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Effect of decentration and tilt on the in vitro optical quality of monofocal and trifocal intraocular lenses

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Abstract

Purpose To evaluate and compare the effect of decentration and tilt on the optical quality of monofocal and trifocal intraocular lenses (IOL).

Methods Optical quality of a monofocal IOL (AcrySof IQ SN60WF; Alcon Laboratories, Inc., USA) and a trifocal IOL (AcrySof IQ PanOptix; Alcon Laboratories, Inc., USA) was assessed using an in vitro optical bench (OptiSpheric IOL R&D; Trioptics GmbH, Germany). At apertures of 3.0 mm and 4.5 mm, modulation transfer function (MTF) at spatial frequency of 50 lp/mm, MTF curve and the United States Air Force (USAF) resolution test chart of the two IOLs were measured and compared at their focus with different degrees of decentration and tilt. Optical quality at infinity, 60 cm and 40 cm and the through-focus MTF curves were compared when the two IOLs were centered at apertures of 3.0 mm and 4.5 mm. Spectral transmittance of the two IOLs was measured by the UV–visible spectrophotometer (UV 3300 PC; MAPADA, China).

Results The SN60WF and the PanOptix filtered blue light from 400 to 500 nm. Both IOLs at the far focus and the PanOptix at the intermediate focus showed a decrease in optical quality with increasing decentration and tilt. The PanOptix demonstrated enhanced optical quality compared to the previous gradient at the near focus at a decentration range of 0.3–0.7 mm with a 3.0 mm aperture, and 0.5 mm with a 4.5 mm aperture, whereas other conditions exhibited diminished optical quality with increasing decentration and tilt at the focus of both IOLs. When the two IOLs were centered, the SN60WF had better optical quality at infinity, while the PanOptix had better optical quality at 60 cm and 40 cm defocus. The optical quality of the SN60WF exceeded that of the PanOptix at far focus, with a 3 mm aperture decentration up to 0.7 mm and a 4.5 mm aperture decentration up to 0.3 mm; this observation held true for all tilts, irrespective of aperture size. As both decentration and tilt increased, the optical quality of the SN60WF deteriorated more rapidly than that of the PanOptix at the far focal point.

Conclusions The SN60WF showed a decrease in optical quality with increasing decentration and tilt. Optical quality of the PanOptix at the near focus increased in some decentration conditions and decreased in some conditions, while it showed a decrease at the other focuses with increasing decentration. While tilt only had a negative effect on optical quality. When both IOLs were centered, the PanOptix provided a wider range of vision, while the SN60WF provided better far distance vision. At the far focus, the SN60WF has better resistance to tilt than the PanOptix, but the optical quality degrades more quickly when decentered and tilted.

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Key messages

What is known:

- The monofocal IOLs exhibit superior optical quality when centered at small apertures

What is new:

- The optical quality of the PanOptix lens demonstrated an increase in near focus under certain decentration conditions, while a decrease was observed under other conditions. Conversely, increasing decentration resulted in a decrease in optical quality at the remaining focal points. Additionally, it should be noted that tilt had a consistently negative impact on optical quality.
- The optical quality of the SN60WF deteriorated more rapidly than that of the PanOptix at far focus as decentration and tilt increased; however, under the same positional conditions, the SN60WF likely exhibits superior optical quality compared to the PanOptix.

Keywords Intraocular lens · In vitro test · Optical quality · Decentration · Tilt

Introduction

Intraocular lenses (IOLs) of different focal designs cater to varying ranges of vision. Monofocal IOLs offer exceptional distance vision but require the use of glasses for near and intermediate visual tasks. Trifocal IOLs offer visual acuity at distance, intermediate, and near distances, catering to activities such as reading, writing, computer work, and driving. They also reduce dependence on near glasses and improve quality of life [1, 2]. There are several available trifocal IOLs, including PanOptix, which is a four-focus design with an intermediate focus set at 60 cm. The AT Lisa Tri 839 is another trifocal IOL with an intermediate focus of 80 cm. Both IOLs effectively address the requirements for intermediate distance vision; however, the former's design aligns better with the reading habits observed in Asian populations. IOLs with various focus designs have varying optical performances that result in distinct clinical outcomes after implantation. Trifocal IOLs distribute light energy differently than monofocal IOLs which can lead to reduced contrast sensitivity and adverse visual symptoms like halos, glare, and starburst sensation at night [3, 4]. Furthermore, the optical performance of the IOLs may be influenced by factors such as the magnitude of spherical aberration and the additional refractive power associated with trifocal IOLs [5, 6]. Previous in vitro studies have predominantly focused on comparing the optical quality of IOLs with different focus designs when IOLs were centered, while there is a paucity of research investigating the performance of decentered and tilted IOLs. In order to further investigate and compare the optical performance of IOLs with diverse focus designs, we conducted this study.

Decentration and tilt of IOLs frequently occur following cataract surgery. In vitro studies have demonstrated that these factors can result in increased wavefront aberrations, including coma, trefoil, and astigmatism, leading to a certain degree of defocusing that impacts visual quality [5, 7]. A study conducted by Lawu et al. [5] revealed that the presence of decentration and tilt in IOLs leads to an increase in wavefront aberrations, including coma and astigmatism. Furthermore, it was found that the design of IOLs with regards to spherical aberration plays a critical role in determining the magnitude of these wavefront aberrations. Previous in vitro optical studies have contributed to clinicians' understanding of the optical performance of IOLs; however, they possess certain limitations. For instance, most previous in vitro studies were conducted at ambient temperature and utilized model corneas with 0 or + 0.20 µm spherical aberration, which differ from those present in the human ocular environment [2, 8]. Consequently, these differences may lead to disparities between study outcomes and clinical results. This study improves these measurement conditions.

In clinical studies, disentangling the potential impact of various factors on actual vision outcomes, such as the influence of the retina and intraocular refractive media, poses a significant challenge. Currently, there exist various instruments for measuring the values of IOL decentration and tilt in clinical practice, such as the IOL Master 700 (Zeiss, Germany) and CASIA 2 (Tomey, Japan), the Scheimpflug analysis system Pentacam (Oculus, Germany), ultrasound biomicroscopy (UBM), among others [9, 10]. However, there are certain limitations associated with the measurements of these instruments, such as the lack of precision in patients with smaller pupil diameters. Furthermore, variations in reference axes chosen by different devices for measuring decentration and tilt may result in discrepancies in measurement outcomes. Additionally, in vivo studies lack control over the degree of decentration and tilt of the IOL, making it challenging to include patients with significant levels of these variables in clinical settings. In vitro studies utilizing an optical quality testing device not only minimize independent and unknown variables but also enable precise control over the degree of decentration and tilt of the IOL. As in previous in vivo studies investigating the impact of IOL decentration on post-surgical visual quality, controlling the degree of IOL decentration remains challenging, and variations in pupil diameters among collected patients further complicate the analysis of this single factor's effect on visual quality. In contrast, in vitro studies offer an opportunity to isolate factors such as pupil diameter and degree of dcentration, enabling a separate exploration of each factor's influence on the optical quality of the IOL with more objective findings. Therefore, this study aimed to evaluate the optical quality of both monofocal IOL SN60WF and trifocal IOL PanOptix using advanced in vitro testing equipment under conditions simulating decentered and tilted positions. The findings will provide valuable insights for clinicians regarding the optical performance of different IOLs and aid rational selection.

Methods

Intraocular lenses

The present study involved the analysis of two IOLs with identical distance power (+20.00 D) and material composition. The two IOLs examined in this study were the AcrySof IQ SN60WF aspheric monofocal IOL (Alcon, USA) and the AcrySof IQ PanOptix aspheric trifocal IOL (Alcon, USA). Table 1 provides a summary of the characteristics of these two IOLs analyzed in the study.

Equipment

The optical quality of the two IOLs was assessed using the OptiSpheric IOL R&D optical bench (Trioptics, Germany), which complied with ISO standard 11979-2 requirements [11]. The device comprises a lighting system, which consists of a multicolor light source and a spectral filter. It also includes a test target that incorporates a cross slit and a USAF resolution test chart. Additionally, there is a collimator, an aperture to simulate the pupil, as well as a model cornea and wet room for placing the IOL under examination. Furthermore, it encompasses both a microscope and a CCD camera. Figure 1 shows the schematic layout of the optical device.

Measuring parameters

The optical quality of each IOL was quantitatively and qualitatively assessed using the modulating transfer function (MTF) and the USAF resolution test chart in this study. Key parameters for the former include the MTF values at spatial frequencies of 50 lp/mm, the MTF curves, and the through-focus MTF. MTF is a widely accepted quantitative parameter used to evaluate optical system performance by reflecting contrast throughout the system for a certain spatial frequency, thereby indicating the impact of optical factors on imaging quality. A higher MTF value corresponds to the superior image quality of the optical system [12–17]. The MTF curve represents the contrast variation across the entire image, and the MTF value at spatial frequencies of 50 lp/mm corresponds to a Snellen visual acuity of 20/40 [16]. The USAF resolution test chart consists of horizontal and vertical lines and numbers of varying sizes, providing a direct reflection of the optical imaging system's resolution capability across spatial frequencies. It is extensively employed for qualitative assessment of the optical performance exhibited by optical systems [12, 18]. The through-focus MTF provides a quantitative assessment of the optical performance of IOLs across various defocus distances and specific spatial frequencies.

Optical quality measurement

The optical quality of monofocal IOL AcrySof IQ SN60WF (Alcon, USA) and trifocal IOL AcrySof IQ PanOptix

Table 1 The characteristics of the analyzed IOLs

	SN60WF	PanOptix
Design	One-piece double loop, monofocal	One-piece double loop, trifocal
Material	Hydrophobic acrylate	Hydrophobic acrylate
Color	Yellow	Yellow
Morphology of loops	L-shaped loop	L-shaped loop
Spherical aberration (μm)	−0.20	−0.10
Total diameter (mm)	13	13
Optic diameter (mm)	6	6
Dioptric power (D)	+ 20.00 D	+ 20.00 D
Near/Intermediate addition (D)	–	+ 2.17 D / + 3.25 D

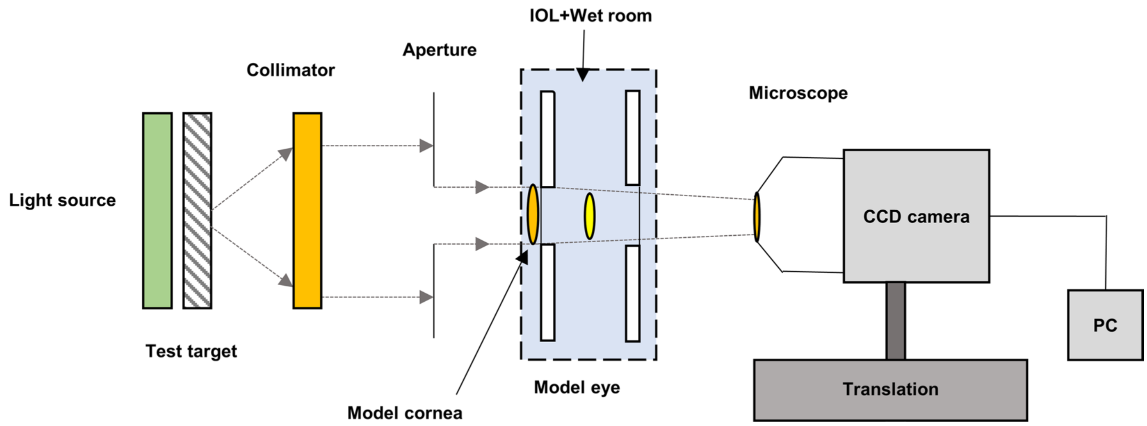


Fig. 1 A schematic layout of the OptiSpheric IOL R&D

(Alcon, USA), both with a power of + 20 D, was assessed for different degrees of decentration and tilt using the OptiSpheric IOL R&D optical bench (Trioptics, Germany). The data were measured and processed in accordance with the methodologies employed in previous studies [19–22]. A model cornea with a spherical aberration of + 0.28 μm was utilized for all measurements in this study. Light source wavelength was set at 546 nm. The IOLs were positioned on an IOL holder within the wet chamber of the model eye, which was filled with saline having a refractive index of 1.336 at 25 ℃. Initially, the MTF values at spatial frequencies of 50 lp/mm, MTF curves, and USAF resolution test charts at the focus were measured for each IOL when the IOLs were centered, decentered (of 0.3 mm, 0.5 mm, 0.7 mm, 0.9 mm, and 1.1 mm), and tilted (of 3°, 5°, 7°, 9°, and 11°), with apertures set at both 3.0 and 4.5 mm.

Additionally, the MTF at special frequencies of 50 lp/mm at infinity, 60 cm, and 40 cm was measured when the two IOLs were centered at two apertures. Finally, through-focus MTF was evaluated for both IOLs when they were centered. All measurements were performed in triplicate, with the center of the IOL adjusted to align with the optical axis center of the optical bench before each subsequent measurement. Moreover, with the exception of through-focus MTF values that represent a single measurement point, all other MTF values and curves discussed in this paper were obtained by averaging three tangential MTFs and three sagittal MTFs. In addition, spectral transmittance of the two IOLs was measured by the UV 3300 PC UV–visible spectrophotometer (MAPADA, China).

Data processing and analysis methods

The spectral transmittance data of each IOL was imported into GraphPad Prism and the corresponding spectral transmittance images were plotted. The MTF values at spatial frequencies of 50 lp/mm and 0–150 lp/mm spatial frequency at the focal point of each IOL at decentration and tilt were imported into Microsoft Office Excel (Microsoft, USA) software. The mean MTF values were calculated by averaging the tangential MTF values and sagittal MTF values separately. Then, the calculated averages of the two parameters were imported into GraphPad Prism, and line plots and bar charts of the MTF values at spatial frequencies of 50 lp/mm spatial frequency were plotted, as well as MTF curves graphs. In addition, the data of through-focus MTF curves for each IOL was imported into GraphPad Prism to plot the through-focus MTF curves. Finally, a combination of spectral transmittance images, line plots and bar charts of the MTF values at spatial frequencies of 50 lp/mm for different comparison conditions, MTF curve graphs and USAF resolution test graphs, as well as through-focus MTF curves are further plotted in PowerPoint.

Results

The spectral transmittance

According to Fig. 2, the spectral transmittance images of SN60WF and PanOptix exhibit a remarkable overlap, demonstrating comparable spectral filtering characteristics within the wavelength range of 400–500 nm.

MTF values at spatial frequencies of 50 lp/mm

Figures 3 and 4 illustrate MTF values at spatial frequencies of 50 lp/mm for the SN60WF and the PanOptix at two apertures (3.0 and 4.5 mm) when the two IOLs were decentered and tilted. The MTF values at spatial frequencies of 50 lp/mm at the far focus of both the SN60WF and the PanOptix demonstrated a decline with increasing decentration and tilt

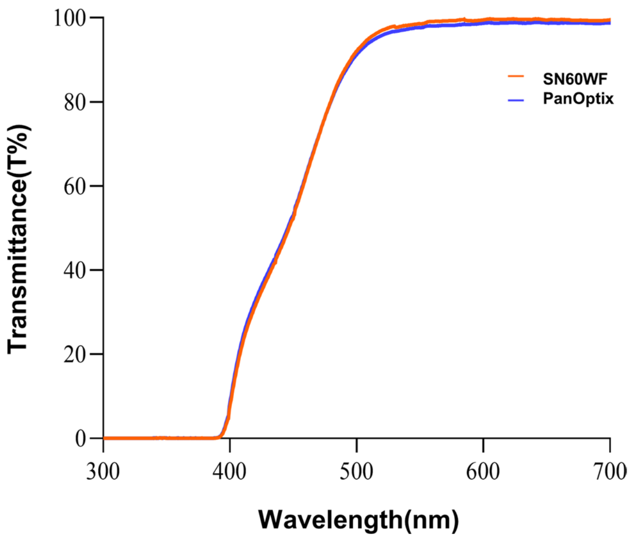


Fig. 2 The spectral transmittance images of the SN60WF and the PanOptix

at both apertures. The MTF values at spatial frequencies of 50 lp/mm exhibited an increase in the intermediate focus of the PanOptix under specific conditions, including 0.9 mm decentration with a 3.0 mm aperture, and also at decentrations of 0.5 mm and 1.1 mm and a tilt of 9° with a 4.5 mm aperture. Additionally, at the near focus, similar improvements were observed except for a decentration of 0.9 mm and tilts of both 7° and 11° with a 3.0 mm aperture; furthermore, enhancements were noted for decentrations of both 0.5 mm and 0.7 mm and a tilt of 9° with a 4.5 mm aperture. For other conditions, an increase in decentration and tilt at the intermediate and near focus resulted in a decrease in MTF values at spatial frequencies of 50 lp/mm. Notably, the disparity between tangential and sagittal MTF values amplified with decentration and tilt. Hence, it is important to note that even if average values increased under certain circumstances, this did not necessarily indicate superior optical quality. Furthermore, the MTF values of 50 lp/mm do not fully capture the complete contrast variation in the image. Hence, it is imperative to analyze them in conjunction with both the original data and the corresponding MTF curves. The MTF values at spatial frequencies 50 lp/mm for both IOLs exhibited higher levels when measured with a smaller aperture compared to a larger aperture, maintaining the same positional conditions. The tolerance to decentration and tilt was superior for both IOLs with a 3.0 mm aperture compared to a 4.5 mm aperture. The optical quality of the SN60WF was superior to that of the PanOptix at far focus, with a maximum decentration of 0.7 mm at an aperture of 3.0 mm and 0.5 mm at an aperture of 4.5 mm, regardless of tilt magnitude. The MTF values at spatial frequencies of 50 lp/mm for the SN60WF decreased more rapidly with increasing decentration compared to those of the PanOptix at the far focus. Furthermore, when decentered and tilted, the negative impact on PanOptix was more pronounced at the far focus than at the intermediate and near focus.

Figure 5 shows that the MTF values at spatial frequencies of 50 lp/mm are highest at the far focus, followed by the intermediate focus, and lowest at the near focus when the PanOptix is centered. Furthermore, when both IOLs are centered, the SN60WF exhibits significantly higher MTF values at spatial frequencies of 50 lp/mm than the PanOptix at infinity, and this trend reverses at 60 cm and 40 cm defocus. These findings highlight that while the SN60WF offers

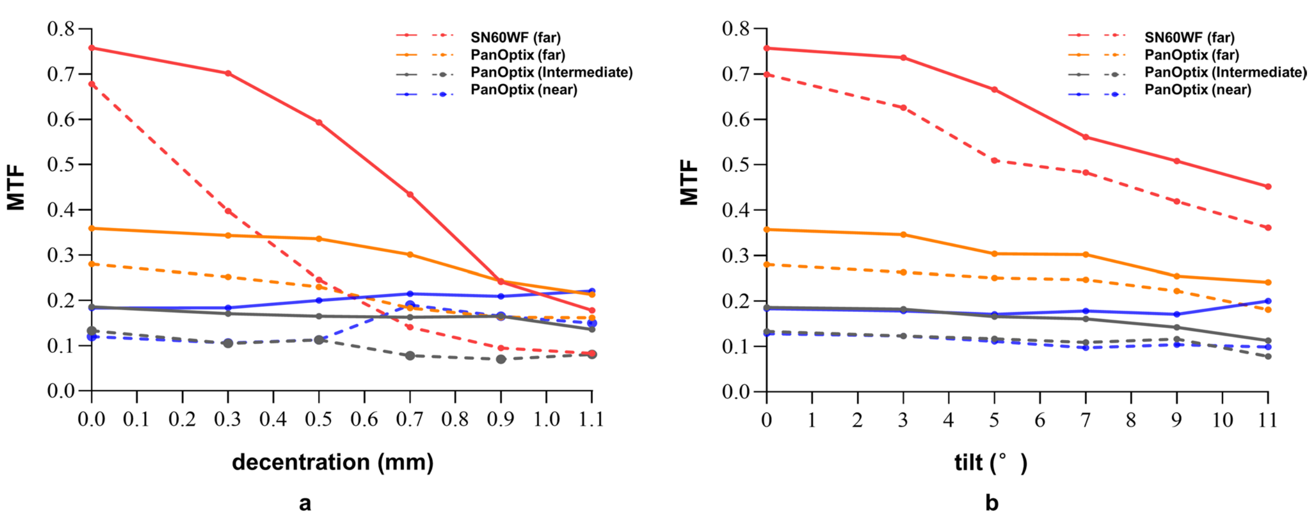


Fig. 3 Line Plot of MTF values at spatial frequencies of 50 lp/mm for the SN60WF and the PanOptix at two apertures (3.0 and 4.5 mm) when the two IOLs were decentered (**a**) and tilted (**b**). Solid lines represent the measured data with a 3.0 mm aperture and dashed lines represent the measured data with a 4.5 mm aperture

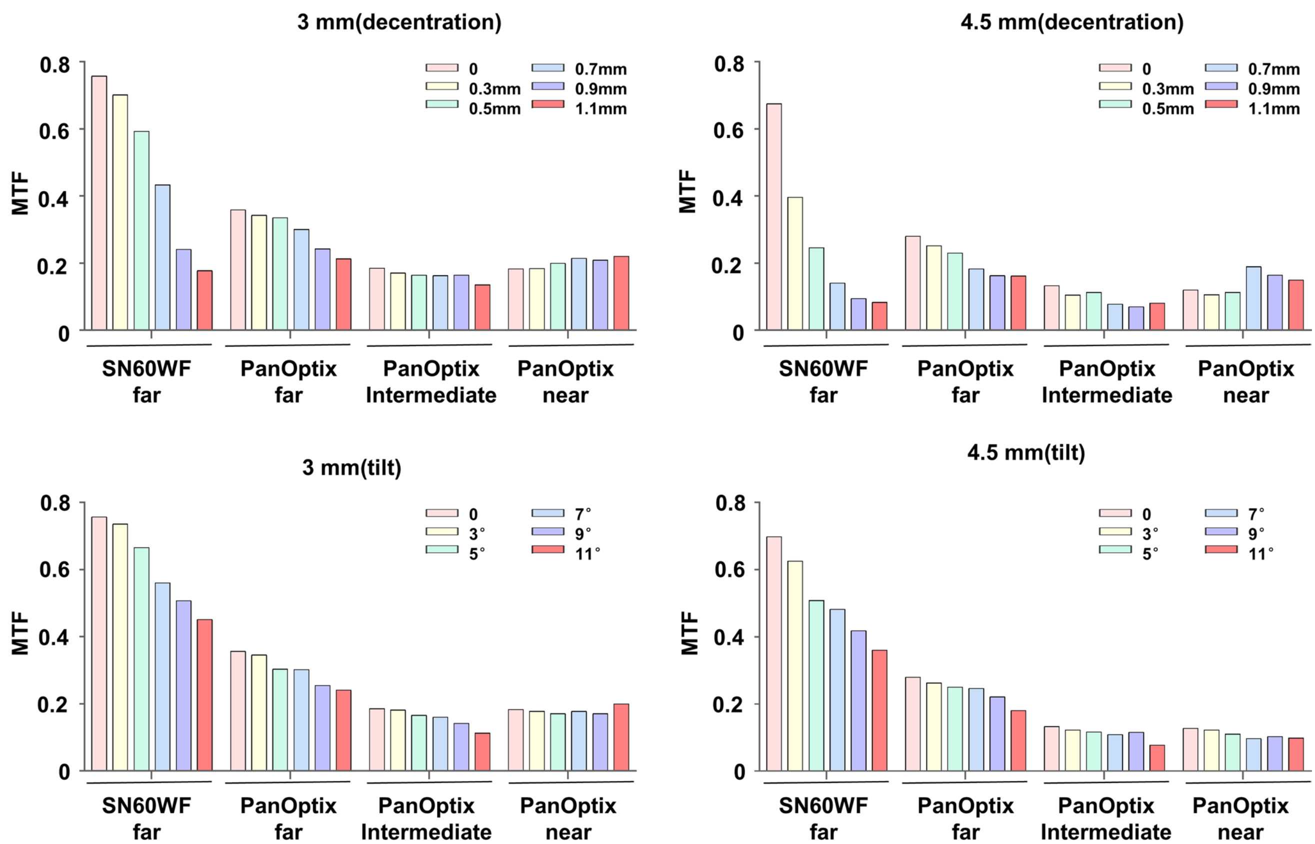


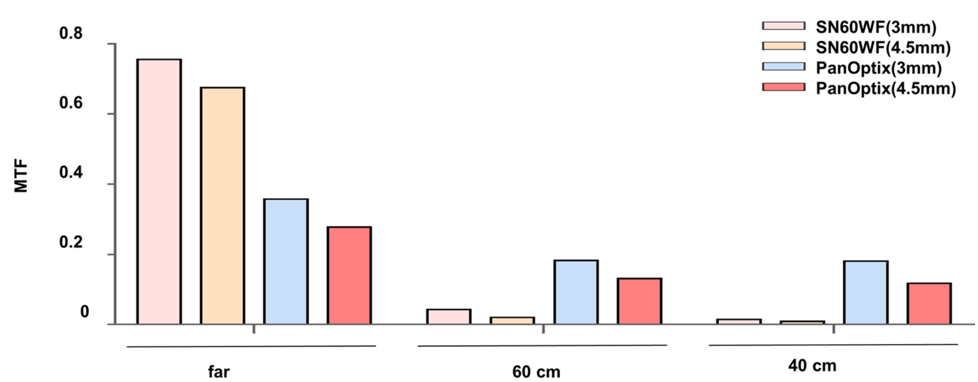
Fig. 4 Bar chart of MTF values at spatial frequencies of 50 lp/mm for the SN60WF and the PanOptix at two apertures (3.0 and 4.5 mm) when the two IOLs were decentered and tilted

superior distance vision, the PanOptix excels in providing better intermediate and near vision.

MTF curves

Figure 6 illustrates MTF curves for the SN60WF and the PanOptix at two apertures (3.0 and 4.5 mm) when the two IOLs were decentered and tilted. The results of the MTF curves were largely consistent with those obtained from the MTF values at spatial frequencies 50 lp/mm. In contrast, the MTF curves demonstrate a consistent increase compared to the previous gradient specifically for the PanOptix at near focus with a decentration range of 0.3–0.7 mm using a 3.0 mm aperture, and at a decentration of 0.5 mm and 0.7 mm when employing aperture size of 4.5 mm. When combined with the original data, it was observed that the disparity between the tangential and sagittal MTF curves at the near focus of PanOptix, with a decentration of 0.7 mm and a 4.5 mm aperture, exhibited a significant increase compared to the previous gradient.

Fig. 5 MTF values at spatial frequencies of 50 lp/mm at infinity, 60 cm and 40 cm when the SN60WF and the PanOptix were centered at apertures of 3.0 and 4.5 mm



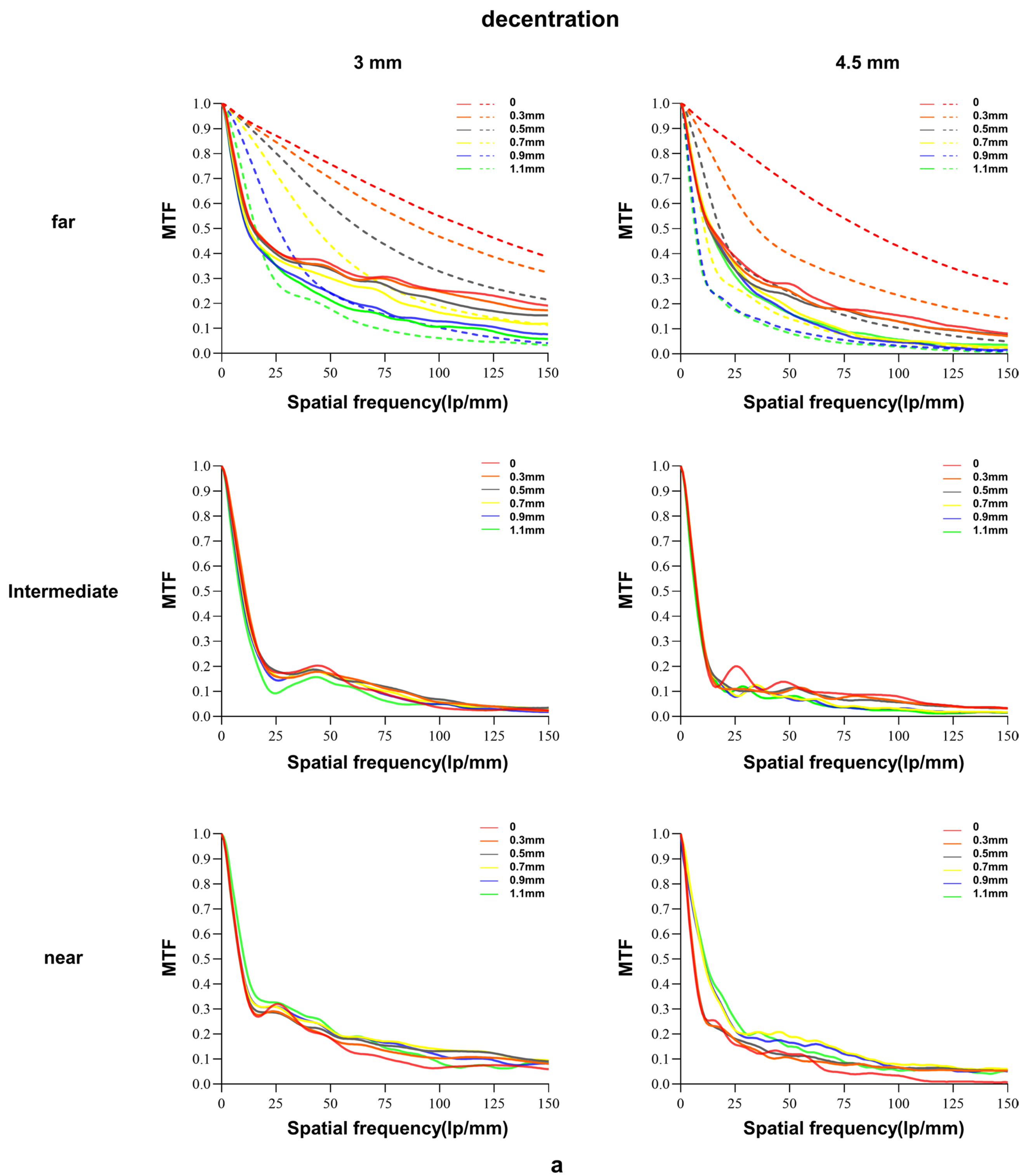


Fig. 6 MTF curves for the SN60WF and the PanOptix at two apertures (3.0 and 4.5 mm) when the two IOLs were decentered (**a**) and tilted (**b**). Solid lines represent data of the PanOptix and dashed lines represent data of the SN60WF

Hence, the optical quality did not necessarily increase in this condition and needs to be analyzed by combining the USAF resolution test charts. Furthermore, when both decentered by 0.50 mm with a 4.5 mm aperture, the MTF curves at the far focus of SN60WF were found to be lower than those of PanOptix.

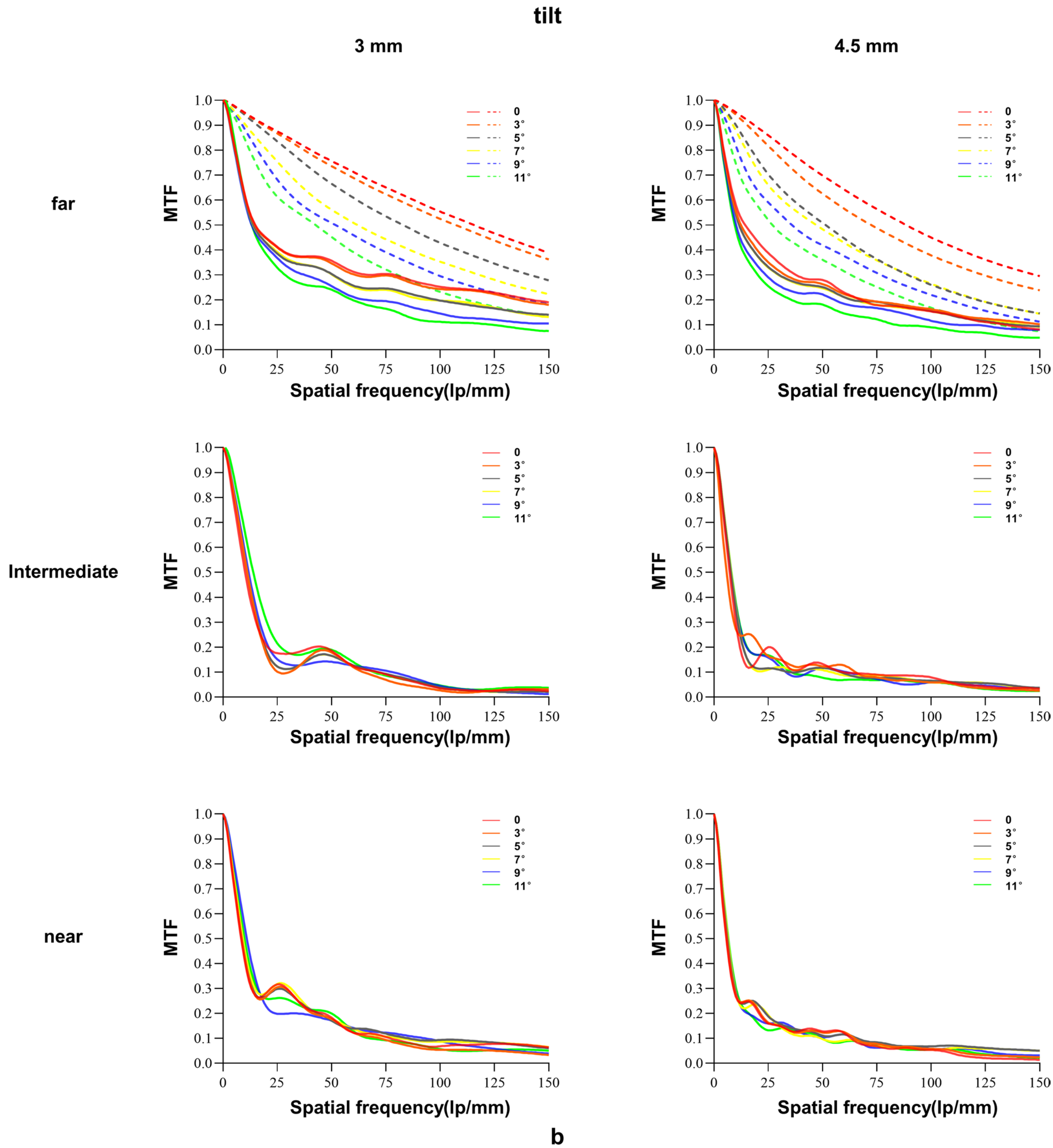


Fig. 6 (continued)

Through-focus MTF curves

Figure 7 demonstrates that PanOptix exhibits significant MTF peaks at far, intermediate, and near distances, whereas SN60WF only displays such peaks at far distances. In addition, the MTF peak of the SN60WF is higher than that of the PanOptix at far distances, while the MTF peak of the PanOptix is higher than that of the SN60WF at intermediate and near distances. It can be seen that the PanOptix provides a wider range of vision than the SN60WF, but the optical quality is better with the SN60WF at the far focus. Furthermore, both IOLs exhibit

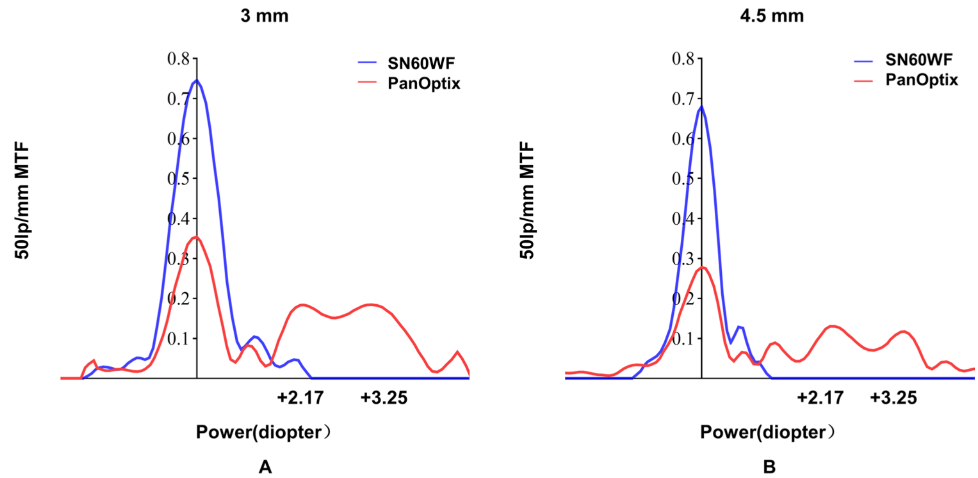


Fig. 7 The through-focus MTF curves at spatial frequencies of 50 lp/mm for the SN60WF and the PanOptix when the two IOLs were centered at 3.0 (**a**) and 4.5 mm (**b**) apertures

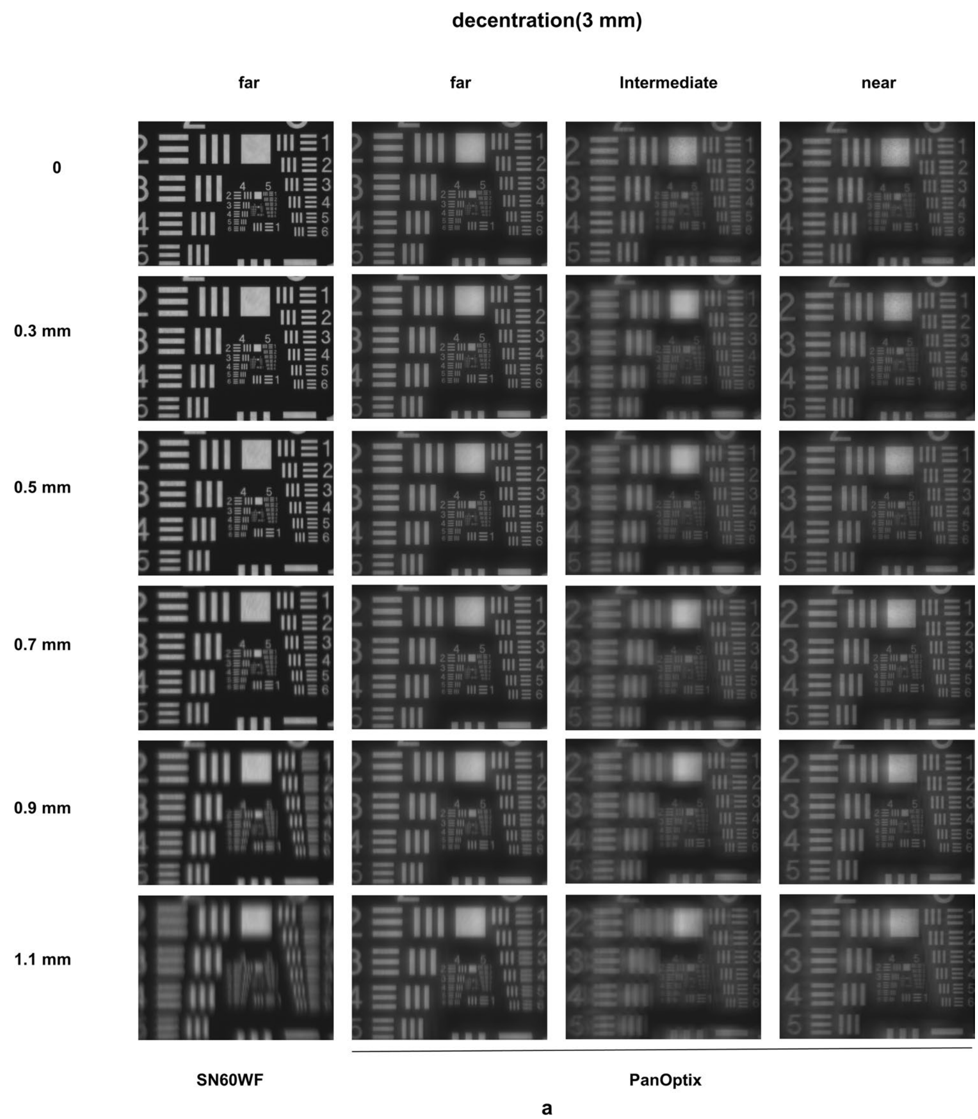
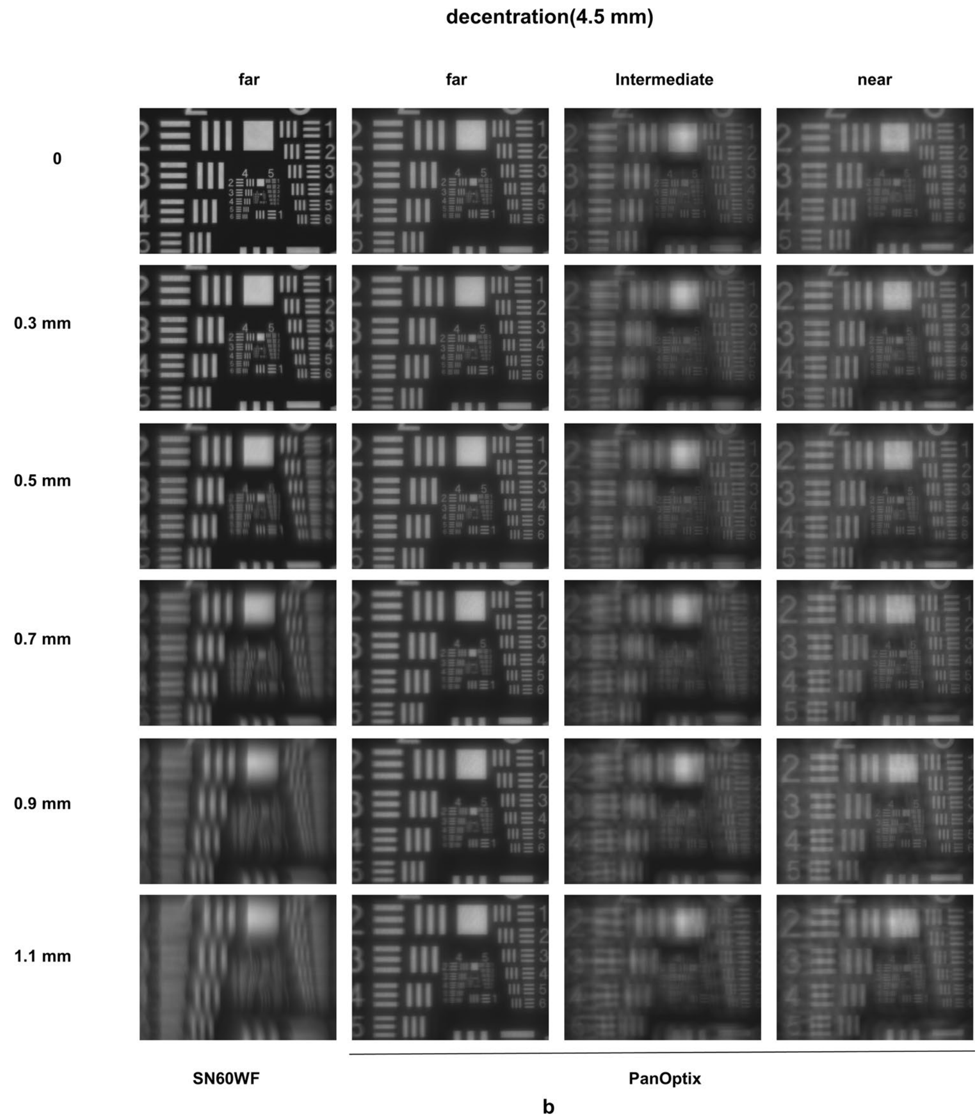


Fig. 8 USAF resolution test charts for the SN60WF and the PanOptix: **a** The two IOLs at 3.0 mm aperture when decentered. **b** The two IOLs at 4.5 mm aperture when decentered. **c** The two IOLs at 3.0 mm aperture when tilted. **d** The two IOLs at 4.5 mm aperture when tilted

Fig. 8 (continued)



higher MTF values at the focus with a 3.0 mm aperture than with a 4.5 mm aperture.

USAF resolution test charts

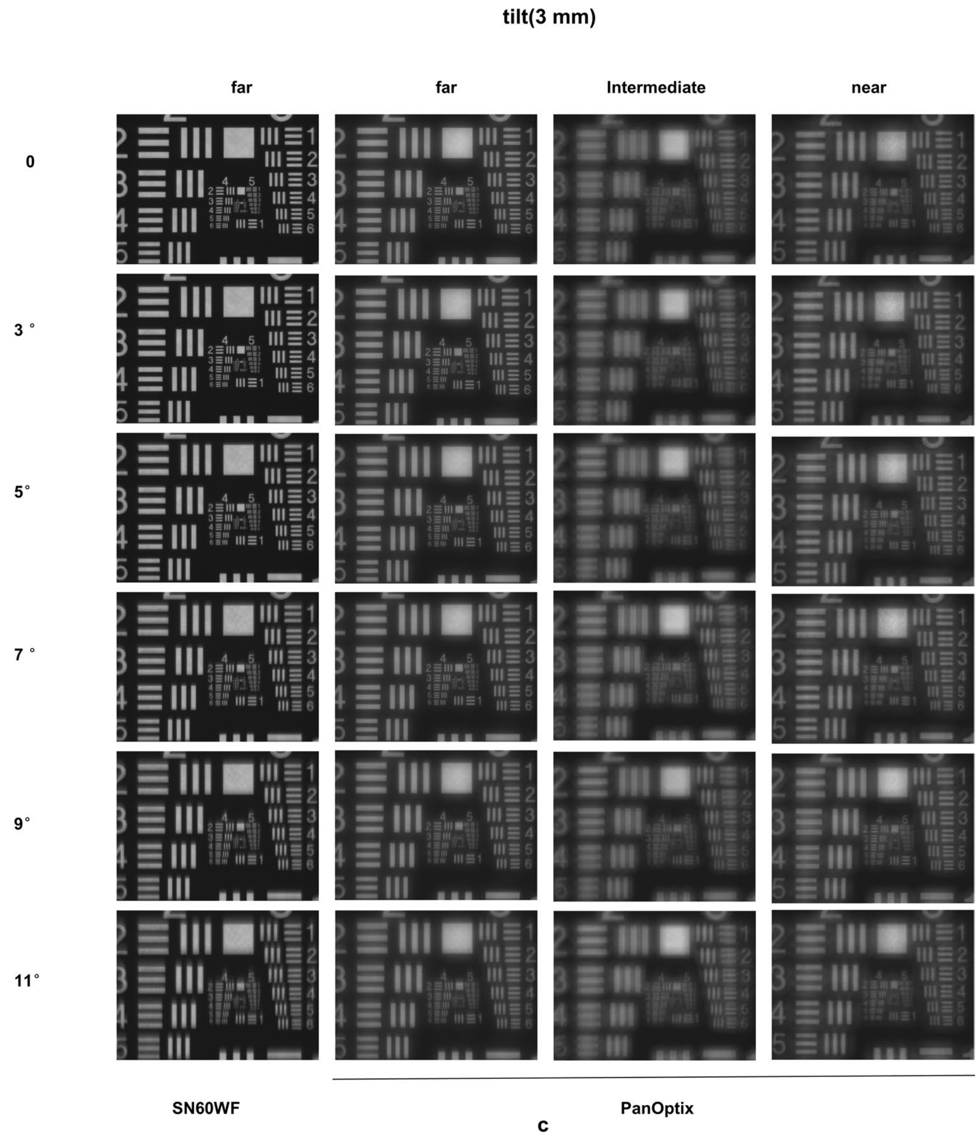
Figure 8 shows the USAF resolution test charts are consistent with those of the MTF curves, except for a degradation in image quality observed at the near focus of PanOptix with a decentration of 0.5 mm at an aperture of 4.5 mm, compared to the previous gradient.

Discussion

The SN60WF and the PanOptix both exhibit significant blue light attenuation within the 400 to 500 nm wavelength range. This effective filtration of blue light is achieved through the use of yellow chromophores which confer a protective effect on retinal photoreceptor cells and pigment cells [23, 24].

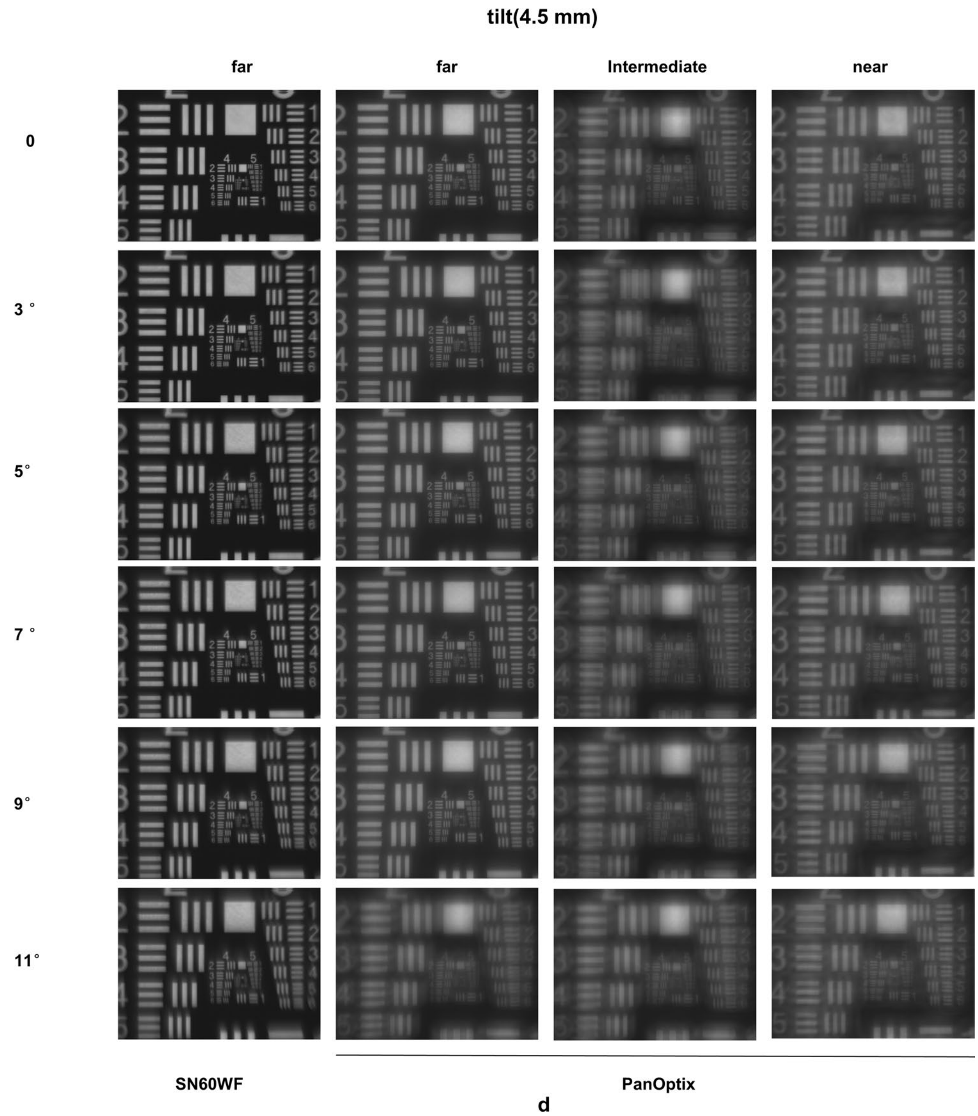
The IOLs implanted after cataract surgery commonly exhibit a decentration of up to 0.2–0.3 mm and a tilt of 2-3º, while approximately 10% of patients experience a greater than 0.5 mm decentration and a tilt exceeding 5º [7, 25]. It is evident that the prevalence of decentration and tilt in IOLs is substantial in clinical practice, necessitating a comprehensive investigation into their impact on visual quality. Currently, there is a lack of existing in vitro optical studies investigating the optical quality of PanOptix IOLs across a wide range of decentered and tilted positions, as well as comparative studies between the optical quality of SN60WF and PanOptix IOLs under similar conditions. Therefore, this study was designed to address these gaps. Previous in vitro studies have demonstrated that aspheric IOLs exhibit greater susceptibility to decentration and tilt compared to spherical IOLs, particularly when high levels of negative spherical

Fig. 8 (continued)



aberration are present, thereby impacting their optical quality [26]. Several in vivo studies have found a correlation between decentration and tilt between crystalline lens and IOL [27–29]. Therefore, preoperative measurement of crystalline lens decentration and tilt can aid in predicting the postoperative decentration and tilt of IOLs. This study evaluates the optical quality of SN60WF and PanOptix at varying degrees of decentration and tilt, providing physicians with a valuable reference for selecting IOLs in clinical practice. Through comprehensive analysis of the indicators in these results, we have derived the following conclusions. The optical quality at the focus of both IOLs exhibited a decrease with increasing decentration and tilt under all conditions, except for an increase in optical quality observed at the near focus of PanOptix at 3.0 mm aperture with decentration ranging from 0.3 to 0.7 mm, as well as at 4.5 mm aperture with a decentration of 0.5 mm. The enhancement in optical quality may be attributed to the augmented optical energy at the proximity of the near focus. Perez-Gracia et al. [26] performed numerical simulations and experimental measurements of IOLs with spherical and aspheric designs using the optical design software OSLO and the PMTF optical bench, respectively, and showed only a decrease in the optical quality of the monofocal IOL with negative spherical aberration design when it was decentered and tilted. By evaluating the optical quality of the rotationally asymmetric multifocal IOL SBL-3 (Lenstec, USA) when it was decentered, Liu et al. [8] demonstrated that the effect of decentration on the optical quality of the IOL is two-sided, with tilt having only a negative effect. The above studies are consistent with the findings of this study. Ortiz et al. [30] analyzed the effect of decentration on the optical quality of the trifocal IOL AT LISA tri 839MP (Carl Zeiss Meditec, Germany). Their findings revealed a decrease in optical quality with increasing

Fig. 8 (continued)



decentration, which is not exactly the same as the pattern when the trifocal IOL is decentered in our study. This discrepancy may be attributed to variances in the optical design between these two types of IOLs. Furthermore, this study revealed that decentration exerts a more pronounced impact on the optical quality of IOLs compared to tilt, aligning with previous research findings [9, 26, 31].

Our findings demonstrated consistent superior optical quality of the two IOLs at a smaller aperture compared to a larger aperture under identical positional conditions. Furthermore, SN60WF exhibited a slower decline in optical quality when decentered and tilted at a smaller aperture, as opposed to a larger aperture. The PanOptix followed the same pattern as the SN60WF for each focus when decentered, and for intermediate and near focus when tilted; however, it displayed an opposite trend for far focus when tilted. The in vitro study by Tandogan et al. [21] demonstrated that the optical quality of monofocal IOLs is superior at a 3.0 mm aperture compared to a 4.5 mm aperture when the IOLs were centered, as evaluated through the assessment of various spherical and aspherical monofocal IOLs at various aperture diameters, which aligns with our findings. Another in vitro study conducted by the same team demonstrated that the trifocal IOL AT LISA 839 M (Zeiss, Germany) exhibited superior optical quality and enhanced resistance to decentration at both far and intermediate focus when evaluated with a 3.0 mm aperture compared to a 4.5 mm aperture, which aligns with our findings. However, their study revealed a superior resistance to decentration at the near focus with a 4.5 mm aperture, potentially attributed to variances in optical design between AT LISA 839 M and PanOptix [32]. Compared to the small apertures, PanOptix exhibited lower MTF values at each focus when centered at the large aperture, and even further reduction when decentered and tilted, particularly at the intermediate focus. Therefore, meticulous patient selection is crucial for individuals with a larger pupil diameter and heightened expectations of intermediate vision. The optical quality of the SN60WF surpassed that of the PanOptix at far focus, regardless of aperture size or tilt as long as the decentration remained within 0.7 mm at a 3.0 mm aperture and 0.3 mm at a 4.5 mm aperture. With increasing decentration and tilt, the optical quality of the SN60WF decreases more rapidly than the PanOptix at the far focal point, potentially attributed to its higher negative spherical aberration. The previous study demonstrated that IOLs exhibiting a high degree of negative spherical aberration experienced a more rapid deterioration in optical quality when subjected to decentration [26]. When the PanOptix was centered, optical quality at the far focus surpassed that at the intermediate and near focus, with a more pronounced decline observed in optical performance at the far focus when PanOptix was decentered and tilted. These findings align consistently with previous research on decentered multifocal IOLs [32]. Additionally, our study demonstrated that the monofocal IOL exhibited superior distance vision when both IOLs were centered, trifocal IOL offered a broader range of vision, consistent with previous findings and in accordance with the optical characteristics of these two types of IOLs [32].

This study provides valuable insights into the optical performance of the SN60WF and the PanOptix, facilitating precision medicine. However, it is important to note that this study only evaluates IOLs with a refractive distance power of + 20.00 D, limiting its generalizability to IOLs with significantly higher or lower refractive distance power. Moreover, the model eye utilized in this study incorporated a model cornea with + 0.28 μm spherical aberration, which may not accurately represent higher-order aberrations observed in all patients. Additionally, it is important to acknowledge that in vitro optical bench testing cannot account for factors such as neuroadaptation, discrepancies between optical media in vivo and in vitro, and variations between parameters of the model eye and those of the human eye; these differences could potentially impact the outcomes of both in vitro and in vivo investigations [32, 33]. Despite the aforementioned limitations, in vitro and in vivo studies consistently yield similar. Future research can improve generalizability of experimental results by setting refractive power gradients.

In summary, The SN60WF and the PanOptix have the same spectral transmittance. The optical quality of different IOLs was influenced differently by decentration and tilt. Specifically, for the SN60WF IOL, decentration and tilt resulted in a decrease in optical quality. On the other hand, for the PanOptix IOL, decentration could lead to either an increase or a decrease in optical quality at the near focus, while all other focuses showed a decrease in optical quality. Tilt only caused a decrease in optical quality for both IOLs. Notably, both IOLs exhibited better optical quality when focused through a small aperture. The PanOptix exhibited optimal optical quality at the far focus when centered, and the most negative impact on optical quality at this focus when it was decentered and tilted. The optical quality of the SN60WF was better than that of the PanOptix at the far focus when the decentration of no more than 0.7 mm at a 3.0 mm aperture and 0.3 mm at a 4.5 mm aperture, and this finding was true for all tilt degrees regardless of aperture size. Moreover, when both IOLs were centered, the PanOptix provided a wider range of vision whereas the SN60WF offered better distance vision. Furthermore, at the far focus, the SN60WF demonstrates better resistance to tilt than the PanOptix; nevertheless, its optical quality degrades faster than that of the PanOptix when subjected to decentering and tilting.

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Declarations

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Conflict of interest The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

References

1. Alio JL, Plaza-Puche AB, Fernandez-Buenaga R, Pikkel J, Maldonado M (2017) Multifocal intraocular lenses: an overview. Surv Ophthalmol 62:611–634. https://doi.org/10.1016/j.survophthal.2017.03.005
2. Shen Z, Lin Y, Zhu Y, Liu X, Yan J, Yao K (2017) Clinical comparison of patient outcomes following implantation of trifocal or bifocal intraocular lenses: a systematic review and meta-analysis. Sci Rep 7:45337. https://doi.org/10.1038/srep45337
3. Li ZH, Xu WQ, Ye Z (2021) The importance of neuroadaptation after multifocal intraocular lens implantation. Zhonghua Yan Ke Za Zhi 57:6–10. https://doi.org/10.3760/cma.j.cn112142-20201015-00685
4. Sachdev G, Sachdev M (2017) Optimizing outcomes with multifocal intraocular lenses. Indian J Ophthalmol 65:1294. https://doi.org/10.4103/ijo.IJO_1072_17
5. Lawu T, Mukai K, Matsushima H, Senoo T (2019) Effects of decentration and tilt on the optical performance of 6 aspheric intraocular lens designs in a model eye. J Cataract Refract Surg 45:662–668. https://doi.org/10.1016/j.jcrs.2018.10.049
6. Carson D, Xu Z, Alexander E, Choi M, Zhao Z, Hong X (2016) Optical bench performance of 3 trifocal intraocular lenses. J Cataract Refract Surg 42:1361–1367. https://doi.org/10.1016/j.jcrs.2016.06.036
7. Chen XY, Wang YC, Zhao TY, Wang ZZ, Wang W (2022) Tilt and decentration with various intraocular lenses: a narrative review. World J Clin Cases 10:3639–3646. https://doi.org/10.12998/wjcc.v10.i12.3639
8. Liu XM, Xie LX, Huang YS (2019) Effects of decentration and tilt at different orientations on the optical performance of

a rotationally asymmetric multifocal intraocular lens. J Cataract Refract Surg 45:507–514. https://doi.org/10.1016/j.jcrs.2018.10.045
9. Ashena Z, Maqsood S, Ahmed SN, Nanavaty MA (2020) Effect of intraocular lens tilt and decentration on visual acuity, dysphotopsia and wavefront aberrations. Vision 4:41. https://doi.org/10.3390/vision4030041
10. de Castro A, Rosales P, Marcos S (2007) Tilt and decentration of intraocular lenses in vivo from Purkinje and Scheimpflug imaging. J Cataract Refract Surg 33:418–429. https://doi.org/10.1016/j.jcrs.2006.10.054
11. International Organization for Standardization (2014) Part 2: optical propierties and test methods. In: ISO 11979: Ophthalmic impants – Intraocular lenses – Geneva, Switzerland, pp 1–30
12. Borkenstein AF, Borkenstein E, Luedtke H, Schmid R (2021) Optical bench analysis of 2 depth of focus intraocular lenses. Biome Hub 6:77–85. https://doi.org/10.1159/000519139
13. Lang A, Portney V (1993) Interpreting multifocal intraocular lens modulation transfer functions. J Cataract Refract Surg 19:505–512. https://doi.org/10.1016/s0886-3350(13)80615-3
14. Mayer C, Son H, Łabuz G, Yildirim TM, Auffarth GU, Khoramnia R (2020) In vitro optical quality assessment of a monofocal IOL sutured to an artificial iris. J Cataract Refract Surg 46:1184–1188. https://doi.org/10.1097/j.jcrs.0000000000000287
15. Son HS, Labuz G, Khoramnia R, Merz P, Yildirim TM, Auffarth GU (2020) Ray propagation imaging and optical quality evaluation of different intraocular lens models. PLoS ONE 15:e228342. https://doi.org/10.1371/journal.pone.0228342
16. Son HS, Tandogan T, Liebing S, Merz P, Choi CY, Khoramnia R, Auffarth GU (2017) In vitro optical quality measurements of three intraocular lens models having identical platform. BMC Ophthalmol 17:108. https://doi.org/10.1186/s12886-017-0460-0
17. Song SH, Song IS, Oh SJ, Son H, Kang MH (2021) Optical bench simulation for intraocular lenses using field-tracing technology. PLoS ONE 16:e250543. https://doi.org/10.1371/journal.pone.0250543
18. Son H, Łabuz G, Khoramnia R, Yildirim TM, Auffarth GU (2021) Laboratory analysis and ray visualization of diffractive optics with enhanced intermediate vision. BMC Ophthalmol 21:197. https://doi.org/10.1186/s12886-021-01958-8
19. Łabuz G, Auffarth GU, Knorz MC, Son H, Yildirim TM, Khoramnia R (2020) Trifocality achieved through polypseudophakia: optical quality and light loss compared with a single trifocal intraocular lens. J Refract Surg 36:570–577. https://doi.org/10.3928/1081597X-20200715-01
20. García S, Salvá L, García-Delpech S, Martínez-Espert A, Ferrando V, Montagud-Martínez D (2022) Polychromatic assessment of a refractive segmented EDOF intraocular lens. J Clin Med 11:1480. https://doi.org/10.3390/jcm11061480
21. Tandogan T, Auffarth GU, Choi CY, Liebing S, Mayer C, Khoramnia R (2017) In vitro comparative optical bench analysis of a spherical and aspheric optic design of the same IOL model. BMC Ophthalmol 17:9. https://doi.org/10.1186/s12886-017-0407-5
22. Vega F, Millán MS, Garzón N, Altemir I, Poyales F, Larrosa JM (2018) Visual acuity of pseudophakic patients predicted from in-vitro measurements of intraocular lenses with different design. Biomed Opt Express 9:4893. https://doi.org/10.1364/BOE.9.004893
23. Remé CE, Grimm C, Hafezi F, Wenzel A, Williams TP (2000) Apoptosis in the retina: the silent death of vision. News Physiol Sci 15:120–124. https://doi.org/10.1152/physiologyonline.2000.15.3.120
24. Rezai KA, Gasyna E, Seagle BL, Norris JJ, Rezaei KA (2008) AcrySof Natural filter decreases blue light-induced apoptosis in human retinal pigment epithelium. Graefes Arch Clin Exp Ophthalmol 246:671–676. https://doi.org/10.1007/s00417-006-0484-2
25. Qian JL, Liao X, Tang YL, Tan QQ, Zhou GM, Lan CJ (2022) Comparative study of decentration, tilt and visual quality after implantation of aspherical intraocular lenses. Zhonghua Yan Ke Za Zhi 58:521–528. https://doi.org/10.3760/cma.j.cn112142-20211103-00518
26. Pérez-Gracia J, Varea A, Ares J, Vallés JA, Remón L (2020) Evaluation of the optical performance for aspheric intraocular lenses in relation with tilt and decenter errors. PLoS ONE 15:e232546. https://doi.org/10.1371/journal.pone.0232546
27. Hirnschall N, Buehren T, Bajramovic F, Trost M, Teuber T, Findl O (2017) Prediction of postoperative intraocular lens tilt using swept-source optical coherence tomography. J Cataract Refract Surg 43:732–736. https://doi.org/10.1016/j.jcrs.2017.01.026
28. Wang L, de Souza RG, Weikert MP, Koch DD (2019) Evaluation of crystalline lens and intraocular lens tilt using a swept-source optical coherence tomography biometer. J Cataract Refract Surg 45:35–40. https://doi.org/10.1016/j.jcrs.2018.08.025
29. Gu XX, Chen XY, Yang GY, Wang W, Xiao W, Jin GM, Wang LH, Dai Y, Ruan XT, Liu ZZ, Luo LX, Liu YZ (2020) Determinants of intraocular lens tilt and decentration after cataract surgery. Ann Transl Med 8:921. https://doi.org/10.21037/atm-20-1008
30. Ortiz C, Esteve-Taboada JJ, Belda-Salmerón L, Monsálvez-Romín D, Domínguez-Vicent A (2016) Effect of decentration on the optical quality of two intraocular lenses. Optom Vis Sci 93:1552–1559. https://doi.org/10.1097/OPX.0000000000001004
31. Pérez-Gracia J, Ávila FJ, Ares J, Vallés JA, Remón L (2020) Misalignment and tilt effect on aspheric intraocular lens designs after a corneal refractive surgery. PLoS ONE 15:e243740. https://doi.org/10.1371/journal.pone.0243740
32. Tandogan T, Son HS, Choi CY, Knorz MC, Auffarth GU, Khoramnia R (2017) Laboratory evaluation of the influence of decentration and pupil size on the optical performance of a monofocal, bifocal, and trifocal intraocular lens. J Refract Surg 33:808–812. https://doi.org/10.3928/1081597X-20171004-02
33. Barbero S, Marcos S, Jimenez-Alfaro I (2003) Optical aberrations of intraocular lenses measured in vivo and in vitro. J Opt Soc Am A Opt Image Sci Vis 20:1841–1851. https://doi.org/10.1364/josaa.20.001841