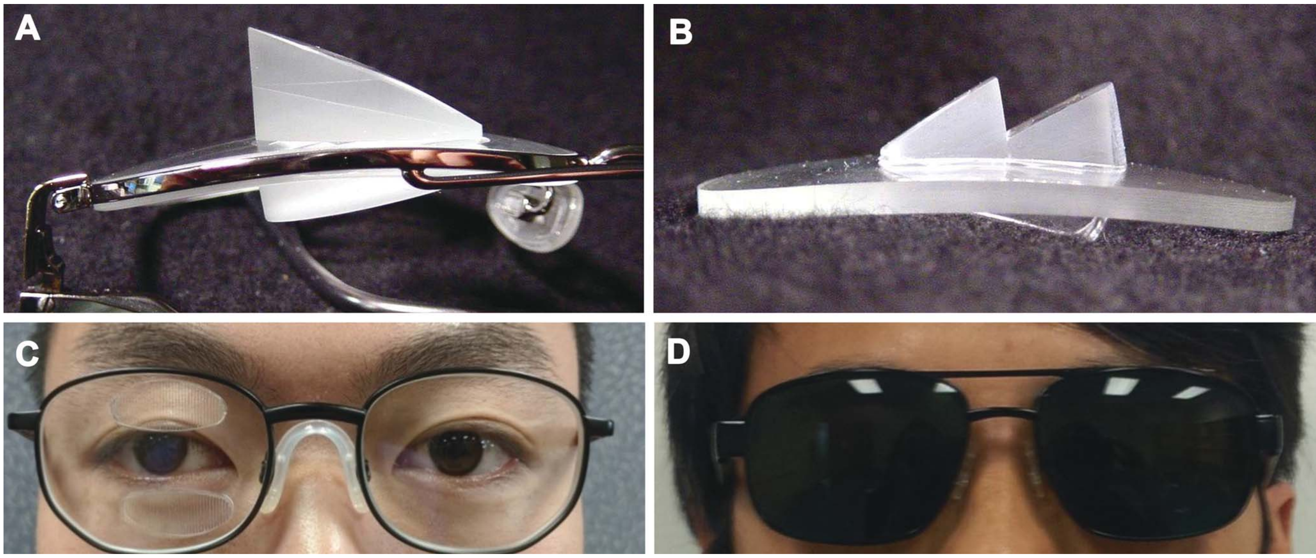

FIGURE 6. Progression in improving the cosmetics of the peripheral prisms. (A) Ophthalmic prism segment of 40Δ embedded through the carrier results in a very heavy and thick-edge prism with a dangerously sharp edge near the eye. (B) A degenerated 30Δ Fresnel-like prism in front of the lens and a single 10Δ segment behind the lens, produced with a rounded edge to avoid the risk of sharp injury. (C) The 40Δ permanent CR39 solid Fresnel prism segments embedded into the carrier lens, shown here in the design implemented by Multi Optical of Sweden. (D) A person wearing the permanent prisms, which are completely invisible behind the sunshade clip-on.

viewing through the lower part of a spectacle lens. The patients therefore need to have a different pair of reading glasses with them at all times, so that they can switch back and forth between the two pairs. We have been looking for ways to resolve this difficulty and realized that magnetic clip-on frames may work for this (Fig. 7A). These frames are designed and constructed for clip-on sunshades. Some of these clip-on frames on the market enable replacement of the dark lenses using standard ophthalmic laboratory procedures. With Chadwick Optical, we experimented with fitting the permanent prism into a plano clear lens mounted in the magnetic clip-on. This was found to be a very advantageous design. The clip-on is removable and replaced easily and quickly. The clip-on is easier to carry around than two pairs of glasses. The prisms are available on-demand and are removable when a need to read close material arises. The regular glasses under the clip-on may be bifocal or progressive addition lenses, supporting reading for the presbyopic patients, who are the majority of patients with homonymous hemianopia. Although the cost of this system is slightly higher at the outset, as two sets of lenses are included, and the frame may be a little more expensive, in the long run this arrangement is more economic. If the prescription changes for any reason, only the regular prescription lenses have to be changed, and the more expensive peripheral prisms embedded in the clip-on plano lenses need not change. When arriving at a social gathering of any sort, the patient can easily remove the prisms and avoid any potential unwelcome attention or questions. The improved image quality through the prisms is an additional important advantage of this design. In most other designs, the peripheral prisms are mounted through the prescription carrier lens and do not benefit from the refractive correction. However, with the clip-on design, the refractive correction is available to the prisms and, as a result, provides better image quality for the expanded field of view through the prisms.

The magnetic clip-on turned out to be advantageous in many ways except one. The selection of frame shapes was limited. The appropriate magnetic clip-on frames are available in about two dozen shapes from two manufacturers. As we know, the selection of spectacles frames available to people covers many more options. Every optical shop has hundreds of frame shapes, sizes, designs, and colors. Discovering that only a few frame options work with the clip-ons dampens the initial delight that patients experience when finding an effective field-expansion solution. Luckily, a new magnetic clip-on came on the market, called Chemistrie (Eyenavision, Inc., Pittsburgh, PA) (Fig. 7B). The Chemistrie magnetic clip-on can be used with virtually any frame or frame style. High-power minimagnets are embedded into the far temporal side of the prescription lenses. A rimless clip-on composed of thin plano lenses and a bridge piece is constructed to fit the shape of the patient's preferred frame and the base curve of its lenses. The peripheral prisms and corresponding mini magnets are embedded into the clip-on lenses. The clip-on can be easily clipped onto the prescription lenses and just as easily removed. This setup has all the advantages of the magnetic clip-on described previously, with the addition of frame selection flexibility and the use of thinner and lighter clip-on lenses.

Third parties interested in the peripheral prisms have come up with other ways to provide the clip-on experience. The Tongling Eye Clinic in Shenzhen, China, has adopted a commonly used flip-up clip-on to carry the peripheral prisms (Fig. 7C). This design also fits most frame shapes and styles and has all the other advantages of the magnetic clip-on. It is not as easy to place on or remove from the glasses, but the peripheral prisms can be flipped up out of the way to support unimpeded reading or other functionality. The clip-on was also adapted to enable vertical height adjustment, permitting this device to be produced as a one-size-fits-all commodity, which can be mass-produced to lower the cost. The height can then be adjusted in the clinic to fit an individual patient's needs. MultiLens in Mölnlycke, Sweden, developed their own clip-on–like option, which they call the Hang-on (Fig. 7D). This upper frame with temples and semirimless plano lenses is fitted over the

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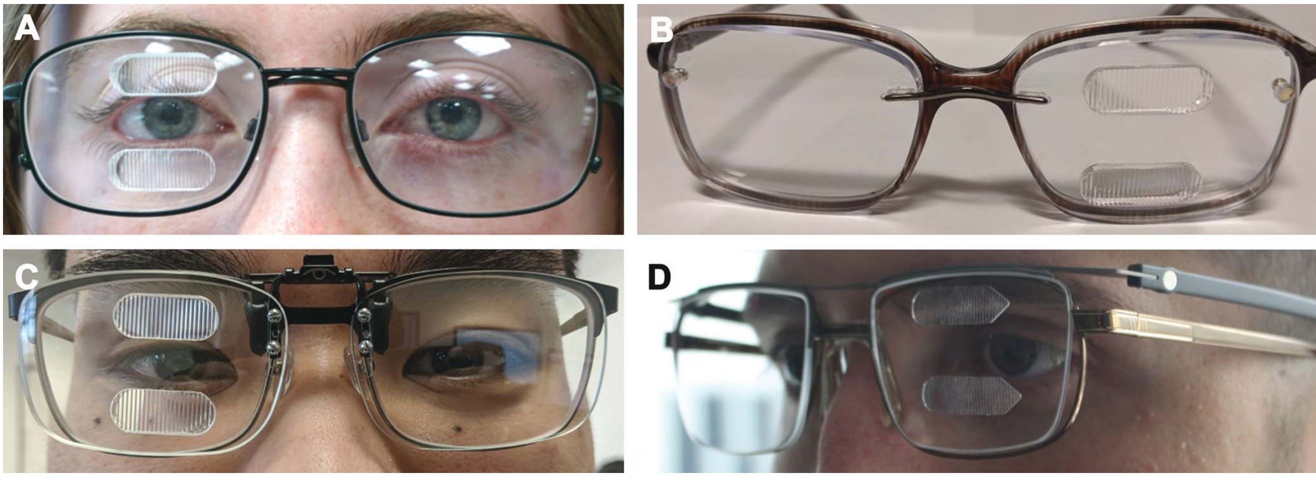

FIGURE 7. Clip-on options for peripheral prisms for homonymous hemianopia. (A) Easyclip magnetic clip-on frame with the peripheral prisms embedded in the plano clip-on lenses. Only the double bridge seen from this viewing angle indicates the presence of the clip-on. (B) Chemistrie magnetic clip-on. Two high-power magnets are embedded into the prescription lenses and the clip-on plano lenses, at the temporal ends of the lenses. The peripheral prisms are embedded into the thin and lightweight plano clip-on lens. (C) The Tongling clip-on/flip-up is an adaptation of a widely used clip-on/flip-up mechanism to provide a commodity peripheral prism option. (D) The MultiLens Hang-on design, shown here with Fresnel prisms attached to the plano lens. This device is placed over the prescription glasses, and the peripheral prisms have to be fitted to the individual patient and the frame used.

patient's existing glasses, and the peripheral prisms are embedded into the plano lenses. The position of the prisms is individually fitted based on the patient's features (e.g., pupillary distance) and the type and height of the frame's top eye wire.

The process of developing the various clip-on designs is a manifestation of the principle of universal design. Universal design is defined in the Disability Act 2005 as a concept that suggests design and composition of an environment so that it may be accessed, understood, and used to the greatest possible extent, in the most independent and natural manner possible, in the widest possible range of situations, without the need for adaptation, modification, assistive devices, or specialized solutions, by any persons of any age or size or having any particular physical, sensory, mental health, or intellectual ability or disability. It means creating products, services, or systems so that they may be used by any person. Here, with the implementation of a clip-on, we were pursuing ways to improve the cosmetics of the peripheral prisms and to support a more convenient utility, being able to access the prism on demand for mobility and to remove them for tasks such as reading, where the prisms are not helpful and may even be disruptive. The clip-on solution, however, brought additional advantages, providing refractive correction through the prism segments, thus improving image quality and enabling updating optical correction less expensively, as there is no need to replace the more expensive lenses with the peripheral prisms.

FURTHER UNDERSTANDING AND IMPROVEMENTS OF THE FUNCTION OF THE PERIPHERAL PRISM

While working with the peripheral prisms for almost two decades, we greatly improved our understanding of the prisms in their application as field-expansion devices. As a result, we developed novel ways to overcome the limitations of the earlier prism designs, especially for mobility. We analyzed the needs of the patients with homonymous hemianopia for field expansion when walking[64] and when driving.[57]

Pedestrian Collision Risk when Walking

Colliding with other pedestrians is a common complaint of patients with homonymous hemianopia. It is both socially embarrassing and physically dangerous. The lateral expansion area created by a peripheral prism is designed to support the detection of these impending collisions. A pedestrian on a collision course remains at a constant bearing angle relative to the patient's heading.[65] Detecting and avoiding the collision are unlikely if the bearing angle is outside the patient's residual seeing field. Using a new approach to analyzing the needs of patients with field loss, we calculated the collision risk with pedestrians approaching from all bearing angles in open-space walking environments such as shopping malls or transportation terminals. We found that the highest risk of collision is from pedestrians approaching at a bearing of 45° who remain at an eccentricity of 45° (Fig. 8).[64] Patients with homonymous hemianopia would not be able to detect any of these risks on the blind side. Lateral head or eye scanning could possibly facilitate the detection of approaching pedestrians from the blind side. However, we found that lateral eye scanning of patients with homonymous hemianopia was not wider than that of normally sighted people (Vargas-Martin F, Peli E. IOVS 2002;43:ARVO Abstract S3809), mostly <15°,[66] so they would not be able to detect pedestrians on the blind side with regular eye scanning. Thus, greater field expansion is crucial to detect and avoid possible collisions with other pedestrians on the blind side for homonymous hemianopia. Because the highest power of clinically available Fresnel prisms is only 57Δ (≈30°), higher-power prisms (100Δ = 45°) would facilitate higher risk reduction (Fig. 8). Realizing the need for wider field expansion to be the primary requirement, we have looked for ways to implement higher-power prisms. In the process, we encountered a secondary side effect of

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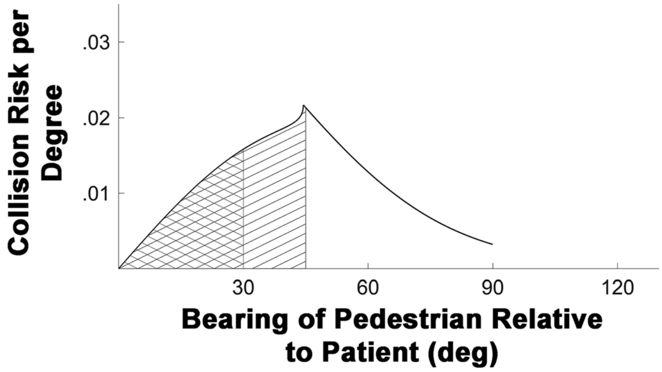

FIGURE 8. Blind-side collision risk with another pedestrian as a function of bearing angle relative to the patient.[64] The total area under the curve is normalized to 1. The area under the curve between any two bearings represents the amount of risk monitored by vision in that section. A patient with homonymous hemianopia cannot detect any collision on the blind side but can detect 26% of the risk using the 57Δ (≈30°) prisms (cross hatched area), but as much as 53% of the risk can be detected with 45° of prism field expansion (right leaning lines including cross hatched area). The figure is an adaptation for homonymous hemianopia from Fig. 4 in Peli et al.[64]

higher-power prisms, when used as field-expansion devices that needed to be addressed as well.

Requirements of Higher-power Prisms to Address Collision Risks

In analyzing the consequences of using high-power peripheral prisms for homonymous hemianopia, it became apparent that we needed to consider the impact of total internal reflection.[33] We found that, although the effective prism power is increased with angle of incidence toward the base (blind) side, the increment is bounded by the area of total internal reflection.[33] Total internal reflection severely restricts the utility of a prism, as it represents a range of eccentricities where the prism does not transmit the desired shifted images. As the line of sight approaches total internal reflection, the shifted image is dim and severely distorted (minified), further restricting the utility of the prism. This lowered image quality may reduce hazard detection performance, suggesting that improved image quality is another desired property. See more about this hereinafter.

For conventional 57Δ Fresnel prisms, total internal reflection starts at just 5° toward the base from the primary position of gaze. Although it does not affect the use of the prism in expanding the hemianopic field at the primary position of gaze, total internal reflection limits any additional potential benefit of farther expansion when the eye is scanning toward the blind side. This is a severe limitation on mitigating collision risks of drivers with homonymous hemianopia at intersections. When walking with the current 57Δ Fresnel prisms, patients with homonymous hemianopia may detect 26% of potential colliding pedestrians on the blind side (Fig. 8) and 39% with 5° of eye scanning toward the blind side, but because of total internal reflection, there is no further improvement with farther eye scanning. Within the total internal reflection range, the invisibility of the desired imagery (shifted view) results in increased visibility of spurious reflections,[33] which may cause false alarms.

We have shown that flipping the Fresnel prism serrations so that they face toward the eye (rather than away from the eye) reduces the impact of total internal reflection and distortions.[8,33] However, this approach reduces the effective prism power and increases other spurious reflections, representing a compromise between various competing needs. We further developed and tested three novel designs of higher prism power.[47] All three options also enabled wider eye-scanning ranges by shifting the total internal reflection limit farther peripherally. Nevertheless, these three designs were still affected by strong prism distortions and poor image quality. Therefore, a better solution that addresses the primary (higher prism power), secondary (wider eye-scanning range), and image quality requirements was required.

Reviving an Older Solution and Facing an Unexpected Difficulty

Addressing all these requirements, we returned our attention to a mirror-based periscopic design that I originally proposed in my peripheral prism patent.[49] We fabricated a crude proof-of-principle demonstration of the design.[47] This system, based on a pair of mirrors, each at 22.5° to the other, results in a large image shift of 45°. Such an element, however, covers a relatively narrow field of view only 10° to 15°. Therefore, a cascade of multiple elements is needed to cover 45° or more field of view of the needed field expansion. Our early proof-of-principle prototype was a tabletop large structure[47] and was not practical for use in spectacles, even if it were of the right size. We set out to design a more practical periscopic mirror image-shifting device that will be of such dimensions and construction that can be mounted in spectacles.[67] In an attempt to translate the design into practice by building a prototype, we ran into an unexpected problem. Numerous manufacturers we approached agreed to produce the components as a PMMA prism of specified dimensions with silver coating on two of the surfaces to serve as the mirrors. However, all of the manufacturers refused either to glue the components together for us or to provide any type of warranty for the gluing. We were well aware of the difficulties of apparently simple tasks such as gluing. In fact, when we developed the permanent peripheral prisms, Karen Keeney of Chadwick Optical had evaluated about 100 glues before she was able to find a working solution. None of the manufacturers would explain why they refused to glue the components. We suspected two possible issues: these manufacturers typically glue glass or plastic elements to similar ones. They might not have had experience in gluing a coated surface to another. Furthermore, most optical glues are UV activated, and if that type of glue is placed between the two coated surfaces, the UV light cannot reach the glue.

Dr. Fernando Vargas-Martin, who was a post-doctoral fellow in my laboratory two decades ago, was helping us in the optical design efforts and also tried to find for us European manufacturers to produce the periscopic devices. We discussed the gluing difficulty and the need to overcome the obstacle that presented. The issue of blocking the UV with the coated surface directed our thinking toward trying to find a solution for that problem. As we considered this problem, Fernando and I simultaneously and independently came up with the same solution. The solution was to replace one of the silvered mirrors with a total internal reflection surface. My back-of-the-envelope calculation suggested that it should work. I Skyped Fernando to confirm my calculations using his ray tracing program. He smiled at me and said that he knew it would work. I asked him how he knew. Fernando said that he had already tested it. He then picked up a crude prototype from his desk and showed me on Skype that it actually worked. Fernando bought a couple of inexpensive binoculars, broke them apart, and used the half-penta prisms from the binoculars to construct a cascade of these elements, demonstrating the effectivity of his and my proposed design.

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The Multiperiscopic Prism

This was the birth of our latest invention, the multiperiscopic prism.[68] The multiperiscopic prism is a cascade of half-penta prisms (commonly used in binoculars) that provide 45° (100Δ) shift using double reflection based on one silvered mirror surface and one transparent total internal reflection surface. Because the multiperiscopic prism uses double reflections, it is largely free of refractive image quality issues, such as prism distortion (minification), image dimming, and contrast reduction due to color dispersion (Peli E, et al. IOVS 2018;59:ARVO E-Abstract 638). The new device is also designed so that the spectacles correction can be incorporated, further improving image quality, especially for patients with high refractive errors. The improved imaging should support better detection of potential hazards. The cascade covers as much as a 45° field of view in the primary position of gaze. With eye scanning toward the "base," it enables an additional 15° of field of view expansion (Fig. 9A). The multiperiscopic prism, using the half-penta prisms, is different from the earlier periscopic mirror devices, not only in its use of the total internal reflection surface as one of the mirrors but also in that the same surface serves as the observation port used by the patient (Fig. 9A). This difference enables the construction of a more compact device compared with the earlier mirror periscopic design.[67] The half-penta prisms were assembled using 3D printed modules (Figs. 9B, C). The wide lateral field expansion and high-quality image provided by the multiperiscopic prism may help address blind-side detection deficits of homonymous hemianopia drivers, especially at intersections requiring a wide field of view (Fig. 9D).

The half-penta prisms have to be mounted onto the spectacles lens in the exact positions given in the optical design. Critically, the air space next to the total internal reflection surfaces needs to be kept clear and not touched by anything else, to function as a total internal reflection surface. Luckily, we had a young mechanical engineering student from India in the laboratory, Nish Mohith Kurukuti, who came to the laboratory to work on his senior-year project, using 3D printing (serendipity shows up again). We realized that 3D printing may be an ideal way to create modules (Fig. 9B)

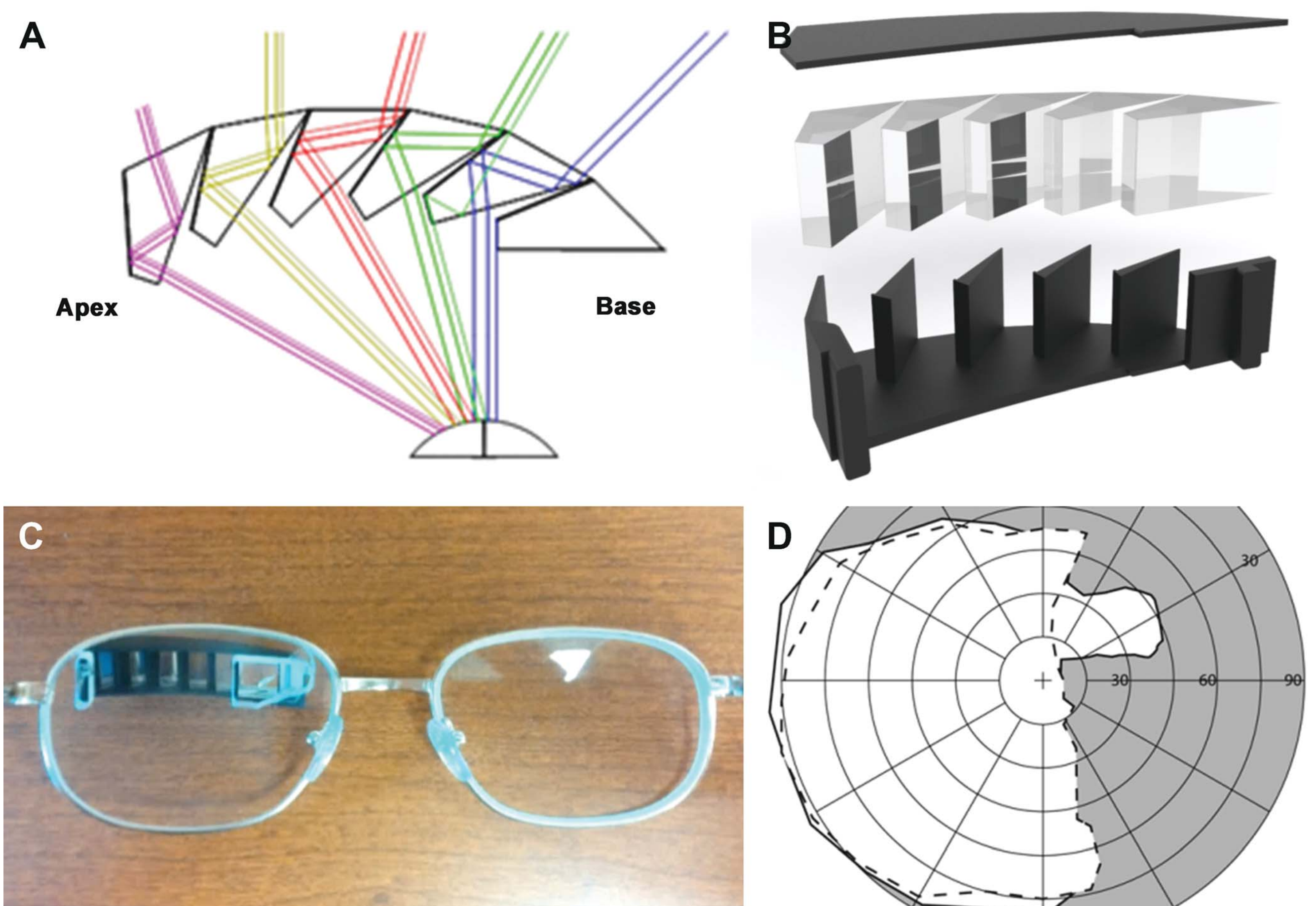

FIGURE 9. Multiperiscopic prism prototypes for field expansion. (A) Optical ray tracing early design of multiperiscopic prism (6 units of 8-mm-width half-penta prisms), for right homonymous hemianopia (HH) with base right. Different colors indicate rays within subvisual field at 15° steps (0–60°), all showing 45° shift and the rightmost one permitting additional 15° of eye scanning into the blind side. (B) Computer-aided design of multiperiscopic prism for HH with base right. The five half-penta prisms shown are glued into 3D printed housing components to be mounted on the spectacles lens. (C) A prototype with the upper multiperiscopic prism mounted in the spectacles for right HH (base-in), viewed from the patient side. Note the mounting holes are through the carrier lens, but the multiperiscopic prism module is in front of the prescription lens. Here, unlike with the conventional prism designs, the device for a right HH is mounted on the left lens. (D) Measured field diagram with the prototype in panel C (solid line; the dashed line is the field measured without the prism). The patient measured here has incomplete HH.

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that would hold the half-penta prisms in their relative positions, protect the total internal reflection surfaces, and have the facilities to mount the whole module to the spectacles carrier lens (Fig. 9C). Indeed, the magic of 3D printing, a fast and inexpensive process, enabled us to have a prototype created and mounted in a spectacles lens in a mere 6 months.

DISCUSSION AND CONCLUSIONS

Many evaluations of the impact of peripheral prisms and other field-expansion devices were based on questionnaires. One may argue that if patients believe the device is helpful, that should be sufficient. However, various effects may lead to positive responses from patients despite little or no real effect. Without actual improvement, the positive responses will not be long-lasting. Therefore, it is important that objective performance-based measures should be used for proper development and evaluation of visual aids in general and field-expansion devices in particular.[69] Perimetry could be an objective measure for the magnitude of field expansion but not for the performance in practical daily life.

Many patients with field loss are not able to drive and may not be qualified. We have developed driving simulator procedures to evaluate the impact of hemianopia on the performance of driving-relevant tasks, mostly detecting pedestrians approaching the driving lane from the blind side on a collision course. These have enabled us to compare the performance on the seeing side to the performance on the blind side, thus eliminating much of the individual variability in driving performance. We have recently demonstrated that the use of the peripheral oblique prisms significantly improved performance on the blind side in the simulator.[59]

Developing a method to evaluate the impact of the peripheral prisms in walking is also necessary. We have developed a novel walking scenario for pedestrian detection and collision judgment using our driving simulator.[6] Such a driving simulator–based test, however, is expensive and complicated to operate and therefore not suitable for implementation in the multicenter clinical trials, which are a necessary next step. We propose to implement a low-cost virtual-reality walking simulator version of our walking scenario on a driving simulator, using computer-game virtual reality and a large-screen TV. In the longer term, a similar test could be implemented as a tool for use in rehabilitation clinics.

Translational research is, indeed, a journey. It never really ends. Bringing a product to the market is a very prominent landmark on this journey, but that is all it is. The same is true of drug development, but it is even more the case in device development, and particularly in the development of visual aids. To be successful, one must enjoy the journey, not just reaching a certain destination. There are many rewards on this journey. Winning an award and recognition like the Prentice Medal is certainly a great reward. However, the joy and relief that one can bring to patients with a successful device, even though greater improvement is yet to come, is a wonderful reward. This may be experienced almost daily on this journey, especially if one is interacting with patients directly in the clinic. Being on the journey means that even now, after two decades of working on prism treatments for hemianopia, we are far from any end to our efforts.

POSTLUDE

In October 2019, we were funded by the National Eye Institute of the National Institutes of Health to continue our work on visual field expansion for patients with field loss. We plan to develop clinically usable multiperiscopic prism modules and will develop the protocols and outcome measures to be implemented in multicenter clinical trials. We will iteratively improve the designs of the multiperiscopic prism to optimize functionality, cosmetics, and safety. We will develop and validate low-cost virtual-reality walking simulator systems for deployment in the multicenter studies to test the utility of the multiperiscopic prism designs. For this project, we propose to design and produce multiperiscopic prisms using the prototyping process we have already used (Fig. 9), incorporating glass half-penta prisms into 3D printed modules mounted onto the spectacles lens. Thanks to the low cost of 3D printing, the proposed prototyping process is very economical for refinement and clinical testing. Once the designs have been tuned further and proven in the clinical trials, we will pursue partnerships for advanced manufacturing of molded multiperiscopic prism elements for hemianopia.

ARTICLE INFORMATION

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Conflict of Interest Disclosure: 1) Dr. Peli has a number of patents related to the material describe. The patents are assigned to The Schepens and 2 of them have been licensed to Chadwick Optical. 2) The sponsors NIH and DoD only funded the research and had no role in the design, conduct analyses, and reporting of the results. 3) Dr. Peli has full access to the data reported here. Much of it has been previously reported as this is a review manuscript.

Study Registration Information: Most of the studies reported here were not registered. They were conducted before such studies were required to be registered in clinicaltrials.gov.

Author Contributions and Acknowledgments: Conceptualization: EP; Writing – Original Draft: EP; Writing – Review & Editing: EP.

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