Copolymer-Based Progressive Addition Lens with Graded Index Designed for Astigmatism and Distortion Correction

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ABSTRACT In this research, we propose to reduce astigmatism and distortion in a progressive addition lens (PAL) by employing a polymer-based graded-index (GRIN) material. We adopted the diffusion copolymerization method for the GRIN-PAL fabrication. The GRIN material was prepared by partial diffusion of methyl methacrylate (MMA) and 2,2,2-trifluoroethyl methacrylate (3FMA) monomers into the cross-linked benzyl methacrylate polymer gel. GRIN-PAL was prepared by polymerization of the GRIN material in a mold of commercially available PAL. As a result, methods to control Δn, the diffusion length, and the order of the GRIN profile in polymeric GRIN materials were demonstrated. In a combination of the PBzMA gel and the MMA/3FMA diffusion monomer, 50/50 in volume provides the highest Δn. The diffusion period mainly affects the diffusion length. These two parameters consequently determine the order of the GRIN profile and the focusing power that the GRIN provides. The difference in the ease of diffusion caused by the difference in the cross-linking density provides a method for positional control of the GRIN profile. Furthermore, GRIN-PAL using a polymeric material was successfully fabricated. Improvement in astigmatism and distortion was demonstrated using GRIN. Therefore, the GRIN material is suggested to be applicable for the further modification of the PAL with low astigmatism and distortion.

KEYWORDS: graded index • progressive addition lens • aberration • astigmatism • distortion • presbyopia

INTRODUCTION

Graded index (GRIN) is an additional design that can be used to control the optical characteristics of materials, which enables more flexible optical design compared to a conventional homogeneous medium. The interest in GRIN evolved from a motivation to reduce spherical aberration and chromatic aberration of optical lenses (1, 2), and it has been used for various applications such as rod lenses and optical fibers (3−5). In this research, we propose to use GRIN to control astigmatism in a nonrotationally symmetric lens, progressive addition lens (PAL), and demonstrate a fabrication method of GRIN-PAL by polymeric materials.

A PAL is a multifocal ophthalmic lens for presbyopia, which permits distant, intermediate, and near vision without any discontinuity in the transition zone. This function has been achieved by nonrotationally symmetrical aspheric geometry at the lens surfaces. There are three parts in a PAL, namely, the far-vision region in the upper part, the near-vision region in the lower part, and the intermediate-vision region between them, as shown in Figure 1a. In the intermediate-vision region, surface curvature is steepened from the far-vision region to the near-vision region along the vertical meridian, which leads to a gradual increase in the focusing power along the vertical meridian. For this curvature design, an umbilic surface is employed in order to eliminate astigmatism (6). Astigmatism, which causes blurriness in the wearer's vision, is caused by the difference of the focusing power in each direction at arbitrary points on the lens. It is defined by eq 1 and explained schematically in Figure 1b (7−9). Because in an astigmatic lens a point on

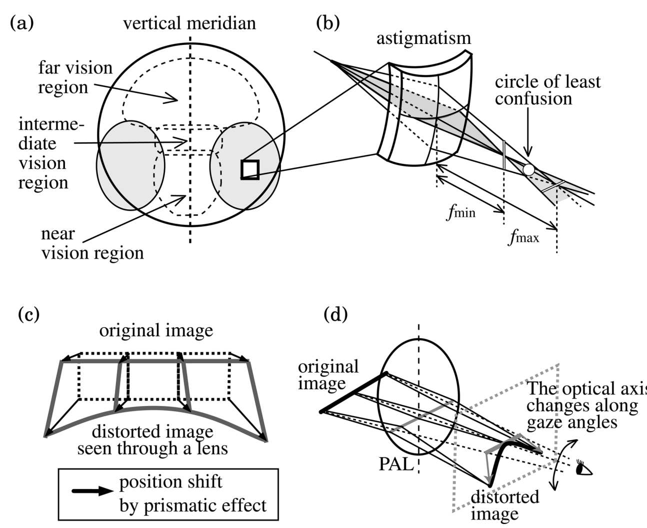

FIGURE 1. (a) Schematic of a PAL. There are three parts in a PAL, namely, the far-vision region in the upper part, the near-vision region in the lower part, and the intermediate-vision region between them. (b) Schematic of astigmatism. Astigmatism is caused by the difference of the focusing power ($1/f_{max} - 1/f_{min}$) in each direction at any arbitrary point in the vertical meridian. Because an umbilic surface is designed to have the local curvatures at each surface point equal in every direction, the vertical meridian of PAL provides an astigmatism-free vision. (c and d) Schematic of the skew distortion.

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the lens has different focusing power in every direction, the mean focusing power is defined by eq 2 to evaluate the focusing characteristic of the point. The mean focusing power corresponds to a circle of least confusion of focus, where the human retina is considered to be adjusted.

$$[\text{astigmatism}] = \left|\frac{1}{f_{\min}} - \frac{1}{f_{\max}}\right| \quad (1)$$

$$[\text{mean focusing power}] = \frac{1}{2}\left|\frac{1}{f_{\min}} + \frac{1}{f_{\max}}\right| \quad (2)$$

In eq 1, f_{max} and f_{min} respectively represent the maximum and minimum focal lengths at a considering point of a lens (Figure 1b). The unit is diopter (D), which corresponds to 1/m. An umbilic surface is a surface that is designed to have the local curvatures at each surface point equal in every direction, which means that there is no astigmatism on this surface. In conventional PALs, astigmatism along the vertical meridian is eliminated because of the employment of an umbilic line. However, away from the umbilic along the meridian, the minimum and maximum curvatures of the lens surface begin to depart, resulting in astigmatism in the lower sides of the PAL (Figure 1a) (6, 10).

Another aberration that degrades wearer's vision is skew distortion in the lower part of the PAL (6). With distortion, images seen through a lens are warped. Specifically, a lattice is seen as warped obliquely at both sides in the lower half of the PAL, as shown in Figure 1c. One of the biggest causes of distortion is improper prismatic power distribution. The prismatic effect means the lateral deviation of an image from the optical axis, as shown in Figure 1d. Here, the optical axis is defined as the parallel-to-gaze angles of an eye. Lateral deviation means that the focusing point moves on the plane perpendicular to the optical axis. The prismatic power represents the ray bending power. The unit is prism diopter (PD), and 1 PD bends a ray 1 cm in the lateral direction after 1 m of propagation from the bending point. If the prismatic power of each point is not carefully managed, images seen through the lens are distorted, as shown in Figure 1c.

Reduction of such astigmatism and distortion has been researched for decades, and PALs with lower astigmatism and distortion have been developed by optimizing the front- and back-surface geometries of the lenses (11, 12). There are also some reports about GRIN-PAL. In these cases, GRIN is used to achieve power progression (13), to smoothen the focusing power variation in a bifocal lens (14), or to simplify the manufacturer's procedure for cost reduction (15).

Here, we propose a combination of the GRIN and the surface geometry modification in order to fabricate a PAL with less affection of astigmatism and distortion. Specifically, while keeping the power progression function of the PAL, astigmatism and distortion are compensated for by the role of GRIN.

GRIN is effective for controlling the light-focusing power in a substance. For example, GRIN in which the refractive index increases toward the center of the lens in the radial direction gives a light-focusing function (5). Because astigmatism is caused by the difference in the focusing power at each direction, the addition of GRIN distributed in the direction with the smallest power compensates for the focusing power in that particular direction, which leads to the reduction of astigmatism. In addition, rays are bent in a GRIN medium toward the direction that refractive index increases, and the focusing points move laterally toward that direction, which consequently increases the prismatic power in that direction. Thus, the prismatic power in PAL can also be controlled using GRIN.

EXPERIMENTAL SECTION

Control and Optimization of the GRIN Profile. Although there are a variety of methods to obtain GRIN materials, here we adopted the diffusion copolymerization mothod (16). In this method, lower-refractive-index monomers diffuse into higher-refractive-index cross-linked polymer gel. The positional difference in the concentration of the lower-refractive-index monomer provides a GRIN profile. This method was adopted here because it provides a GRIN profile that has a large refractive index difference and a long diffusion length. The detailed process of the method in this research is as follows.

A solution of benzyl methacrylate (BzMA; Wako Pure Chemical Industries, Ltd.), cross-linking agent ethylene glycol dimethacrylate (EDMA; Wako Pure Chemical Industries, Ltd.), and photopolymerization initiator 2-hydroxy-2-methyl-1-phenyl-1-propanone (DAROCURE 1173; Ciba Specialty Chemicals Corp.) was prepared in a mold that consists of two glass plates with a Teflon ring placed in between them, and the solution was polymerized to the gel state by UV irradiation (Figure 2a). Two parts of the Teflon ring (Figure 2b opening pattern 1) were removed, as shown in Figure 2b, and the gel in the side-opened mold soaked the mixed solution of methyl methacrylate (MMA; Wako Pure Chemical Industries, Ltd.) monomer and 2,2,2-trifluoroethyl methacrylate (3FMA; Wako Pure Chemical Industries, Ltd.) monomer for T h (Figure 2c). In this process, the solution was diffused into the cross-linked PBzMA gel from the ring opening and the GRIN was formed due to the difference in the MMA and 3FMA ratio at each point of the PBzMA gel. The pair of monomers MMA, 3FMA, and BzMA was chosen based on their refractive index relationship. MMA (n_d at polymer = 1.492) and 3FMA (n_d at polymer = 1.421) that have lower refractive indices are diffused into the PBzMA (n_d at polymer = 1.568) gel substrate that has a higher refractive index from the ring opening (Figure 2b). After diffusion of the MMA and 3FMA monomers, the gel was again polymerized by UV irradiation to the solid state. In this process, diffused MMA and 3FMA were copolymerized with BzMA, which stabilizes the GRIN profile.

The relationship between the fabrication condition and the obtained GRIN profile was investigated. First, varieties of MMA/3FMA ratios were tested, namely, 100/0 (sample 1), 60/40 (sample 2), 50/50 (sample 3), and 30/70 (sample 4) in volume. Although 3FMA has lower refractive index than MMA, diffusion of only 3FMA erodes the PBzMA gel. On the other hand, although the PBzMA gel swells by MMA diffusion, it does not erode the PBzMA gel. Hence, a mixture of the two was diffused into the PBzMA gel so that the erosion and the swelling compensate for each other to obtain a lower minimum refractive index. Second, the GRIN plate was prepared with various diffusion periods, namely, 12 h (sample 5), 24 h (sample 1), 48 h (sample 6), and 72 h (sample 7). Third, GRIN plates that have different cross-linked densities, namely, 2 wt % (sample 8) and 8 wt % (sample 1), were prepared. The refractive indices of these samples were measured by a prism coupler (Metricon Corp. model 2010). Table 1 shows specific conditions in which the samples were prepared.

Fabrication of GRIN-PAL and Evaluation of Astigmatism and Distortion. GRIN-PAL was prepared by polymerization of

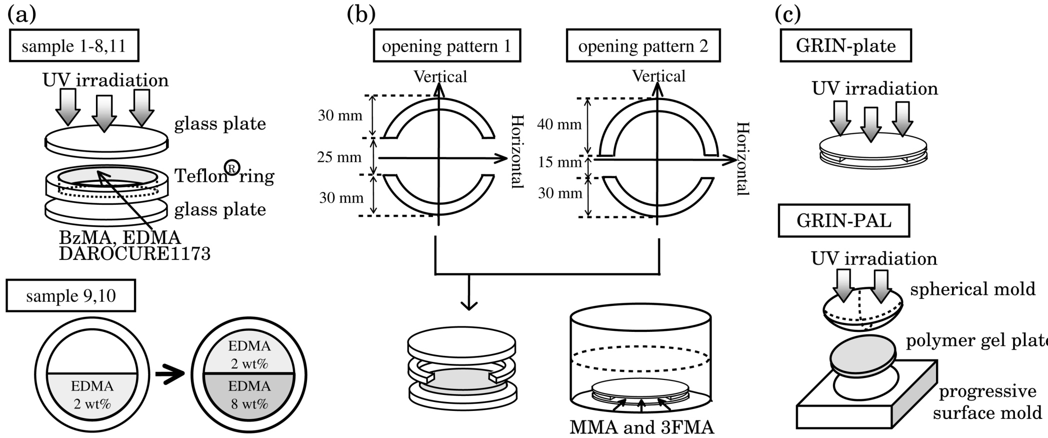

FIGURE 2. GRIN-PAL fabrication using the diffusion copolymerization method: (a) preparation of the cross-linked PBzMA gel; (b) removal of parts of the Teflon ring and diffusion of the MMA and 3FMA monomers into the cross-linked PBzMA gel; (c) attachment of the molds and polymerization by UV.

Table 1. Sample Numbers and Fabricated Conditions of Flat GRIN Plates

sample no.	EDMA amount (to BzMA) (wt %)	diffused monomer (volume ratio)	diffusion period *T* (h)	ring-opening pattern	lens type
1	8	MMA only	24	1	GRIN plate
2	8	MMA/3FMA = 60/40	24	1	GRIN plate
3	8	MMA/3FMA = 50/50	24	1	GRIN plate
4	8	MMA/3FMA = 30/70	24	1	GRIN plate
5	8	MMA only	12	1	GRIN plate
6	8	MMA only	48	1	GRIN plate
7	8	MMA only	72	1	GRIN plate
8	2	MMA only	24	1	GRIN plate

Table 2. Sample Numbers and Fabricated Conditions of Flat GRIN Plates and GRIN-PAL

sample no.	EDMA amount (to BzMA) (wt %)	diffused monomer (volume ratio)	diffusion period *T* (h)	ring-opening pattern	lens type
9	2 (upper) 8 (lower)	MMA/3FMA = 50/50	48	2	GRIN plate
10	2 (upper) 8 (lower)	MMA/3FMA = 50/50	48	2	GRIN-PAL
11	8				PAL

the GRIN-P(BzMA/MMA/3FMA) gel attached to a PAL mold. Taking the result of the last section into account, the PBzMA gel that contains 2 wt % EDMA was prepared in the upper part, the PBzMA gel that contains 8 wt % EDMA was prepared in the lower part, the mixture ratio of MMA/3FMA was 50/50 in volume, and the diffusion period was 48 h. Because general PAL has astigmatism at both of its sides in the lower half, the Teflon ring has the side opening in the lower area (Figure 2b, ring opening 2).

After diffusion of MMA and 3FMA, the obtained GRIN material was attached to a PAL mold and was polymerized to the solid state by UV irradiation, as shown in Figure 2c (sample 10). The PAL mold consists of a progressive-addition front-surface mold made of silicone rubber (Shinetsu Silicone) and a spherical back-surface mold made of glass (curvature radius: 104 mm). The progressive-addition surface was molded from a purchased PAL, HOYA LUX GP 1.50. This PAL, which was used for molding purposes, has a geometry lacking the transverse focusing power at both sides in the lower half of the lens, which is a typical astigmatism distribution of the commercially available PALs. For comparison purposes, a PAL made only with PBzMA (sample 11) was prepared. To confirm the GRIN profile of the GRIN-PAL, a flat GRIN plate was fabricated by the same method except for the mold attachment (sample 9). Table 2 shows specific conditions in which the samples were prepared.

The refractive index distribution of the GRIN plate (sample 9) was measured by the prism coupler. The mean foucing power, astigmatism, and prismatic power of the PAL (sample 11) and GRIN-PAL (sample 10) were obtained by using a lens meter (NIDEK LM-990A) and eqs 1 and 2.

RESULTS AND DISCUSSION

Relationship between Diffusion Condition and the GRIN Profile. Figure 3a shows the relationship between MMA/3FMA ratios and obtained GRIN profiles. Figure 3b shows the relationship between the diffusion period and the GRIN profile. Characteristics of GRIN are determined by the order of the GRIN profile, Δn, and the diffusion length. The order of the GRIN profile refers to the steepness of the gradient. The higher order profile provides larger focusing power. The diffusion length is the length that monomer diffuses in the medium. It determines the area that provides additional focusing power. Δn is the difference between the highest and lowest refractive indices. Under the same Δn, the order of the GRIN and diffusion length is in a drawback relationship. Hence, to achieve a high-order GRIN profile in a large area, a high Δn is desired. Therefore, Δn is

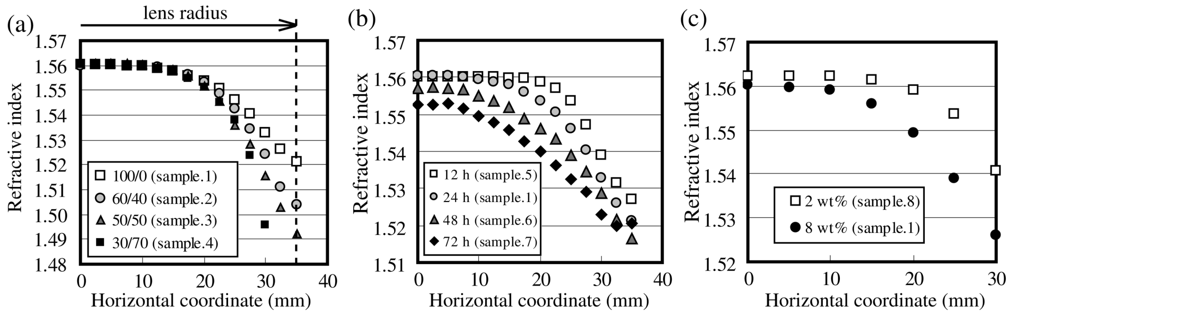

FIGURE 3. GRIN profile obtained under various conditions: (a) relationship between diffused MMA/3FMA ratios (in volume) and the refractive index; (b) relationship between the diffusion period and the refractive index; (c) relationship between the refractive index and the amount of the EDMA (cross-linking agent) ratio.

a factor prior to the other two in achieving a GRIN profile that provides large focusing powers in a large area.

From Figure 3a, the ratio of MMA/3FMA mainly affects Δn. A large amount of 3FMA erodes the PBzMA gel, which consequently determines the saturation concentration of 3FMA in the PBzMA gel. In this case, MMA/3FMA = 50/50 provides the highest Δn. To obtain a larger Δn, a more effective combination of substrate-gel and diffusion monomers is desired. From Figure 3b, the diffusion period affects the diffusion length, which consequently determines the order of the profiles. A longer diffusion length and a lower order profile are achieved by a longer period diffusion.

From Figure 3c, it is confirmed that a low concentration of EDMA prohibits monomer diffusion into the polymer gel. Using this characteristic, positional control of GRIN is possible. By variation of the EDMA concentration for some parts in a medium, different Δn, diffusion length, and the profile order can be obtained under the same diffusion period and diffusion monomers.

Fabrication of GRIN-PAL and Evaluation of Astigmatism and Distortion. Figure 4a shows mean focusing power distributions along the vertical meridian of the PAL (sample 12). The power progression from the upper region to the near region is confirmed. Figure 4b shows the astigmatism distribution of the PAL. The length and direction of the lines in Figure 4b represent the astigmatism values and the direction with the smallest focusing power, respectively. Large astigmatism is observed at both sides in the lower half, and these regions lack transverse focusing power. Vectors in Figure 4c represent the prismatic power of the PAL. The direction of the vector indicates the direction of the image shift from the original point when seen through the lens. The length of the vector is proportional to the prismatic power. The warped grid is drawn so that each line passes the pointing sides of each vector, which represents the image when a background coordinate lattice is seen through the PAL. The power progression along the vertical meridian, the astigmatism profile, and the prismatic power profile of fabricated PAL are all similar to those of the purchased PAL, which shows that the front-surface mold is precisely fabricated by the silicone rubber.

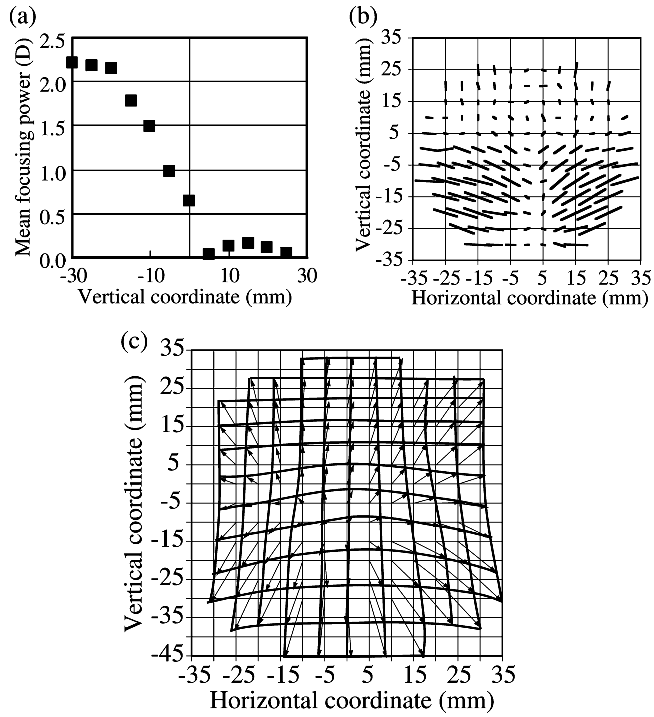

FIGURE 4. Mean focusing power and astigmatism distribution of fabricated PAL (sample 11): (a) mean focusing power distributions along the vertical meridian of the PAL; (b) astigmatism distribution of the PAL; (c) prismatic power distribution of the PAL.

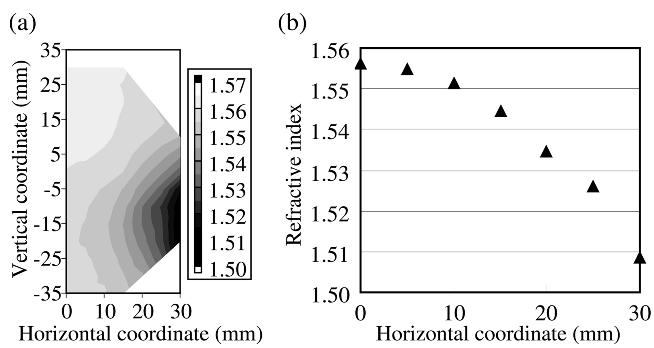

FIGURE 5. GRIN profile of a fabricated GRIN plate (sample 9): (a) contour plot; (b) along the horizontal coordinate where the vertical coordinate is −15 mm.

Figure 5 shows the GRIN profile of the GRIN plate (sample 9): (a) contour plot; (b) along the horizontal meridian where the vertical coordinate is −15 mm. The addition of GRIN is confirmed in a significant area. Because the PAL has astigmatism at both of its sides in the lower half, as shown in Figure 4b, the Teflon ring has the side opening in the lower area (Figure 4b, opening pattern 2) and the EDMA concentration was 2 wt % in the upper area and 8 wt % in the lower

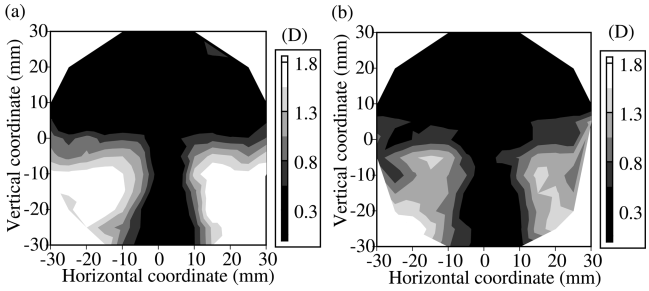

FIGURE 6. Contour plot of the astigmatism distribution of (a) the PAL (sample 11) and (b) the GRIN-PAL (sample 10).

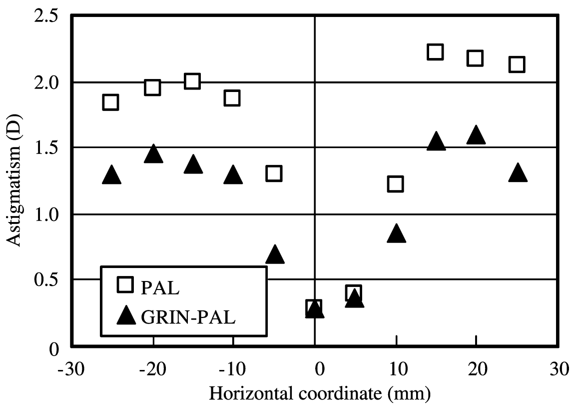

FIGURE 7. Astigmatism distribution of the PAL (sample 11) and the GRIN-PAL (sample 10) along the horizontal coordinate where the vertical coordinate is −15 mm.

area. As a result, monomer diffusion was inhibited in the upper part and the GRIN is confirmed mainly in the lower area.

Figure 6 shows the astigmatism distribution of the PAL (sample 11) and the GRIN-PAL (sample 10). Figure 7 shows the astigmatism distributions along the horizontal direction where the vertical coordinate is −15 mm. From this figure, reduction of astigmatism in the lower half is confirmed. In the lower half in Figure 5a, the refractive index increases transversely toward the vertical meridian or in the oblique direction with a slightly downward element. These directions approximately coincide with the direction of the focusing power lacking in Figure 4b, which means the GRIN compensates for the focusing power and consequently reduces astigmatism in the lower half in Figure 6. In the middle region (the vertical coordinate is from 0 to 10 mm) in Figure 5a, the refractive index increases in the oblique direction with a slightly upward element. The horizontal increase of the refractive index in Figure 5a reduces the horizontal elements of astigmatism, and the vertical increase of the refractive index in Figure 5a increases the vertical element of astigmatism. Hence, astigmatism remained or slightly changed in the middle area in Figure 6. In the upper area in Figure 5, the GRIN profile is not steep and increases astigmatism little in the upper area in Figure 6. As a whole, astigmatism in the GRIN-PAL was successfully reduced compared to that of the PAL.

Figure 8 shows the prismatic power distribution of the PAL (sample 11) and GRIN-PAL (sample 10). Because the refractive index increases in the oblique direction with

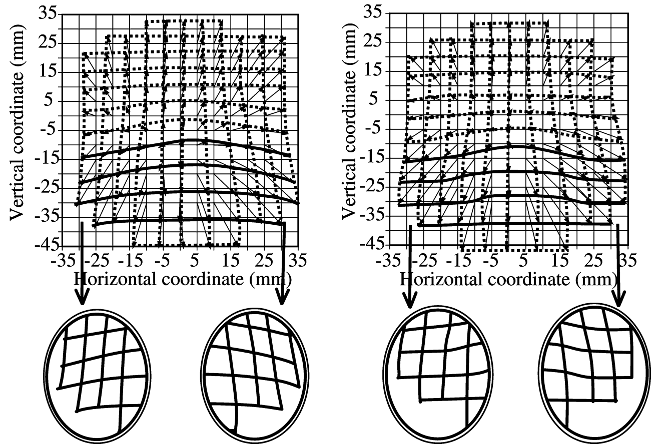

FIGURE 8. Distortion distribution of (a) the PAL (sample 11) and (b) the GRIN-PAL (sample 10) caused by the prismatic effect.

slightly downward elements (Figure 5a), the image seen through the lens moves toward the opposite direction by the effect of the GRIN, which consequently improves the skew distortion. In fact, from parts a to b of Figure 8, the side warp of the horizontal image lines in the lower half (solid lines) was flattened. This improved the oblique distortion, and the warped quadrangles in Figure 8a are slightly corrected to squares in Figure 8b. GRIN successfully corrected distortion in PAL in addition to astigmatism.

Thus, both astigmatism and distortion were corrected by the effect of the GRIN. The PAL (sample 10) and GRIN-PAL (sample 11) have the same surface geometry as one of the state-of-the-art commercially available PALs (HOYA LUX GP 1.5). Therefore, aberration correction in the fabricated PAL means development in the commercially available PAL. It is true that there are other types of commercially available PALs, and some of them have less astigmatism and distortion than HOYA LUX GP 1.5. However, employment of GRIN materials for the base material of the PAL is considered to be effective for other types of PALs when the optimum GRIN profile is designed for each PAL. This is because the basic concept of aberration correction by GRIN demonstrated here is applicable regardless of the surface design of PAL.

From these results and discussion, it was indicated that GRIN has the potential to correct both astigmatism and distortion further than the conventional method in which only surface geometries are optimized. For further reduction, higher Δn is desired, which consequently indicates the necessity of more effective monomer combinations that provide larger Δn.

CONCLUSION

Methods to control Δn, the diffusion length, and the order of the GRIN profile in polymeric GRIN materials were demonstrated. In a combination of the PBzMA gel and the MMA/3FMA diffusion monomer, 50/50 in volume provides the highest Δn. The diffusion period mainly affects the diffusion length, which consequently determines the order of the profile and the focusing power that the GRIN provides. The difference in the ease of diffusion caused by the difference in the cross-linking density provides a method for positional control of the GRIN profile.

ARTICLE

Furthermore, a GRIN-PAL using polymeric materials was successfully fabricated. Improvement in astigmatism and distortion was demonstrated using GRIN. Therefore, the GRIN material is indicated to be applicable for further modification of astigmatism and distortion in PAL.

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