Development of a novel multifocal lens using a polarization directed flat lens: Possible candidate for a multifocal intraocular lens

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Abstract

Background: A polarization-directed flat (PDF) lens acts as a converging lens with a focal length (f) > 0 and a diverging lens with f < 0, depending on the polarization state of the incidental light. To produce a multifocal lens with two focal lengths, a PDF and a converging lens having shorter focal length were combined. In this study, we tested to determine its potential as a new multifocal intraocular lens (IOL).

Methods: Constructed a multifocal lens with a PDF lens (f=+/- 100 mm) and a converging lens (f= +50 mm). In an optical bench test, we measured the lens's focal lengths to test the multifocal function. The multifocal function and optical quality of the lens in various situations were tested. An Early Treatment Diabetic Retinopathy Study (ETDRS) chart as a near target and a parking lot as a distant target were photographed using a digital single-lens reflex (DSLR) camera. Both lenses (multifocal and monofocal) were tested under same conditions.

Results: In the optical bench test, the multifocal lens's focal lengths were 31.2 and 71.2 mm. In the DSLR test using the multifocal lens, the parking lot appeared slightly cloudy compared to the monofocal lens results. With the multifocal lens, the ETDRS chart's images became blurry as the ETDRS chart's distance decreased, but became very clear again at a certain position.

Conclusions: We confirmed the multifocal function of the multifocal lens using a PDF lens. This lens can be used as a multifocal IOL in the future.

Background

The use of multifocal intraocular lenses (IOLs) in cataract surgery continues to increase. Diffractive multifocal IOLs and refractive multifocal IOLs are predominant among the currently applied multifocal lenses.[1] We recently developed a new multifocal lens by combining a polarization-directed flat (PDF) lens and a converging lens.

A PDF lens consists of a thin flat film in which photo-aligned geometric phase holograms are recorded.[2-5] The phase holograms cause phase shifts that depend on the polarization states of the incidental light illuminated onto the PDF lenses.[2-5] When the incidental light is right-handed circular polarization (RHCP), the focal length of the PDF lenses is positive. On the other hand, left-handed circular polarization(LHCP) generates a negative focal length.[5] That is, the PDF lens acts as both a converging lens with a focal length (f) > 0 and a diverging lens with f < 0, depending on the polarization state of the incidental light (Figure 1). Combining the PDF lens with a converging lens having a shorter focal length creates a multifocal lens with 2 focal lengths (Figure 2). For example, if a +/- 100 mm (+/- 10 D) PDF lens is combined with a + 50 mm (20 D) converging lens, the resulting lens will be a multifocal lens with +10 D (add 20D). According to the manufacturer's data for the PDF lens we used, the lens serves as a converging lens when f > 0 for 50% incidental light and a diverging lens when f < 0 for 50% incidental light, not only for circularly polarized light but also for unpolarized light (https://www.edmundoptics.com/globalassets/documents/polarization-directed-flat-lens-overview.pdf).

Although there many technical reports on PDF lenses,[2-5] this is the first report, to our knowledge, describing a new multifocal lens that combines a PDF lens and a converging lens. In the present study, we tested the multifocal function and optical quality of our multifocal lens to determine its potential as a new multifocal IOL.

Methods

The PDF lens (Edmund Optics, Barrington, NJ) used in this study had a focal length of +/- 100 mm, a diameter of 25 mm, and a thickness of 0.45 mm (Figure 3). Concentric rings were observed under a stereomicroscope (X20, SM-4TZ-30WY-16M3, Amscope, Irvine, CA). The converging lens for used to make the multifocal lens was an achromatic lens (chromatic aberration-free) with a focal length of +50 mm, diameter of 25.4 mm, and thickness of 11.5 mm (Thorlabs Inc., Newton, NJ). This converging lens had a back focal length of 43.4 mm from the flat surface of the lens (Figure 4). The 2 lenses were combined to create a multifocal lens. The experimental setting for measuring the multifocal function and optical quality of this lens was as described below.

1. Optical bench test

A white light-emitting diode (LED; 3-3/4 inch LED Square Plate for Microscopes, AmScope), USAF 1951 resolution target (2" x 2" Negative 1951 USAF Hi-Resolution Target, Edmund Optics), collimating lens (focal length 100 mm), 4 mm-diameter pupil, achromatic lens (focal length 50 mm), PDF lens (focal length +/- 100 mm), 8 mm-diameter pupil, and charge-coupled device (CCD) camera (acA1600-20uc, Basler, Ahrensburg, Germany) were arranged in a line (Figure 5). A polarizer was not used. The distance between the collimating lens with a focal length of 100 mm and the USAF resolution target was 100 mm. The PDF lens was fixed with tape in front of the lens mount of the achromatic lens (near the flat surface of the achromatic lens) and confirmed to be centered. The gap between the flat surface of the achromatic lens and the PDF lens was 2.0 mm. From the collimating lens to the CCD camera, all items were connected to a 30-mm cage system to eliminate the need for additional alignment. The LED and USAF resolution target were fixed to an XYZ translation stage (Thorlabs Inc.). While viewing the image on a monitor connected to the camera, the USAF resolution target was aligned at the axis of the 30-mm cage system by moving the stage.

1) Monofocal lens (achromatic lens only)

USAF resolution targets were photographed with only an LED, USAF 1951 resolution target, collimating lens (focal length 100 mm), 4 mm-diameter pupil, achromatic lens (focal length 50 mm), 8 mm-diameter pupil, and CCD camera without a PDF lens. The camera was moved back and forth to focus the image. When the clearest image was obtained, the distance between the flat surface of the achromatic lens and the CCD sensor was measured. A total of 8 images was taken around this location. Only when the distance between the achromatic lens's flat surface and the CCD camera's sensor was longer than 70 mm was the 8 mm pupil used in front of the camera to block unwanted light.

To quantify the quality of each image of the resolution target, we computed their cross-correlation coefficients. In general, a cross-correlation coefficient is used to quantify the similarity between 2 images. [6-8] To quantify the sharpness of each image, the similarity between the 2 images was compared using the cleanest image as a reference. Therefore, a cross-correlation coefficient that quantifies similarity can be used. As a reference template image for obtaining the cross-correlation coefficient, a middle rectangular area was selected and analyzed from a clear USAF resolution image (from group 2 to 7 elements; Figure 6). The cross-correlation coefficient between the test image f(x, y), including the blurred reference image and the sharp reference image t(x, y), can be obtained as follows.

$$\rho(u,v) = \frac{\sum_{x,y}\left[f(x,y)-\overline{f_{u,v}}\right]\left[t(x-u,y-v)-\bar{t}\right]}{\left\{\sum_{x,y}\left[f(x,y)-\overline{f_{u,v}}\right]^2 \sum_{x,y}\left[t(x-u,y-v)-\bar{t}\right]^2\right\}^{1/2}} \qquad (1)$$

Here, $\bar{t}$ is the mean value of the reference image; $\overline{f_{u,v}}$ is the center of the coordinates (u, v) of the test image and the mean value of the same size image as the reference image.

To calculate the cross-correlation coefficient from the coordinates (u, v) of the test image, the center of the reference image was centered on these coordinates, and the pixels f(u, v) and t(u, v) subtracted by the mean value were multiplied pixel by pixel and normalized by dividing by its magnitude. The cross-correlation ranged from -1 to +1, and +1 indicated that the image was the same as the best query reference image. The cross-correlation indicated that the quality of the image decreased as the value of it decreased. The value of -1 indicated that the black and white pixels of the 2 images were inverted. When it was overlaid on the test image and scanned from the first row to the right column, the cross-correlation coefficient matrix from the first row to the last row was obtained as in equation (1). Among the coefficients of the matrix, the peak value was generally present in one place, and this value was the optimal cross-correlation coefficient. In addition, the best query-like image was obtained from the coordinate u and v information. The experimental results were as follows. The size of the actual test image was 1624 x 1234 pixels and the size of the reference image extracted from it was 474 x 445 pixels (Figure 6).

The cross-correlation coefficient of the acquired test image should be calculated with the image of the same magnification as the reference image. To this end, the magnification of the test image was calculated based on the number of pixels corresponding to the height of the rectangular border area, excluding the numbers of reference images. According to this magnification, the size of the test image was obtained again by a third-order polynomial interpolation method. In obtaining the cross-correlation coefficient with the test image considering magnification, it was possible to obtain the cross-correlation coefficient from most test images. In the scaled image, the partial image at the position where the peak of the cross-correlation occurs was displayed as a rectangular box. If the test image was severely blurred, however, it was not possible to find a matching region with only the maximum value of the correlation coefficient. In some test images, the cross-correlation coefficients were obtained manually. A curve was obtained by measuring the cross-correlation coefficient according to the distance from the flat surface of the achromatic lens to the sensor of the CCD camera, using MATLAB software (MathWorks; Natick, MA).

2) Multifocal lens (PDF lens + achromatic lens)

After the PDF was mounted, the experiment was repeated. First, the CCD sensor was positioned at 31.2 mm from the flat surface of the achromatic lens. (The distance between the flat surface of the achromatic lens and the CCD sensor was 31.2 mm.) Thirteen photos were obtained before the CCD sensor reached 91.2 mm from the flat surface of the achromatic lens. (Due to the thickness of the achromatic lens, thickness of the C-mount adapter, and flange of the C-mount camera [17.526 mm], the CCD sensor could not be closer to the flat surface of the achromatic lens than 31.2 mm.) Only when the distance between the achromatic lens's flat surface and the CCD camera sensor was greater than 70 mm could the 8-mm pupil be used in front of the camera to block unwanted light. At this time, the clearest (in focus) image among the photos obtained with the above monofocal lens (achromatic lens only) was used as a reference image for calculating the cross-correlation coefficient.

During the experiment, the LED brightness and camera settings (exposure time, International Organization for Standardization [ISO], gamma value, white balance, etc.) were not changed.

2. Digital single-lens reflex camera test

The multifocal function and optical quality of a multifocal lens (PDF lens + converging lens) in various conditions were tested using a digital single-lens reflex (DSLR) camera (D610, Nikon, Tokyo, Japan; Figure 7). Because the flange focal distance of the DSLR camera was 46.50 mm, an f = 50 mm achromatic lens could not focus light at a DSLR camera sensor, so an f = 75 mm monofocal lens (back focal length 70.3 mm) was used for the monofocal lens test. The system was made of a 4-mm pupil, achromatic lens (focal length 75 mm), and DSLR camera. They all were connected to a 30-mm cage system to eliminate the need for additional alignment. A polarizer was not used. Focus was achieved by adjusting the distance between the camera and the achromatic lens. When a far object more than 6 m away appeared clear, the achromatic lens was fixed at the cage system. After focusing, the ambient light was shielded with black tape, and objects at far and near distances were photographed or recorded as videos.

To test the multifocal lens, a 4-mm pupil, achromatic lens (focal length 50 mm), focal length +/- 100 mm PDF lens, and a DSLR camera were used. The PDF lens was fixed with tape in front of the lens mount of the achromatic lens (near the flat surface of the achromatic lens) and it was confirmed to be centered. A polarizer was not used.

Focus was achieved by adjusting the distance between the camera and the multifocal lens. At this time, the multifocal lens was positioned so that the longer focus of the multifocal lens was located at the sensor of the camera. After focusing, the ambient light was shielded with black tape, and objects at far and near distances were photographed or recorded as videos.

1) Far distance

During the day, a parking lot was photographed with a DSLR camera, and this was repeated with a monofocal lens and a multifocal lens. Using a tripod, we attempted to capture the same view with both the monofocal and multifocal lenses.

2) Near distance

To test multifocal function, the Early Treatment Diabetic Retinopathy Study (ETDRS) chart (ETDRS 2000 Series chart "2" [Precision Vision, La Salle, IL]) was used as the near target. The ETDRS chart started at 385 mm from the convex surface of the achromatic lens. The ETDRS chart was brought closer to the DSLR camera until it reached 40 mm, i.e., the distance between the convex surface of the achromatic lens and the ETDRS chart was 40 mm; Figure 7.) The approach toward the camera was recorded as a video. General stand lighting was used.

3) Far and near distance

To test the multifocal function in the daytime, the ETDRS chart at near distance was recorded as a video right after recording a distant parking lot. This was repeated for the monofocal lens and the multifocal lens.

Results

1. Optical bench test

Figure 8 shows USAF resolution target images taken with a monofocal lens, and Figure 9 shows USAF resolution target images taken with a multifocal lens. With the monofocal lens, the image was clearest (in focus) when the distance between the achromatic lens back surface and the CCD camera sensor was 43.3 mm, but the images quickly became blurry when it was out of focus (Figure 8). The image at 43.3 mm was used as a reference template for cross-correlation coefficient calculation. The cross-correlation coefficient curve showed a very high and narrow peak centered at 43.3 mm (Figure 10). The cross-correlation coefficient at 43.3 mm was 1.0 by definition. Achromatic aberration was rarely observed.

With the multifocal lens, when the distance between the achromatic flat surface of the achromatic lens and the CCD camera sensor was 31.2 mm, the USAF resolution target image was clear. As the distance increased, the image became blurry, but the image became clear again when the distance between the achromatic lens’s flat surface and the CCD camera sensor was 71.2 mm (Figure 9). Between 31.2 mm and 71.2 mm, there were 3 locations where the image became slightly clearer (35.7, 42.7, 53.2 mm; Figure 9). At most distances, chromatic aberration was observed at the edge of the letters compared with the monofocal lens. The image at 43.3 mm from the monofocal lens (f = 50 mm achromatic lens) was used as a reference template for calculating the cross-correlation coefficient. The cross-correlation coefficient curve showed the profile of a bifocal lens showing two peaks, at 31.2 mm (cross-correlation coefficient: 0.709) and 71.2 mm (cross-correlation coefficient: 0.805; Figure 10). The cross-correlation coefficients were all less than 1.0, however, indicating that they were blurrier than the in-focus image (43.3 mm) obtained with the monofocal lens.

2. DSLR camera test

1) Far distance

Figure 11 shows a far-distant parking lot photograph taken with a monofocal lens (A) and a multifocal lens (B). When focusing at a far distance with a monofocal lens, the distance between the achromatic lens's flat surface and the DSLR camera sensor was 69.3 mm. With the monofocal lens, the parking lot appeared very clear. No chromatic aberration was observed (Figure 11A).

When the longer focus of the multifocal lens was located at the sensor of the camera, the distance between the achromatic lens's flat surface and the DSLR camera sensor was 72.0 mm. With the multifocal lens, the parking lot appeared slightly cloudy (Figure 11B) compared with the results from the monofocal lens. This was especially true around bright objects. Chromatic aberration was observed around the strong reflection areas on the cars.

2) Near distance

Figure 12 and Videos 1, 2 show near-target images recorded with a monofocal lens and a multifocal lens. We tested at 62mm and 385mm which the distance between the achromatic converging lens surface and the DSLR camera sensor. With the monofocal lens, as the distance from the Early Treatment Diabetic Retinopathy Study (ETDRS) chart decreases, the images become increasingly blurry, but there is no chromatic aberration. With a multifocal lens, as the distance from the ETDRS chart decreases, the images become blurry, but they become very clear again at a certain position. At this position, the distance between the achromatic converging lens surface and the DSLR camera sensor is 62 mm. Chromatic aberration is observed at the edges of the letters. As the distance becomes closer, it becomes blurry again (Figure 12).

With the monofocal lens, as the ETDRS chart was brought closer to the camera, the images became increasingly blurry, but there was no chromatic aberration (Video 1). With a multifocal lens, as the ETDRS chart was brought closer to the camera, the images became blurry, but they became very clear again at a certain position (Video 2). At this position, the distance between the achromatic converging lens surface and the DSLR camera sensor was 62 mm. Chromatic aberration was observed at the edge of the letters. As the chart was brought closer to the camera, the image became blurry again.

3) Far and near distance

To test the multifocal function in the daytime, the ETDRS chart at near distance was recorded as a video right after recording a distant parking lot (Figure 13). With the monofocal lens, the parking lot appeared very clear but the letters in the ETDRS chart were impossible to identify at a distance of about 60 mm (Figure 13 A, B, Video 3). With the multifocal lens, the parking lot appeared slightly cloudy compared with the image from the monofocal lens, but the letters in the ETDRS chart appeared very clear (Figure 13 C, D, Video 4). At this time, the distance between the ETDRS chart and the achromatic converging lens surface was about 60 mm.

Discussion

In this study, we clearly confirmed the multifocal function of a new multifocal lens created by combining a PDF lens and a converging lens. As expected, the multifocal lens has the properties of a bifocal lens focusing at 2 points. This multifocal lens, which combines a focal length +/- 100 mm PDF lens and a focal length +50 mm achromatic lens, produced a clear image when the distance between the CCD camera sensor and the achromatic lens's flat surface is 31.2 and 71.2 mm. The focal points obtained through the lens equation based on ray optics are $f1 = 31.4$ mm and $f2 = 72.2$ mm. They are almost the same as our results (Figure 14). Three almost clear images were observed between 31.2 mm and 71.2 mm. The images at undesired focal planes may be an indicator of stray light or leakage effects analogous to unwanted diffraction orders, possibly due to less than 100% diffraction efficiency or less than 50% energy going to the desired planes. This effect is also observed in the cross-correlation graph shown in Figure 10. In the optical bench test, the image at the distant focus of the multifocal lens (cross-correlation coefficient 0.805) was slightly blurry compared with the in-focus image of the monofocal lens (cross-correlation coefficient 1.0 by definition). This was similar to when the distant parking lot was photographed with the DSLR camera using the multifocal lens.

At near distance, the object appeared very clear. In the optical bench test, the image at the near focus of the multifocal lens (cross-correlation coefficient 0.709) was clear. In the DSLR camera test, the ETDRS chart at a distance of 62 mm was very clear when the longer focus was located at the sensor of the camera. This was also demonstrated when the ETDRS chart at near distance was recorded as a video immediately after recording a distant parking lot. This is not because the focusing at far objects more than 6 meters away was incomplete. The multifocal function of the lens produced a clear image of near objects.

The combination of PDF and converging lenses is a completely different principle from that of diffractive multifocal IOLs. Diffractive multifocal IOLs have a multifocal function due to the diffraction of light from the concentric diffractive pattern.[1] Similarly to diffractive IOLs, the PDF lens has concentric rings (Figure 3), so centration of the lens is important for good function. In addition, when the PDF lens was combined with a converging lens, the results showed a definite multifocal function: far objects appeared slightly blurry compared with a monofocal lens. These findings are similar to those using diffractive multifocal IOLs.[9-15]

In this study, we used a converging f = 50 mm lens and a PDF lens with f = + /-100 mm. The PDF lens with f = + /-100 mm was commercially available with the longest focal length. If we used a PDF lens with f = + /-600 mm (+/- 1.67 D) and a converging lens with f = 50 mm (20 D), however, it would be closer to the real multifocal IOL of about 18.33 D (add 3.3 D).

Originally, a PDF lens acts as an f >0 converging lens for right circular polarized light and an f <0 diverging lens for left circular polarized light. If a PDF lens acts only for circularly polarized light, it would not be possible to use it as a multifocal IOL. According to the manufacturer's data about the PDF lens we used, however, it serves as a converging lens f >0 for 50% incidental light and a diverging lens f <0 for 50% incidental light for not only circularly polarized light but also unpolarized light (https://www.edmundoptics.com/globalassets/documents/polarization-directed-flat-lens-overview.pdf), and our experiment demonstrated this. It also has the same function even when incidental light is linearly polarized, just like when wearing sunglasses with polarizing lenses (https://www.edmundoptics.com/globalassets/documents/polarization-directed-flat-lens-overview.pdf). Therefore, this multifocal lens has potential use as a multifocal IOL for cataract surgery.

The advantages of our new multifocal lens are, first, that near objects look very clear. This was verified in the optical bench tests and DSLR camera tests. In this study, however, we did not compare our results with those of existing diffractive IOLs. Second, there was no energy loss because light energy is used 50% at near distance and 50% at far distance. On the other hand, in the case of existing diffractive IOLs, the light energy loss is 15% to 20%.[16] This is a large advantage of the newly invented multifocal lens.

The disadvantages of our new multifocal lens are, first, that there is quite a bit of chromatic aberration. We used achromatic lenses (chromatic aberration–free) as the converging lens, and when using only a 50-mm achromatic lens as a control, there was no chromatic aberration, so the chromatic aberration is considered to be due to the PDF lens, which was confirmed in the optical bench test and when taking photos of a parking lot in the daytime. Chromatic aberration was also found when taking photos of a near ETDRS chart. It may be possible to reduce this chromatic aberration by intentionally adjusting the chromatic aberration of the converging lens. Second, theoretically, the energy at far distance and near distance cannot be arbitrarily adjusted, and light energy is used 50% at near distance and 50% at far distance. Indeed, in the optical bench test, the clarity of the image at near focus (cross-correlation coefficient 0.79 at 31.2 mm) and far focus (cross-correlation coefficient 0.805 at 71.2 mm) were similar. If it is made as a multifocal IOL, near vision will be satisfactory, but distant vision may be relatively unsatisfactory to some patients.

The PDF lens film may be attached to the front or back surface of a monofocal IOL (Figure 15A). The PDF lens used in the present study was stiff, but the PDF lens is an essentially thin flat film in which photo-aligned geometric phase holograms are recorded. Therefore, the IOL beneath the film can be folded for insertion. The biocompatibility of the PDF lens with the human eye, however, is not established, and thus it cannot yet be commercialized. It may be possible to use it by inserting it into an existing monofocal IOL for biocompatibility (Figure 15B). It is still difficult to apply this lens directly to the human eye, but we introduce this new multifocal lens as a lens with the potential to function as a multifocal IOL.

Conclusions

In this study, we clearly confirmed the multifocal function of a new multifocal lens created by combining a PDF lens and a converging lens. It is still difficult to apply this lens directly to the human eye, but we introduce this new multifocal lens as a lens with the potential to function as a multifocal IOL.

Abbreviations

PDF: polarization-directed flat

D: Diopter

IOL: Intraocular lens

ETDRS: Early Treatment Diabetic Retinopathy Study

DSLR: Digital single-lens reflex

LED: light-emitting diode

CCD: Coupled device

ISO: International Organization for Standardization

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for Publish

Not applicable.

Availability of Data and Materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing Interests

Co-author ‘Ho Sik Hwang’ is the Editorial Board Member of BMC Ophthalmology.

The authors declare that they don't have the other competing interests.

The author (HHS) registered a Korean patent for this multifocal lens (10-2017-0130106). The other authors have no financial interest or relationship to disclose.

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Authors' contributions

NKS, LCS and HHS participated in the design of this study, NKS and LCS carried out the experiment. NKS, LCS, KDR, CSY and KEC performed the statistical analysis. NKS, LCS, and KDR drafted the manuscript. KEC, KHS, and HHS performed manuscript review. All authors read and approved the final manuscript.

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Figures

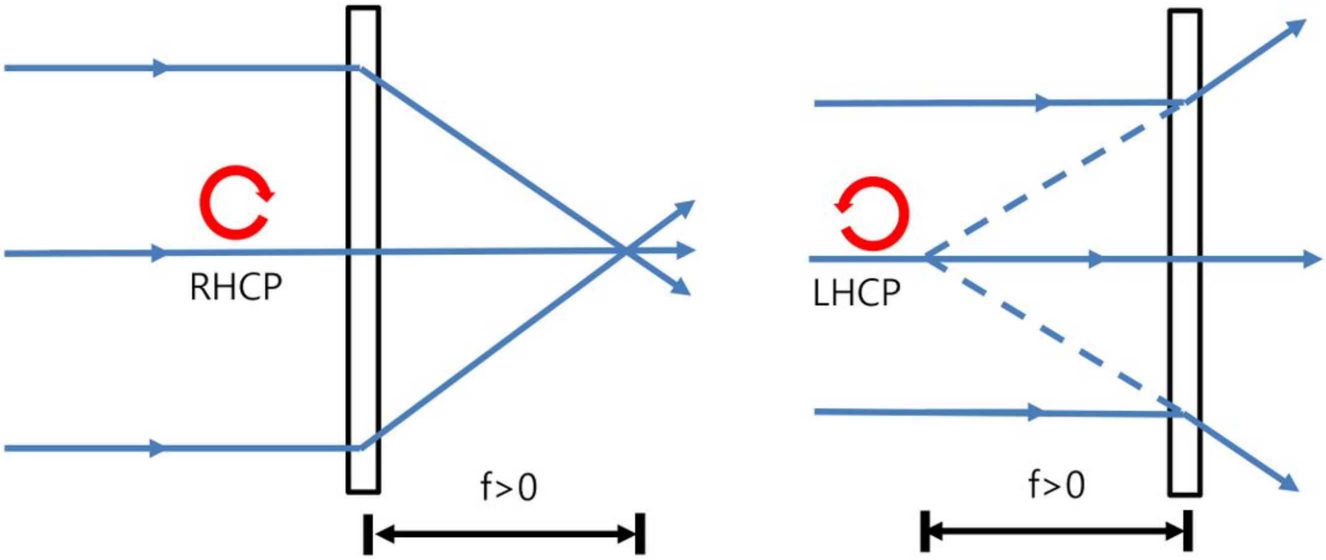


Figure 1

Polarization-directed flat (PDF) lens. When the incidental light is right-handed circular polarization (RHCP), the focal length of the PDF lens is positive. On the other hand, left-handed circular polarization (LHCP) generates a negative focal length. That is, the PDF lens acts as a converging lens with focal length (f) > 0 and a diverging lens with f < 0, depending on the polarization state of the incidental light

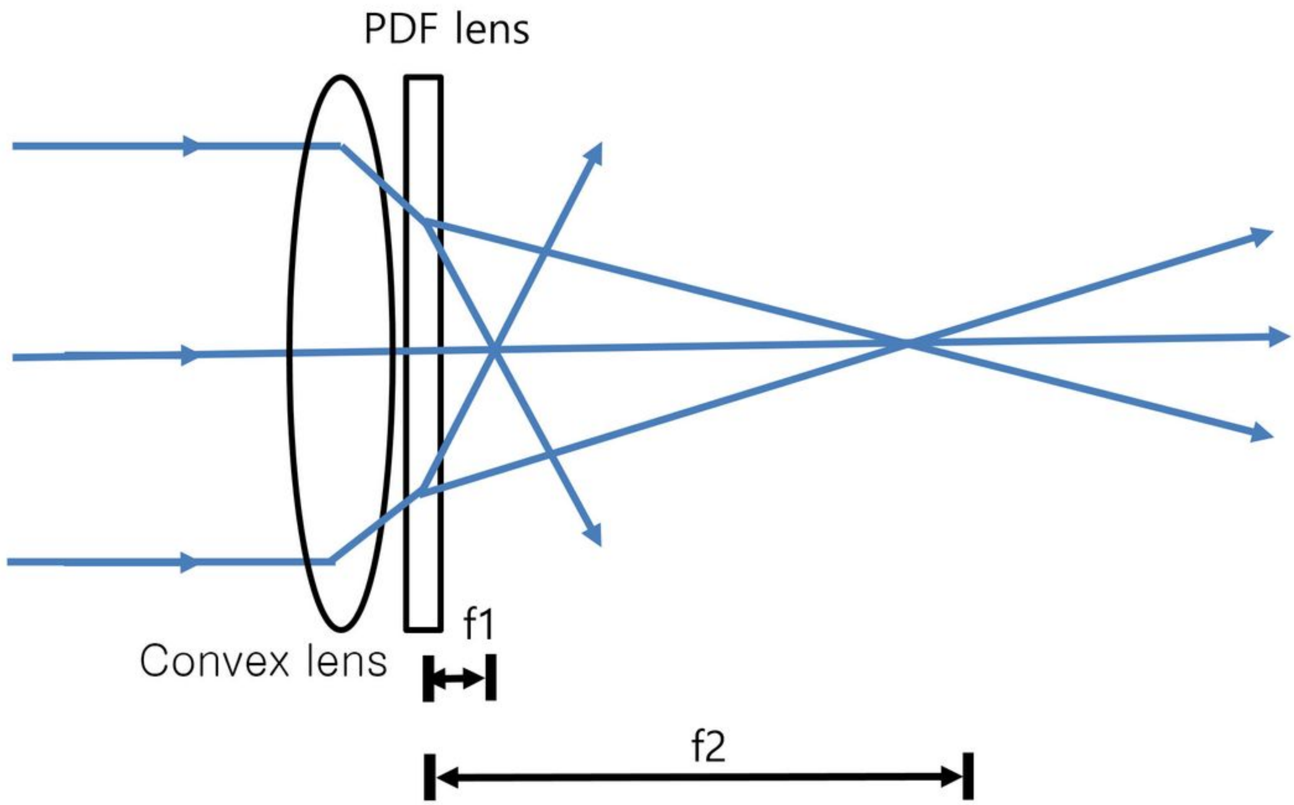


Figure 2

The principle of the new multifocal lens. By combining a polarization-directed flat (PDF) lens and a converging lens with a shorter focal length, a multifocal lens with 2 focal lengths can be constructed.

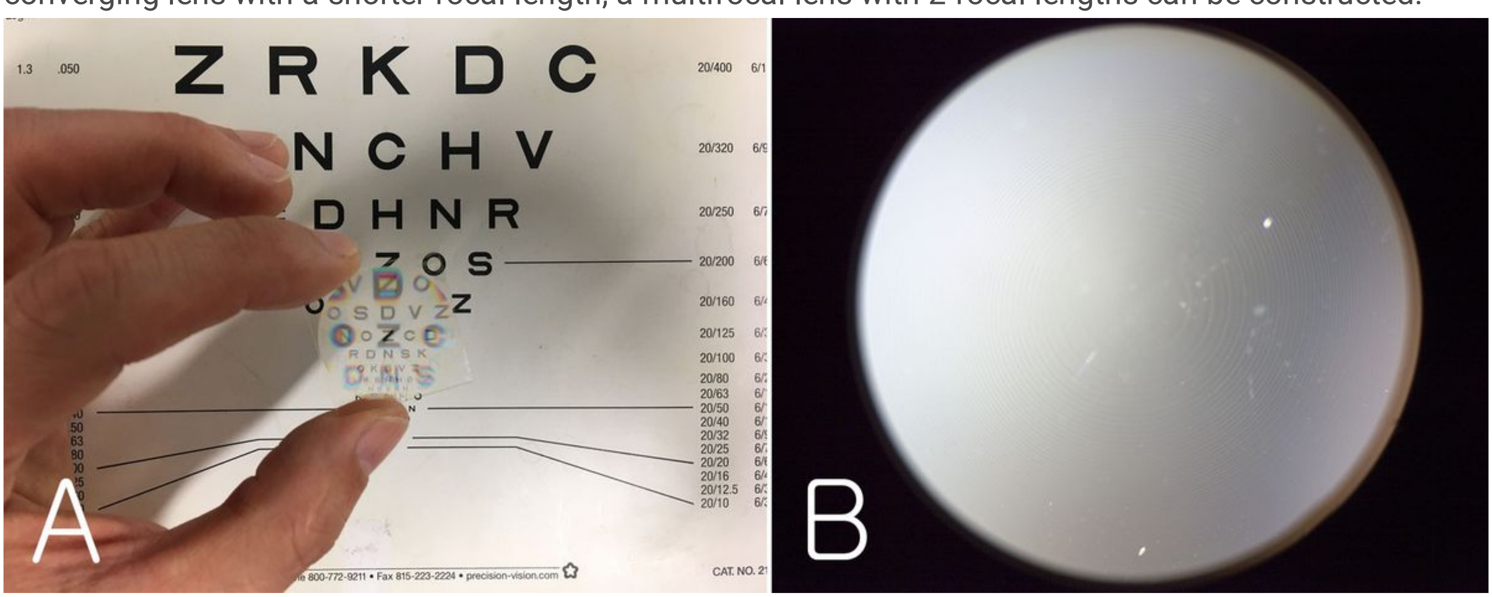


Figure 3

The polarization-directed flat lens used in this study. A: focal length +/- 100 mm, diameter 25 mm, and thickness 0.45 mm; B: Concentric rings could be seen under a stereomicroscope (X20)

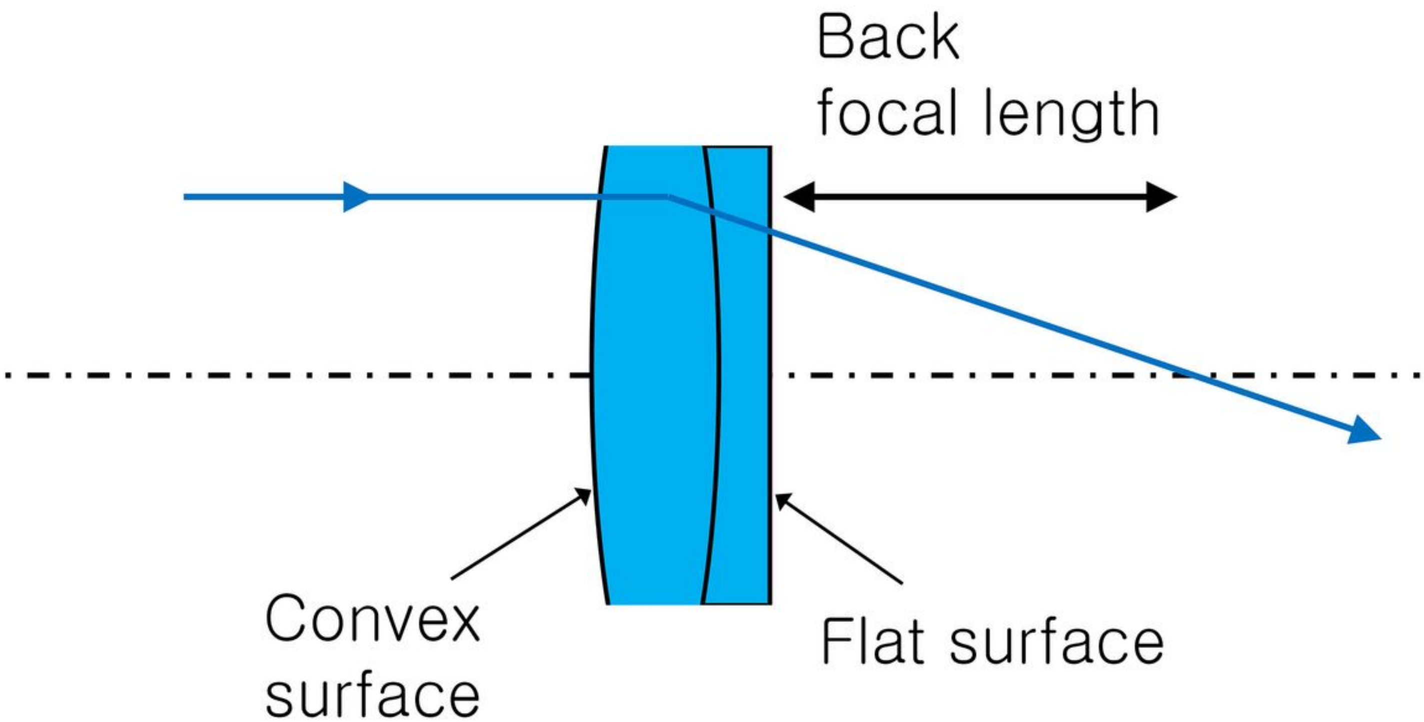


Figure 4

The converging lens for making a multifocal lens. It was an achromatic lens (chromatic aberration-free) with focal length +50 mm, diameter 25.4 mm, and thickness 11.5 mm. This converging lens had a back focal length of 43.4 mm from a flat surface of the lens.

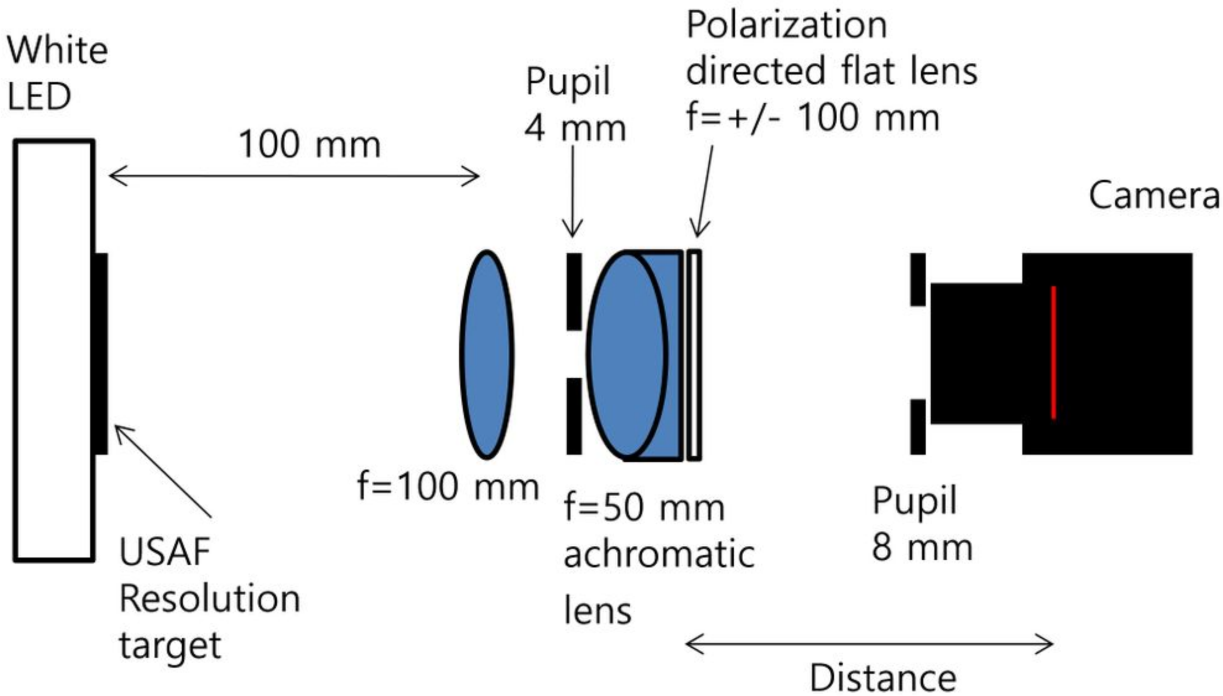


Figure 5

Optical bench test setting. A white light-emitting diode (LED), USAF 1951 resolution target, collimating lens (focal length 100 mm), 4-mm diameter pupil, achromatic lens (focal length 50 mm), polarization-directed flat (PDF) lens (focal length +/- 100 mm), 8 mm-diameter pupil, and charge-coupled device camera were arranged in a line.

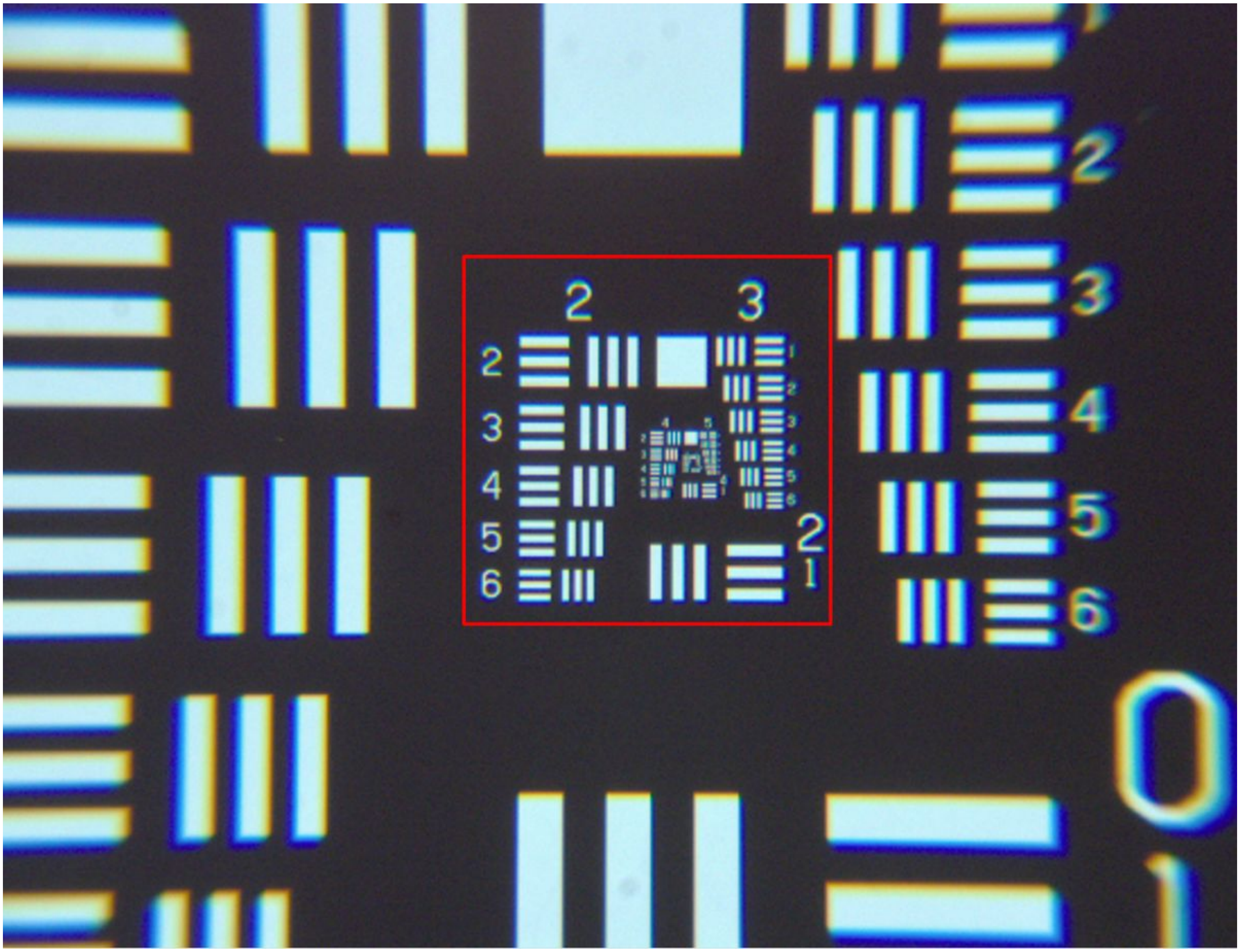


Figure 6

USAF 1951 resolution target. As a reference template image for obtaining the cross-correlation coefficient, a middle rectangular area was selected and analyzed from a clear USAF resolution image (from group 2 to 7 elements)

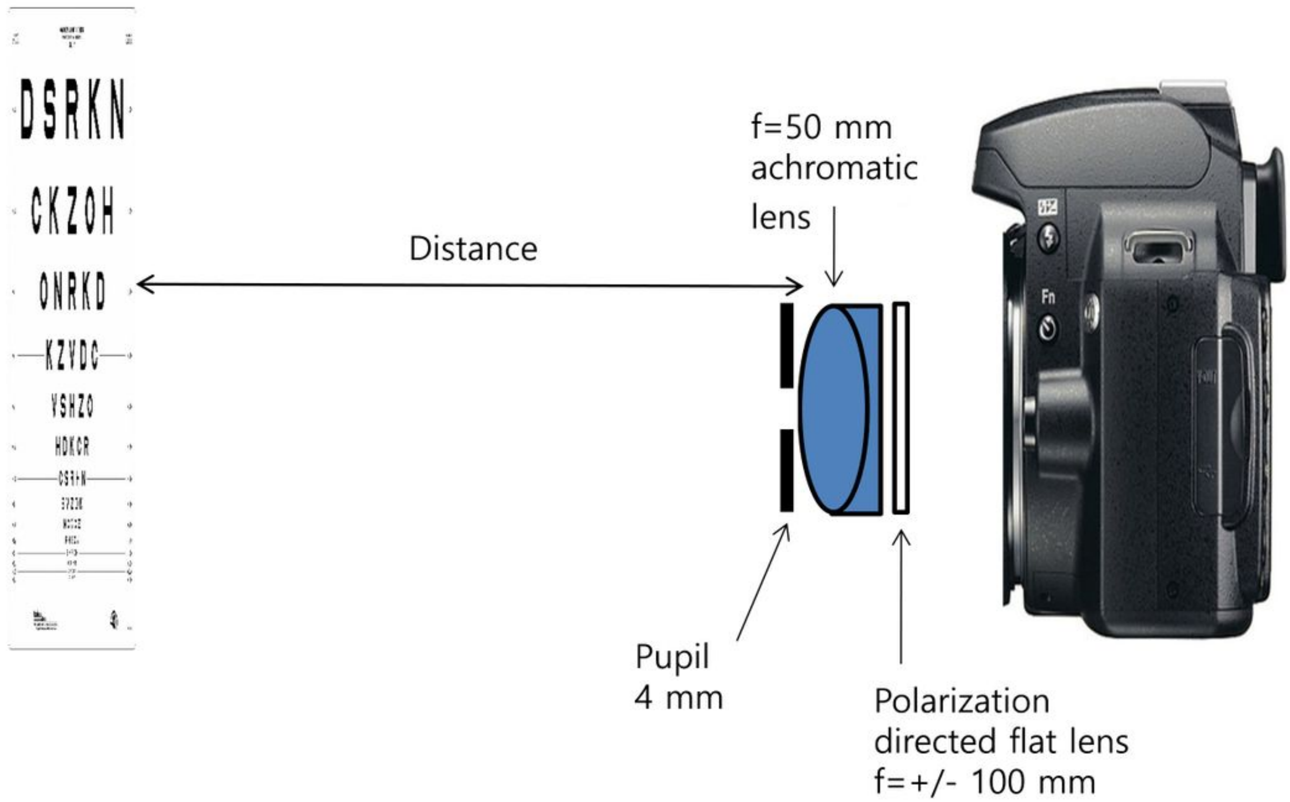


Figure 7

Digital single-lens reflex (DSLR) camera test setting. To test the multifocal lens, a 4-mm pupil, achromatic lens (focal length 50 mm), focal length +/- 100 mm polarization-directed flat (PDF) lens, and a DSLR camera were used.

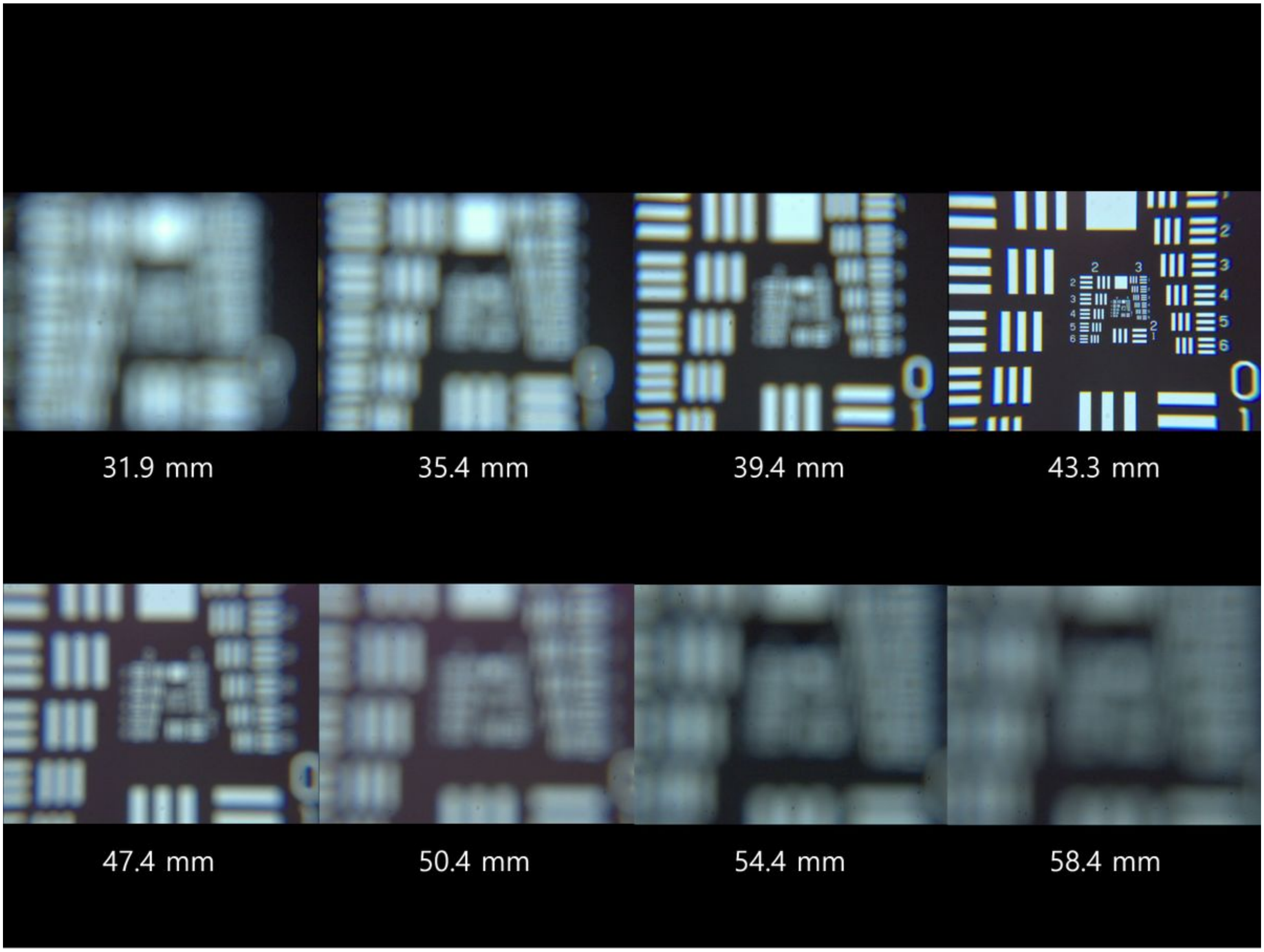


Figure 8

Optical bench test (monofocal lens). This figure shows USAF resolution of target images taken with a monofocal lens. With the monofocal lens, the image was clearest (in focus) when the distance between the achromatic lens back surface and the charge-coupled device camera sensor was 43.3 mm, but the images quickly became blurry when it was out of focus.

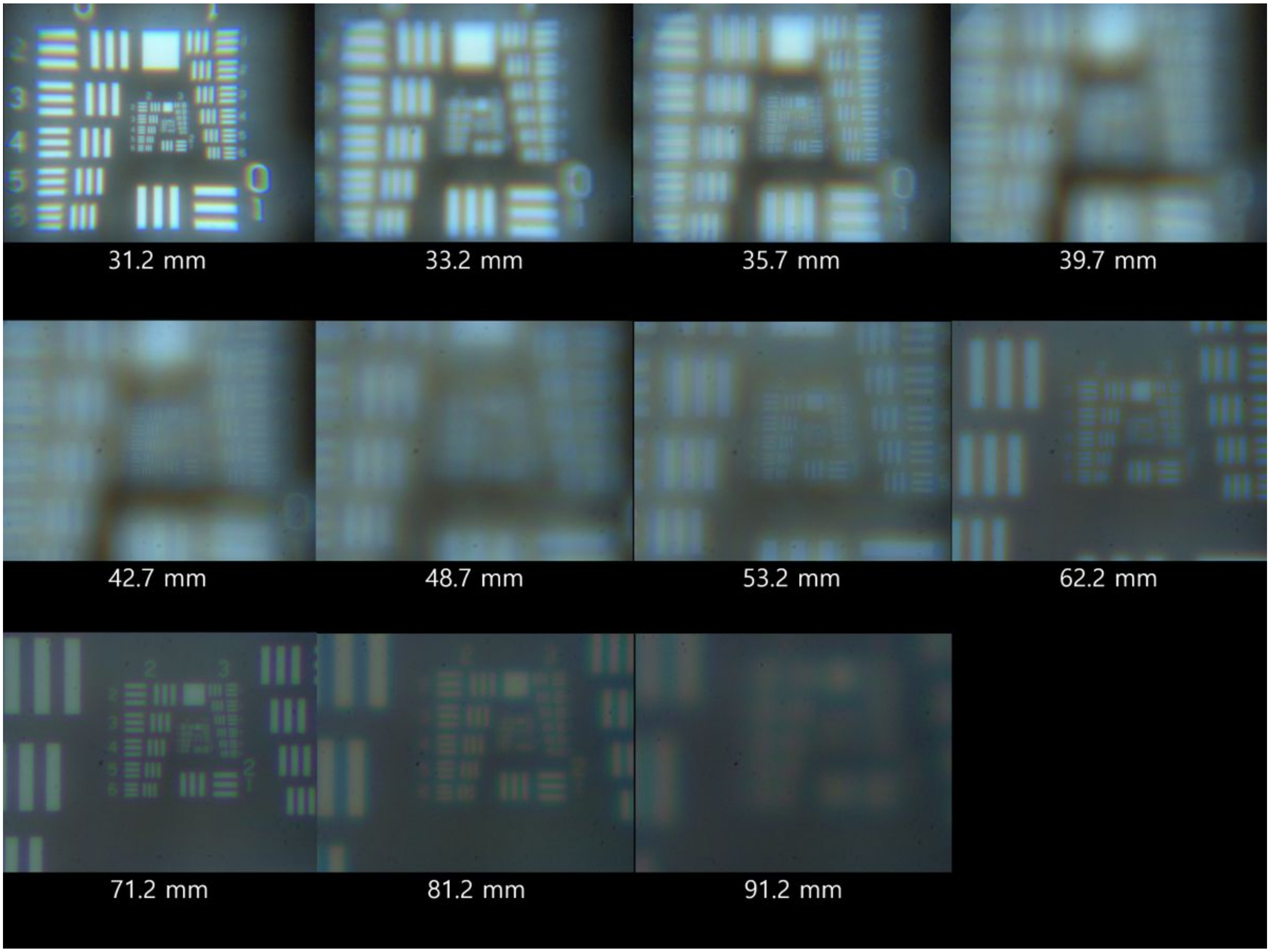


Figure 9

Optical bench test (multifocal lens). This figure shows the USAF resolution target images taken with a multifocal lens. With the multifocal lens, when the distance between the achromatic lens flat surface and the charge-coupled device camera sensor was 31.2 mm, the USAF resolution target image was clear. As the distance increased, the image became blurry, but the image became clear again when the distance between the achromatic lens flat surface and the CCD camera sensor was 71.2 mm. Between 31.2 mm and 71.2 mm, there were 3 locations where the image became slightly clearer (35.7, 42.7, 53.2 mm). At most distances, chromatic aberration was seen in the characters at the edge compared with the monofocal lens.

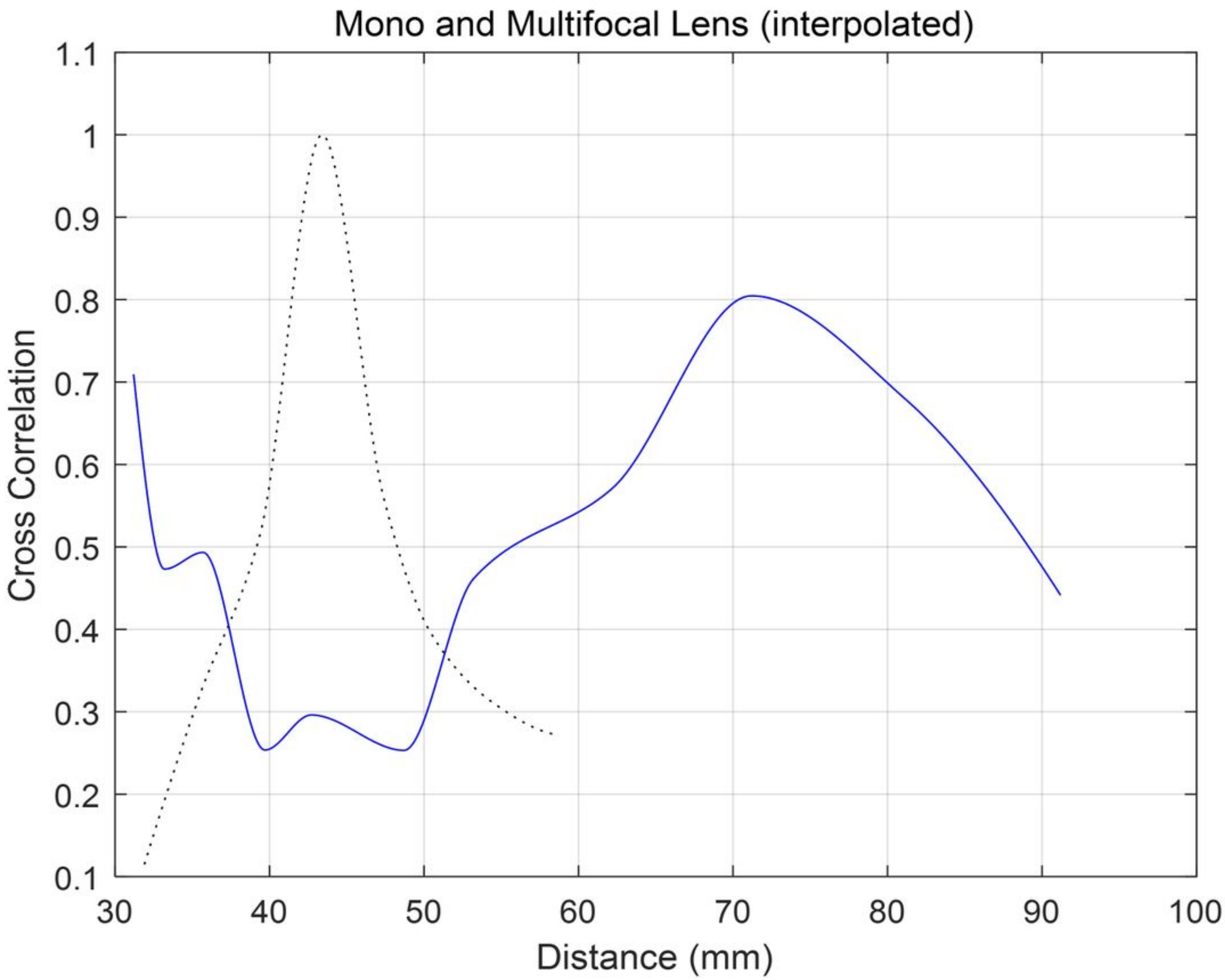


Figure 10

Cross-correlation coefficient of monofocal and multifocal lens. The cross-correlation coefficient curve of monofocal lens showed a very high and narrow peak centered at 43.3 mm. The cross-correlation coefficient at 43.3 mm was 1.0 by definition. The cross-correlation coefficient curve of the multifocal lens showed the profile of a bifocal lens with 2 peaks, at 31.2 mm (cross-correlation coefficient: 0.709) and 71.2 mm (cross-correlation coefficient: 0.805). The cross-correlation coefficients were all values smaller than 1.0, indicating that they were burrier than the in-focus image (43.3 mm) obtained with the monofocal lens (Solid line: Multifocal lens, Dashed line: Monofocal lens)

Figure 11

Digital single-lens reflex (DSLR) camera test (Far distance, day). A: With the monofocal lens, the parking lot appears very clear; B: No chromatic aberration is observed. With the multifocal lens, the parking lot appeared slightly cloudy compared with the results from the monofocal lens. This was especially true around bright objects. Chromatic aberration was seen around the strong reflection area on the cars.

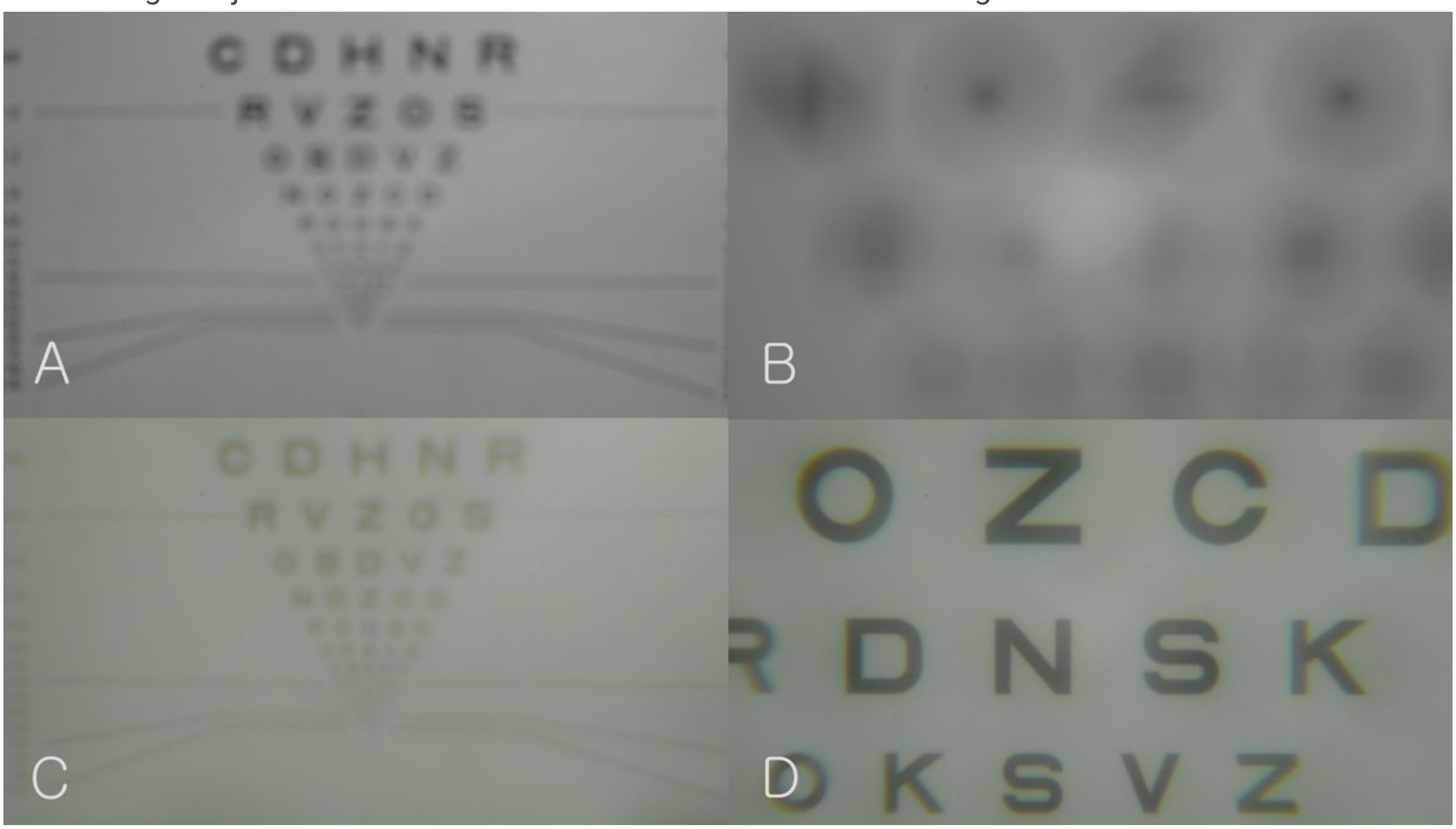


Figure 12

Digital single-lens reflex (DSLR) camera test (Near distance). With the monofocal lens, as the distance from the Early Treatment Diabetic Retinopathy Study (ETDRS) chart decreases, the images become increasingly blurry, but there is no chromatic aberration. With a multifocal lens, as the distance from the

ETDRS chart decreases, the images become blurry, but they become very clear again at a certain position. At this position, the distance between the achromatic converging lens surface and the DSLR camera sensor is 62 mm. Chromatic aberration is observed at the edges of the letters. As the distance becomes closer, it becomes blurry again. A: Monofocal lens (the distance between the achromatic converging lens surface and the DSLR camera sensor: 385 mm); B: Monofocal lens (distance: 62 mm); C: Multifocal lens (distance: 385 mm); D: Multifocal lens (distance: 62 mm)

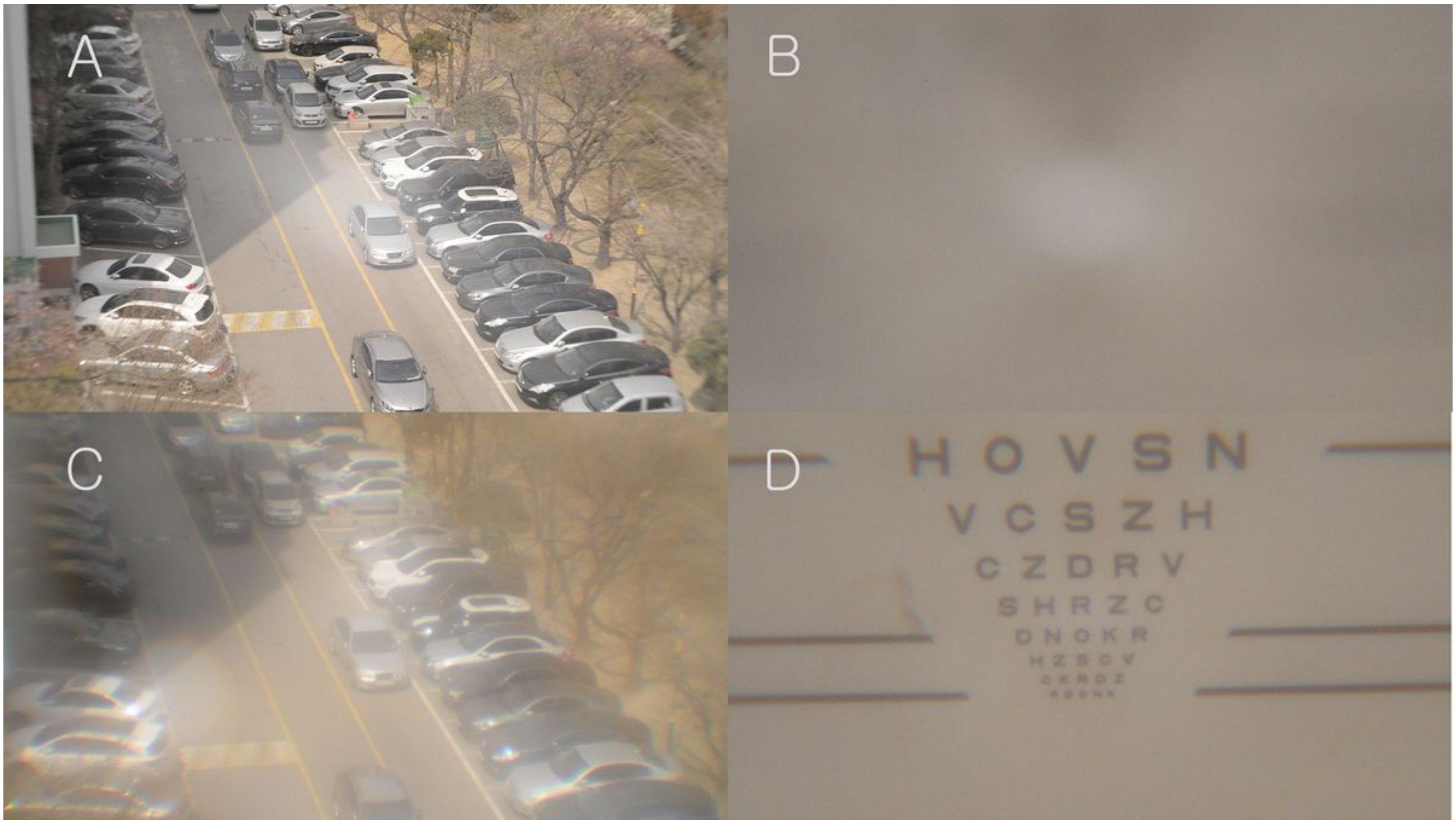
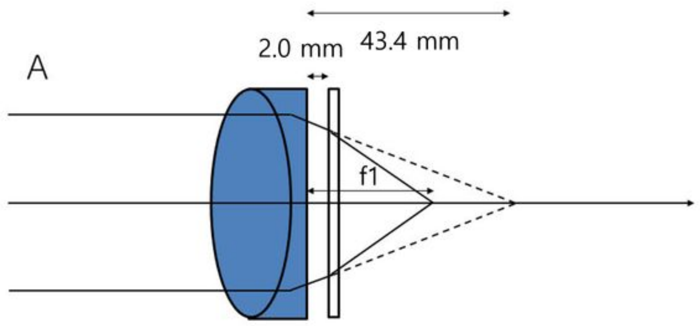


Figure 13

Digital single-lens reflex (DSLR) camera test (Far and near distance). With the monofocal lens, the parking lot appears very clear (A), but the letters in the Early Treatment Diabetic Retinopathy Study (ETDRS) chart are impossible to identify at a distance of about 60 mm (B). With the multifocal lens, the parking lot appears slightly cloudy compared with the image from the monofocal lens (C), but the letters in the ETDRS chart are clear (D). At this time, the distance between the ETDRS chart and the achromatic converging lens surface is about 60 mm.



$$\frac{1}{-(43.4-2.0-0.225)\ \text{mm}} + \frac{1}{f1-(2.0-0.225)\ \text{mm}} = \frac{1}{100\ \text{mm}}$$

$$\frac{1}{-(43.4-2.0-0.225)\ \text{mm}} + \frac{1}{f2-(2.0-0.225)\ \text{mm}} = \frac{1}{-100\ \text{mm}}$$

Figure 14

Two theoretical focal points of the multifocal lens. The focal points obtained through the lens equation based on ray optics are f1 = 31.4 mm (A) and f2 = 72.2 mm (B). The focal points are almost the same as our results.

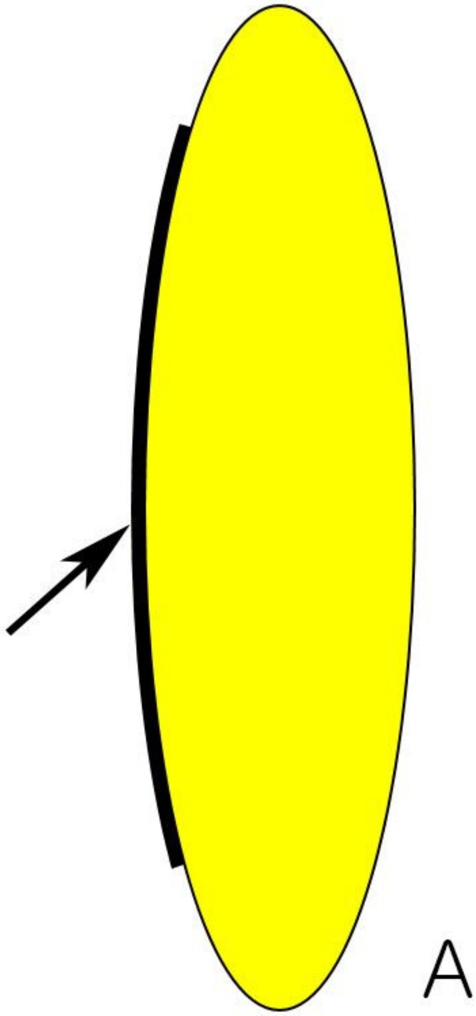


Figure 15

Possible design of new multifocal intraocular lens using polarization-directed flat (PDF) lens. A: PDF lens film on the monofocal intraocular lens, B: PDF lens film in the monofocal intraocular lens (arrow: PDF lens film)

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Video1.mp4

- Video2.mp4
- Video3.mp4
- Video4.mp4