



Evaluating the impact of the water content of hydrophobic intraocular lenses on visual quality

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Abstract

The impact of the water content of hydrophobic intraocular lenses (IOLs) on visual quality remains unclear. This study investigated how the water content influenced photic phenomena. Optical bench studies were conducted to compare two hydrophobic trifocal IOLs: PanOptix® (low-water content IOL) and Clareon® PanOptix® (high-water content IOL). Modulation transfer function (MTF) measurements were used to evaluate optical quality, while point spread function (PSF) images were used to evaluate photic phenomena. To validate the optical bench results, a retrospective observational case series study was conducted using medical records for 85 eyes from 85 patients (PanOptix®, n=38; Clareon® PanOptix®, n=47). Postoperative visual outcomes were evaluated two months after the operation using a defocus curve for uncorrected visual acuity and contrast sensitivity (CS) with and without glare. Subjective satisfaction regarding spectacle independence and dysphotopsia was evaluated using a questionnaire. The optical bench study showed that the high-water content IOL exhibited a 6.16% smaller glare diameter in near-vision PSF analysis, and slightly higher MTF values at near distances. The clinical study supported these results, showing that the high-water content IOL provided better uncorrected visual acuity ($P < 0.05$) and spectacle independence ($P = 0.016$) at near distances. Additionally, the high-water content IOL showed higher contrast sensitivity with glare at 6.3° ($P = 0.040$) and 4° ($P = 0.018$). Hydrophobic IOLs with a higher water content improved contrast sensitivity and subjective satisfaction by reducing glistening and minimizing photic phenomena.

Keywords Intraocular lens · Water content · Optical bench system · Clinical study

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1 Introduction

Advancements in biomedical engineering have contributed to ophthalmology, including corneal biomechanics [1], intraocular pressure regulation [2], ocular drug delivery [3], and glaucoma detection [4]. Despite these advancements, blindness remains an ongoing challenge. Cataracts continue to be a major cause of blindness [5]. Cataract surgery and intraocular lens (IOL) technologies have been developed to restore vision and enhance visual quality [6–9]. Monofocal IOLs are widely used for their low cost, but patients who receive these lenses need spectacles to correct intermediate or near vision [10–12]. Therefore, multifocal IOLs are often selected to improve near vision and spectacle independence [11, 13]. Additionally, researchers have also developed various materials for these lenses to further enhance visual quality and biocompatibility [8, 14].

IOLs can exhibit hydrophilic or hydrophobic properties depending on the material. Hydrophilic IOLs, which have a water content ranging from 18 to 34% [15], have several disadvantages, including elevated posterior capsule opacification (PCO) rates [16, 17]. Thus, hydrophobic IOLs are favored due to their higher intracapsular biocompatibility and lower PCO rates [17–19]. However, how the water content of hydrophobic IOLs affects visual quality remains unclear. To investigate this, we compared two types of hydrophobic trifocal IOL with relatively low and high-water content (PanOptix® and Clareon® PanOptix®, respectively). Because Clareon® PanOptix® contains 2-hydroxyethyl methacrylate (HEMA), it has a water content of 1.5%, compared to only 0.5% for PanOptix®. Some studies have reported that the incorporation of materials with hydroxyl groups such as HEMA into hydrophobic IOLs may reduce glistening [15, 20, 21]. Glistening occurs when microvacuoles form within the lens material, scattering light and degrading visual quality [22–26].

In this paper, we analyze the impact of water content of hydrophobic intraocular lenses on visual quality. To achieve this, we developed an optical bench system. Unlike conventional IOL quality tests, the developed optical bench system can analyze both the modulation transfer function (MTF) and point spread function (PSF) [27]. Notably, PSF is essential for assessing photic phenomena such as glare and halos but cannot typically be measured in conventional IOL evaluation systems. Additionally, we quantified wettability using a custom-made contact angle camera and imaged the IOLs in a salt solution with a microscope to observe the degree of glistening. To investigate whether the optical properties of IOL had an impact on real-world visual performance, we also conducted a clinical study. Through this research, we aim to clarify the impact of water content in

hydrophobic IOLs and its implications for optical performance and patient outcomes.

2 Materials and methods

2.1 Optical bench tests

2.1.1 Optical bench system

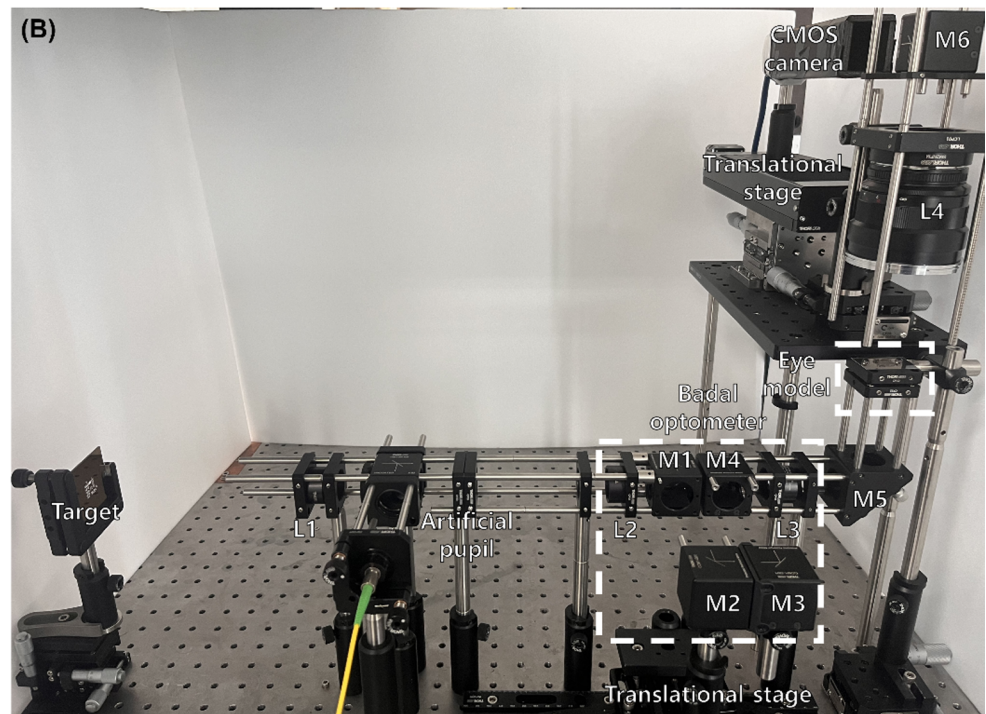
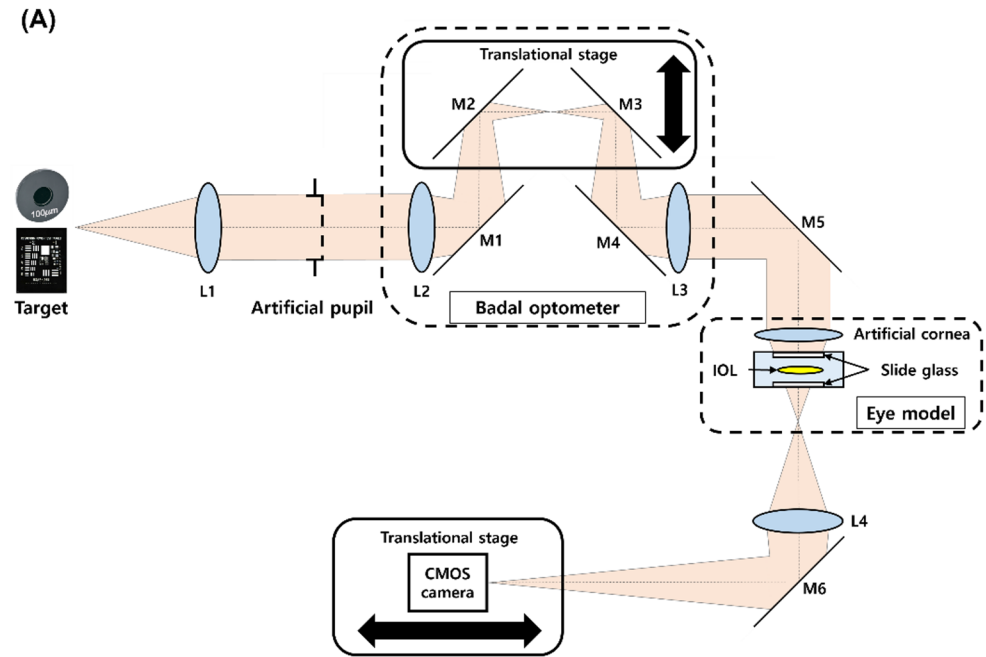
An optical bench system was developed to analyze visual quality based on the MTF and PSF. Glistening increases photic phenomena such as glare, and this can be quantified using PSF analysis [24, 28]. A schematic of the optical bench system is presented in Fig. 1, showing the imaging target, an artificial pupil, a Badal optometer, a model eye, and a complementary metal-oxide semiconductor (CMOS) camera (DMK AFUJ003-M12; Imaging Source, Bremen, Germany). The model eye had an artificial cornea (LB1014-A; Thorlabs, Newton, NJ) and a wet cell with glass slides. The wet cell was filled with a balanced salt solution matching the refractive index of the aqueous humor (1.336). A Clareon® PanOptix® or PanOptix® IOL was positioned inside the wet cell. The lens center was fixed 4.5 mm from the posterior surface of the artificial cornea to replicate the depth of the anterior chamber of the lens [29]. The infinity distance was defined as the peak camera position for the 20/20 Snellen vision bar group. The position of the camera was adjusted using the translational stage. For MTF and PSF analysis, the Badal optometer simulated a range of locations from near distance to infinity. The size of the artificial pupil was 3 mm to approximate the typical photopic pupil [30].

2.1.2 Intraocular lenses

PanOptix® and Clareon® PanOptix® are hydrophobic trifocal IOLs with similar optic designs, lens diameters, dioptric power additions, and refractive indices. However, Clareon® PanOptix® incorporates HEMA, leading to a relatively high-water content (1.5%), while PanOptix® has a water content of only 0.5%. In this paper, PanOptix® is referred to as the low-water content IOL, while Clareon® PanOptix® is the high-water content IOL. Table 1 summarizes the optical properties of IOLs.

To examine the impacts of HEMA, a custom-made contact angle camera was utilized. The high-water content IOL demonstrated a contact angle of 70.392°, compared to 80.551° for the low-water content IOL (Fig. 2 A, B). The lower contact angle for the high-water content IOL indicated higher wettability [31]. Imaging of the IOLs in a balanced salt solution revealed reduced glistening for the high-water content IOL (Fig. 2 C, D). In order to support

Fig. 1 Schematic of the optical bench system (A). Photograph of the optical bench system (B); BS: beam splitter; L1, L2, L3, and L4: achromatic doublet lenses; M1, M2, M3, M4, and M5: mirrors



this observation, we applied threshold adjustment in ImageJ and manually counted microvacuole-like particles. The low-water content IOL showed about four times more particles than the high-water content IOL. The reduced glistening was due to HEMA interacting with the water molecules, which prevented microvacuole formation [32].

2.1.3 Data analysis

The infinity distance was defined as the peak camera position for the 20/20 Snellen vision bar group. The 1951 USAF target images were transformed into a through-focus MTF curve for image quality assessment. This calculation was conducted at a spatial frequency of 14.81 cycles per degree, which was equivalent to a Snellen visual acuity of 20/40 (Fig. 3, left). The through-focus MTF curve exhibited three

Table 1 Properties of the IOLs

	PanOptix® (low-water content IOL)	Clareon® PanOptix® (high-water content IOL)
Optic Design	One piece / combined diffractive–refractive trifocal	
Total Lens / Optic Diameter	13.0 / 6.0 mm	
Base Power	+21.0 D	
Dioptric Power Addition	+2.17 D intermediate addition + 3.25 near addition	
Lens Material	Hydrophobic acrylate/ Methacrylate copolymer	
	–	+HEMA
Water Content	0.5%	1.5%
Refractive Index	1.55	
IOL Color	Yellow	
Spherical Aberration	–0.10 μm	

peaks indicating optimal optical performance at far, moderate, and near distances for the trifocal IOLs used in the experiment.

Using ImageJ, PSF images were logarithmically modified to enhance the representation of the photic phenomena. We measured the diameter of the first circle as the size at 10% of the peak value of the PSF image. The relative glare diameter was determined by dividing the first circle diameter by the full width at half maximum (FWHM) (Fig. 3, right). To compare the photonic phenomena between the two IOLs, Eq. (1) was used:

$$\text{Difference ratio} = \frac{\text{Glare diameter}_{\text{High-water}} - \text{Glare diameter}_{\text{Low-water}}}{\text{Glare diameter}_{\text{Low-water}}} \times 100 \quad (1)$$

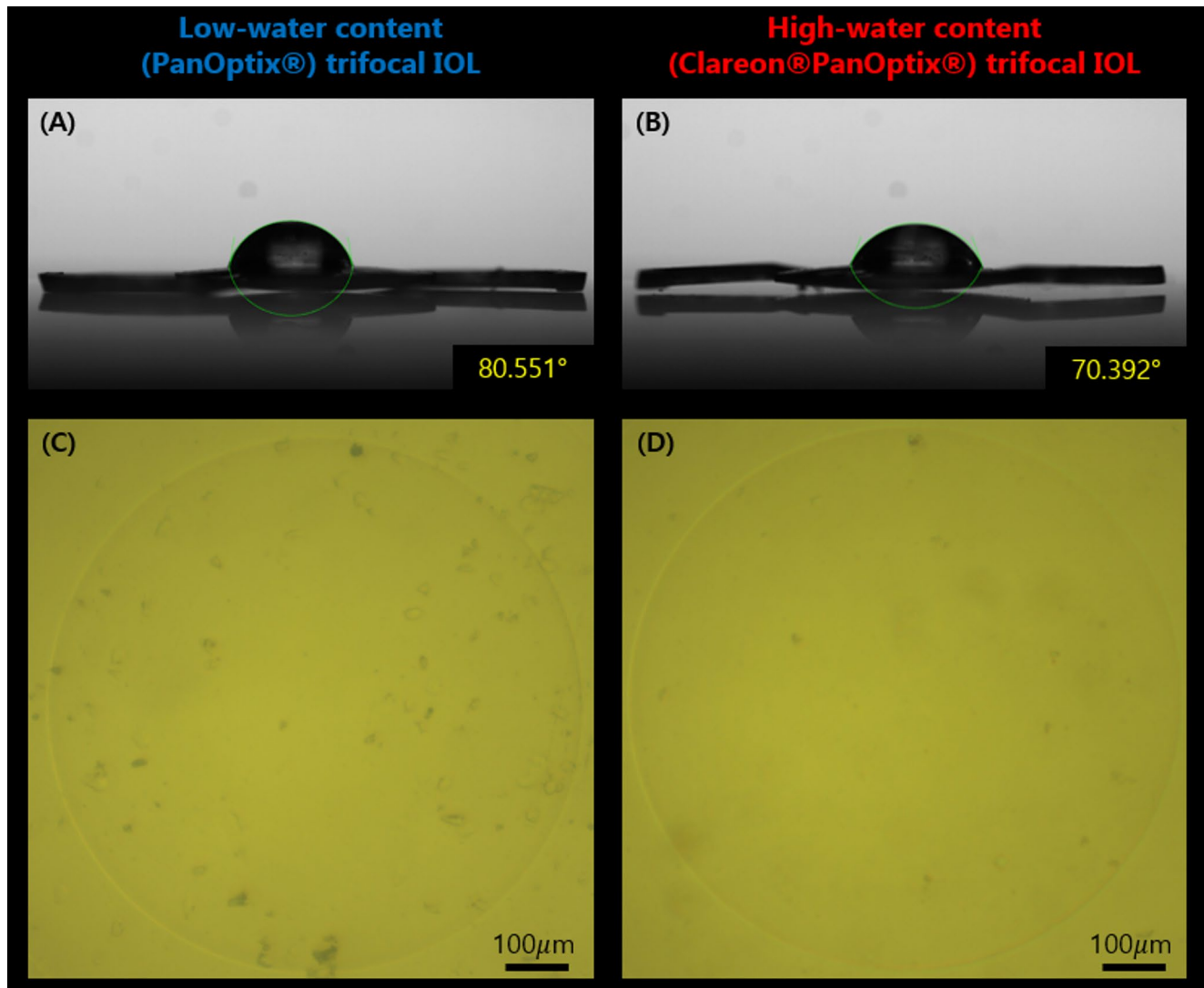


Fig. 2 Contact angle for the **A** PanOptix® and **B** Clareon® PanOptix® IOLs and surface images of the **C** PanOptix® and **D** Clareon® PanOptix® IOLs in a balanced salt solution

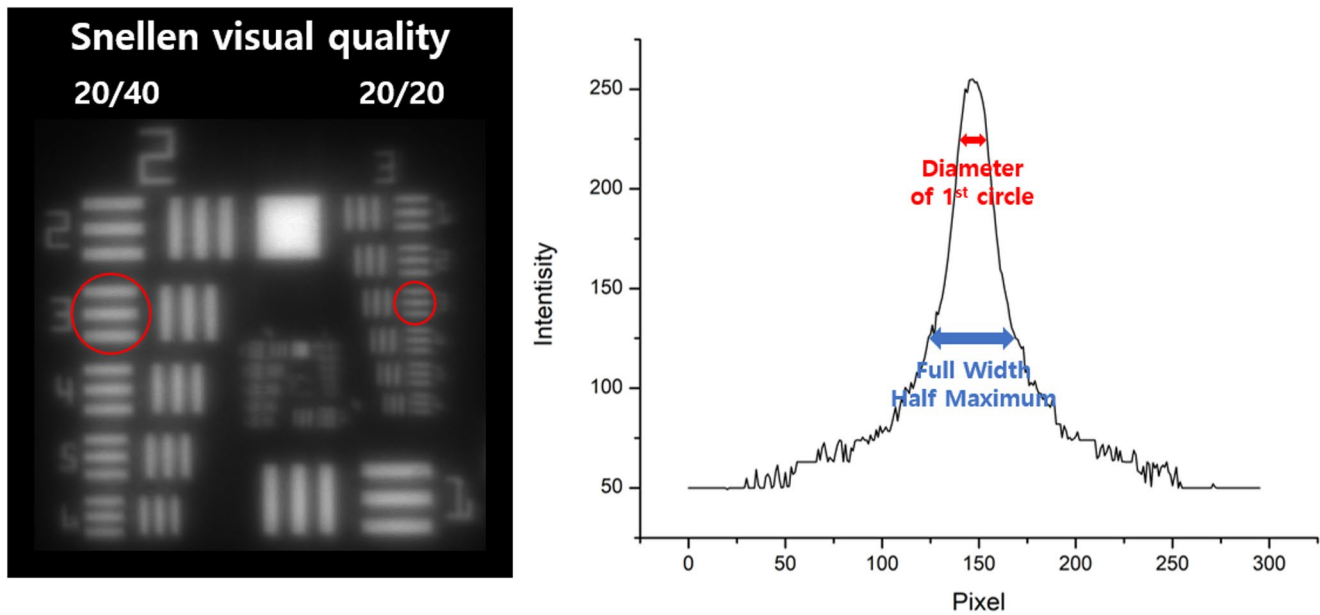


Fig. 3 Snellen visual quality corresponding to the USAF 1951 resolution chart (left) and calculation of the relative glare diameter using the full width at half maximum (FWHM) and diameter of the 1st circle (right)

2.2 Clinical study

2.2.1 Subjects

A retrospective observational case series study was conducted using the medical records of patients who underwent uncomplicated cataract surgery and received either the PanOptix® or Clareon® PanOptix® IOL. The inclusion criteria were patients with a senile cataract and corneal astigmatism of less than 1.0 diopter (D). Exclusion criteria were previous ocular surgeries, such as LASIK or LASEK, that were not corneal refractive procedures, corneal diseases, pseudoexfoliation, zonular weakness, corneal astigmatism of 1.0 D or more, glaucoma, macular disease, and amblyopia. Eyes with a postoperative distant-corrected visual acuity (DCVA) of less than 20/40 were also excluded. In total, the records for 85 eyes from 85 patients were included in this clinical study. The study protocol was reviewed and approved by the St. Mary's Hospital Institutional Review Board (UC22RID10041). The study also followed the tenets of the Declaration of Helsinki. Informed consent was waived for this retrospective study.

2.2.2 Surgical techniques

All surgical procedures followed a standardized, suture-free phacoemulsification technique, involving a 2.2 mm clear corneal incision made in the temporal side under topical anesthesia by an experienced surgeon. Following the execution of continuous curvilinear capsulorhexis of 5.0 mm

and hydrodissection, phacoemulsification of the nucleus and aspiration of residual cortex were performed utilizing a cataract surgery phacoemulsification device (Centurion Vision System, Alcon, Fort Worth, TX, USA). The trifocal IOL was inserted into the capsular bag using an injector and a disposable cartridge system before removing the ophthalmic viscoelastic device. Finally, a balanced salt solution was introduced into the incision site to facilitate the closure of the corneal incision, resulting in edema. Both antibiotic eye drops and anti-inflammatory eye drops were administered four times a day for one month after the surgery. In the subsequent analysis, those patients who received the low-water content IOL (PanOptix®, $n=38$) were classified as Group Low, while those receiving the high-water content IOL (Clareon® PanOptix®, $n=47$) were classified as Group High.

2.2.3 Outcome measurements

The refractive and visual outcomes for the eyes were evaluated two months after cataract surgery. For this, the IOL power closest to emmetropia was determined using the Barrett Universal II formula based on the axial length, corneal curvature, anterior chamber depth, corneal diameter, and lens thickness as measured using a swept-source optical coherence tomography biometer (IOLMaster 700, Carl Zeiss Meditec AG, Jena, Thuringia, Germany). A manifest refraction (MR) test was used to analyze postoperative refractive outcomes, with the prediction error (PE) defined as the predicted spherical equivalent (SE) from the

IOL formula minus the actual postoperative SE, with the mean error (ME) representing the mean PE. Positive and negative PEs represented myopic and hyperopic errors in postoperative refraction, respectively. The mean absolute error (MAE) and median absolute error (MedAE) were also determined. After these refractive measurements were taken, the predictive accuracy for the two trifocal IOLs was calculated. Both ocular and corneal high-order aberrations (HoAs) were measured for a pupil size of 4.0 mm using OPD-Scan III (Nidek, Japan).

To analyze postoperative visual outcomes, uncorrected visual acuity was evaluated based on a defocus curve test using a Snellen chart. Defocus curves were plotted by evaluating the visual acuity under photopic conditions at 4 m while adding lenses in 0.5-D increments from -4.0 to $+2.0$ D. CS was assessed at 3, 6, 12, and 18 cycles per degree using a Contrast Glare Tester 2000® (CGT 2000®, Takagi, Seiko, Japan) under photopic conditions (85 cd/m²) both with and without glare. The results were converted into logarithmic units for statistical analysis.

Five visual artifacts including glare, halos, starburst, hazy vision, and blurred vision were evaluated by presenting images to patients. Patients were instructed to score the frequency, degree, and discomfort related to the visual artifacts on a scale of 0=none, 1=minimal, 2=moderate, or 3=severe. The ratings were averaged for each patient. Artifact images and a questionnaire adapted from the Quality of Vision survey were employed in this study. Satisfaction with near, intermediate, and distance vision measured on a five-point scale (very satisfied, satisfied, neither satisfied nor unsatisfied, unsatisfied, or very unsatisfied) and spectacle dependence were also evaluated using a questionnaire.

2.2.4 Statistical analysis

Statistical analysis was conducted using SPSS version 18.0 (IBM Corp., Armonk, NY, USA), with the two-sided statistical significance set at $P < 0.05$. Most of the measurement outcomes were analyzed using descriptive statistics and presented as the mean \pm standard deviation (SD). The measured decimal visual acuity was converted to logMAR for statistical analysis. If parametric analysis was possible, independent t-tests were conducted for all comparisons between the PanOptix® and Clareon® PanOptix® IOLs. If the variables deviated from a normal distribution, Mann–Whitney tests were applied to evaluate the significance of any differences between the two IOLs.

3 Results

3.1 Optical bench tests

The resolution chart images were visually comparable for both IOLs. The PSF images were transformed into a logarithmic scale to enhance the visualization of photic phenomena such as glare. In pinhole imaging, glare increases as the distance diminishes. Figure 4 presents a 1951 USAF resolution chart alongside 100 μ m pinhole images captured at different distances.

At a near distance of 30 cm, the MTF value of the high-water content IOL (Clareon®) was approximately 4.14% higher than low-water content IOL (PanOptix®). MTF values at far and intermediate distances were comparable between the two IOLs (Fig. 5). These results were in accordance with the clinical study, which showed better results at near distances.

Photic phenomena were evaluated using PSF images. Table 2 presents the diameter of the first circle, FWHM, and relative glare diameter. At far distances, both types of IOL exhibited similar relative glare diameters (Fig. 6). However, as the distance became shorter, the difference in relative glare diameter became more evident, with the high-water content IOL generating a smaller glare diameter.

3.2 Clinical study

There was no difference in the average age or sex ratio of Groups Low and High (all $P > 0.05$, Table 3). They also demonstrated no difference in their ocular biometry, including the axial length, keratometry, corneal astigmatism, and anterior chamber depth (all $P > 0.05$). The optical power of the implanted trifocal IOLs was similar between the two groups ($P = 0.714$).

3.2.1 Refractive outcomes

The target refractions calculated using Barrett Universal II did not differ between Groups Low and High ($P > 0.05$, Table 4), nor was there any difference in their PE and APE (all $P > 0.05$). However, Group High was found to have a lower MedAE than Group Low. In terms of ocular and corneal HoAs, there was no difference between the two groups ($P > 0.05$, Table 5).

3.2.2 Objective visual outcomes

The postoperative mean uncorrected distant visual acuity (UDVA) was 0.048 ± 0.088 and 0.053 ± 0.061 for Groups Low and High, respectively (Fig. 7 A). In the defocus curve tests, the postoperative defocus curve improved with a

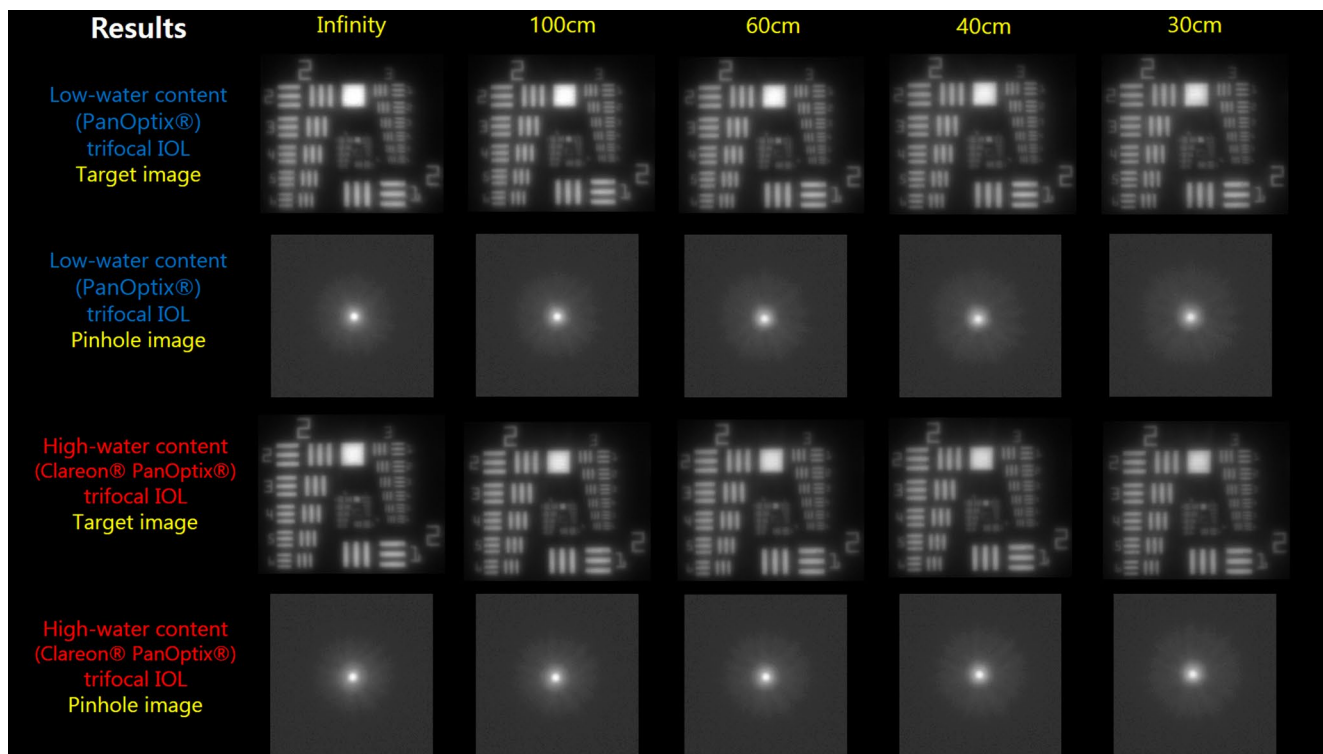


Fig. 4 Representative 1951 United States Air Force (USAF) target and 100 μm pinhole images for the PanOptix® (low-water content) and Clareon® PanOptix® (high-water content) IOLs

diopter defocus of both -2.5 and -3.0 ($P=0.029$ and 0.037 , respectively). Under photopic conditions with glare, Group High exhibited higher CS for a visual angle of 6.3° and 4° to the test target than Group Low ($P=0.040$ and 0.018 , respectively).

3.2.3 Subjective visual outcomes

Group High had a higher level of spectacle independence than Group Low for near distances ($P=0.016$, Fig. 8 A), but there was no difference in glare, halo, starburst, hazy vision, or blurred vision between the two groups (all $P>0.05$).

4 Discussion

This study evaluated the impact of the water content of hydrophobic IOLs on visual quality using an optical bench test and a retrospective comparative cohort study. The high-water content IOL (Clareon® PanOptix®) containing hydroxyethyl methacrylate (HEMA) exhibited slightly higher modulation transfer function (MTF) values than the low-water content IOL (PanOptix®) at near distance. Similarly, the PSF results confirmed that the high-water content IOL had a smaller glare diameter, indicating a reduction in photic phenomena due to lower glistening. This reduction

in glistening contributed to better results in clinical study in the Clareon® PanOptix® group. In clinical study, the Clareon® PanOptix® group demonstrated significantly better near visual acuity ($P<0.05$), contrast sensitivity with glare at a visual angle of 6.3° ($P=0.040$) and 4° ($P=0.018$), and higher spectacle independence ($P=0.016$). Although statistical analysis was not performed for the optical bench test, the results still suggested improved optical quality of the high-water content IOL. These optical bench results were consistent with the clinical improvements in contrast with sensitivity and spectacle independence. Additionally, these results align with previous studies showing that Clareon® PanOptix® provides better contrast sensitivity (CS) and greater patient satisfaction compared to PanOptix® [33, 34]. Previous studies have also shown that hydrophobic trifocal IOLs with hydroxyl materials have reduced surface haze and glint levels compared to other hydrophobic acrylic IOLs [35, 36]. The presence of HEMA in Clareon® PanOptix® leads to a higher water content (1.5%) than that found in PanOptix® (0.5%) [37, 38]. Hydrophobic acrylic IOL materials contain voids in their polymer matrix. In the intraocular environment, infiltrating water may condense within these voids if it is not fully absorbed by the polymer. This process leads to the formation of microvacuoles, resulting in light scatter and reduced image quality [21]. The hydrophilic hydroxyl ($-\text{OH}$) groups of HEMA attract and

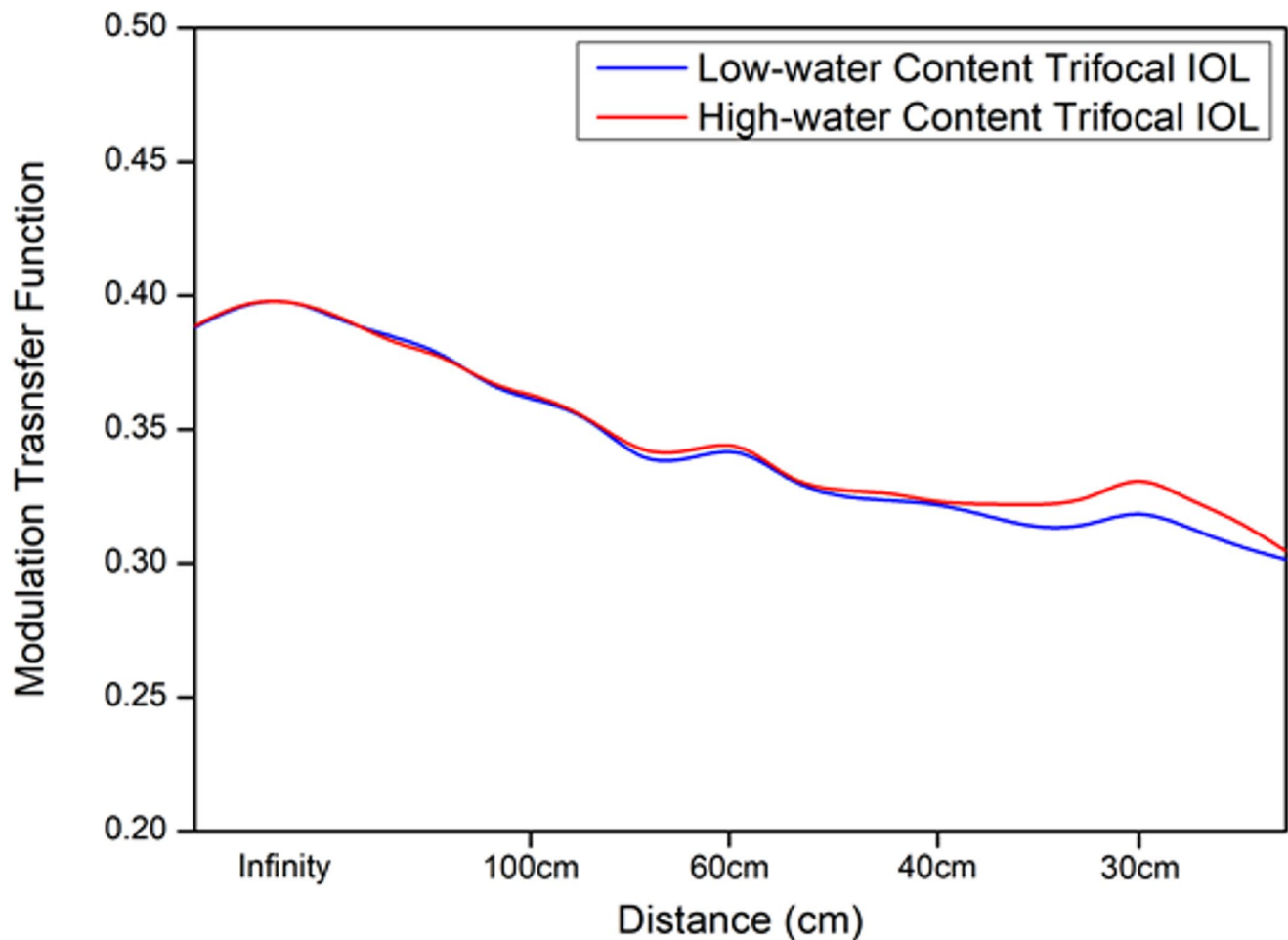


Fig. 5 Through-focus modulation transfer function curve for the PanOptix® (low-water content) and Clareon® PanOptix® (high-water content) IOLs

Table 2 Association between the water content of the IOLs (PanOptix®=low-water content; Clareon® PanOptix®=high-water content) and glare-related parameters from point spread function (PSF) images

Distance [cm]	Type of IOL	Diameter of 1st circle [μm]	Full width at half maximum [μm]	Relative glare diameter [μm]	Difference of glare diameter (%)
Infinity	PanOptix®	21.71	70.14	3.23	0
	Clareon® PanOptix®	21.71	70.14	3.23	
100	PanOptix®	21.71	71.81	3.31	0
	Clareon® PanOptix®	21.71	71.81	3.31	
60	PanOptix®	23.38	80.16	3.43	2.08
	Clareon® PanOptix®	23.38	78.49	3.36	
40	PanOptix®	23.38	85.17	3.64	4
	Clareon® PanOptix®	23.38	81.83	3.50	
30	PanOptix®	23.38	88.51	3.79	6.16
	Clareon® PanOptix®	23.38	83.5	3.57	

retain water molecules. The water molecules are distributed uniformly throughout the polymer network which prevents the formation of microvacuoles [21, 35, 36]. Nonetheless, glistening develops over time and can increase for up to 10–15 years following implantation [39, 40]. A long-term

study will be required to fully evaluate postoperative CS, glistening, and PCO.

As a retrospective study, this work was inherently limited by the absence of randomization, blinding, and sample size calculation. In addition, this study did not account for clinical variables such as incision size and PCO rates. Further

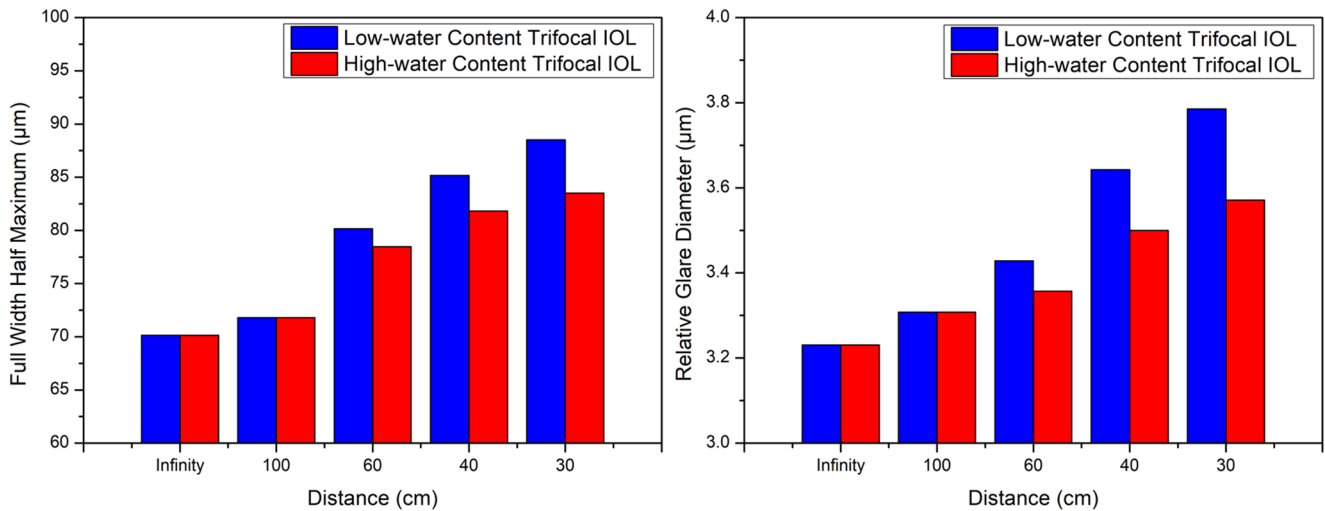


Fig. 6 Full width at half maximum (FWHM) for the PSF images (left) and the relative glare diameter (right) for the PanOptix® (low-water content) and Clareon® PanOptix® (high-water content) IOLs. The relative glare diameter was calculated by dividing the first circle diameter by the FWHM

Table 3 Baseline demographics

	Group Low (PanOptix®)	Group High (Clareon® PanOptix®)	P-value
Number	38	47	
Age (years)	55.8±5.9	58.6±5.2	0.056*
Sex (M:F)	17:21	21:26	0.113†
Axial length (mm)	24.12±1.21	24.66±1.63	0.193*
Keratometry (mean, D)	43.68±1.24	43.82±1.31	0.595*
Steep K	44.06±1.26	44.29±1.45	0.806*
Flat K	43.31±1.26	43.35±1.23	0.419*
Corneal astigmatism (D)	-0.40±0.24	-0.47±0.28	0.932*
Anterior chamber depth (mm)	3.37±0.37	3.43±0.34	0.327*
IOL power (D)	20.94±3.06	20.39±4.33	0.714*

*Mann–Whitney test, †Chi-square test

Table 4 Refractive outcomes

	Group Low (PanOptix®)	Group High (Clareon® PanOptix®)
Target refraction (D)	-0.086±0.22	-0.071±0.16
Prediction error (D)	-0.22±0.39	-0.20±0.37
Absolute prediction error (D)	0.34±0.28	0.31±0.22
MedAE (D)	0.35	0.32

Prediction Error=(Postoperative Refraction) – (Target Refraction)

research is needed to determine whether similar trends are observed in hydrophobic IOLs of other designs or materials in randomized controlled trials.

In conclusion, hydrophobic IOLs with higher water content provide improved near visual acuity, contrast sensitivity, and spectacle independence. The presence of HEMA increases the water content and reduces glistening, thus minimizing photic phenomena. These findings highlight the importance of considering material characteristics when

Table 5 Ocular and corneal high-order aberrations (HoAs)

		Group Low (PanOptix®)	Group High (Clareon® PanOptix®)	P-value
Ocular aberrations	Total HoAs (RMS, micron)	0.16±0.067	0.20±0.088	0.122
	Spherical aberration (micron)	0.014±0.038	-0.0035±0.037	0.184
	Spherical aberration (RMS, micron)	0.030±0.027	0.028±0.024	0.919
Corneal aberrations	Total HoAs (RMS, micron)	0.17±0.069	0.17±0.052	0.657
	Spherical aberration (micron)	0.061±0.037	0.053±0.035	0.174
	Spherical aberration (RMS, micron)	0.068±0.021	0.056±0.029	0.118

selecting IOLs to improve contrast sensitivity and patient satisfaction following cataract surgery.

Fig. 7 Defocus curve (A), contrast sensitivity under photopic conditions without glare (B), and with glare (C) at two months after surgery. Group Low = PanOptix® (low-water content IOL); Group High = Clareon® PanOptix® (high-water content IOL)

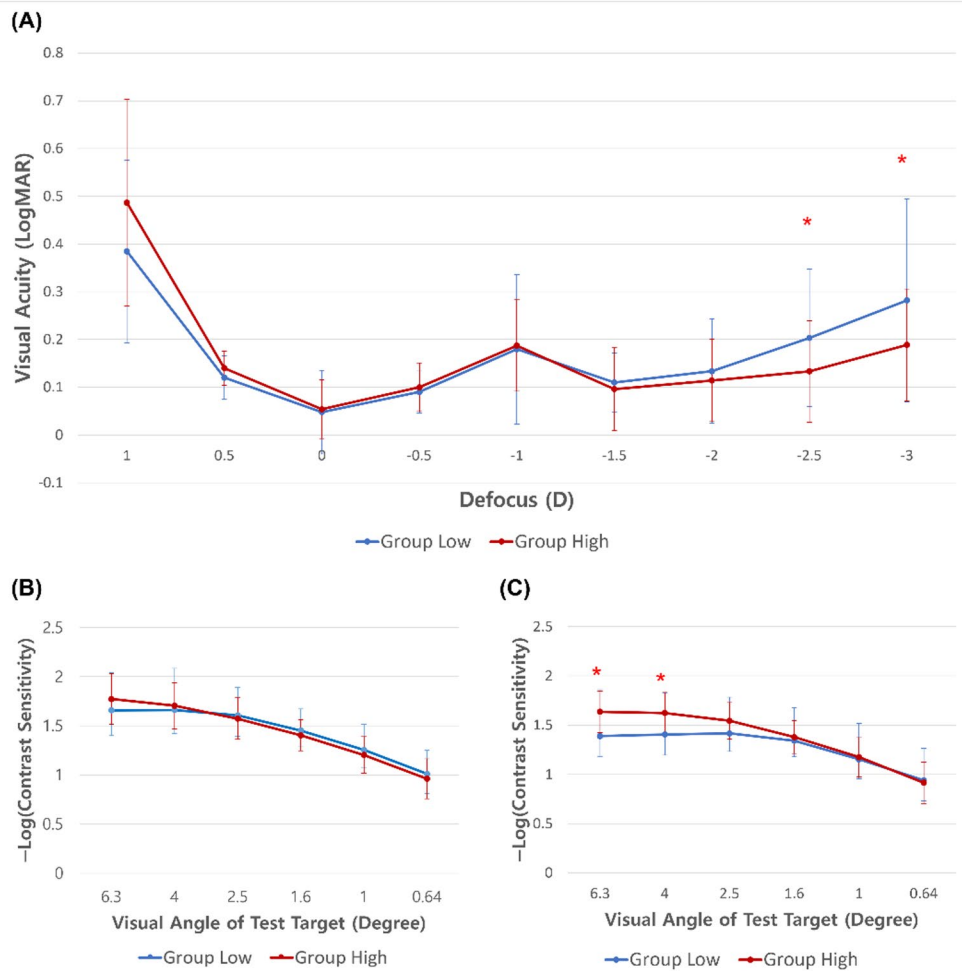
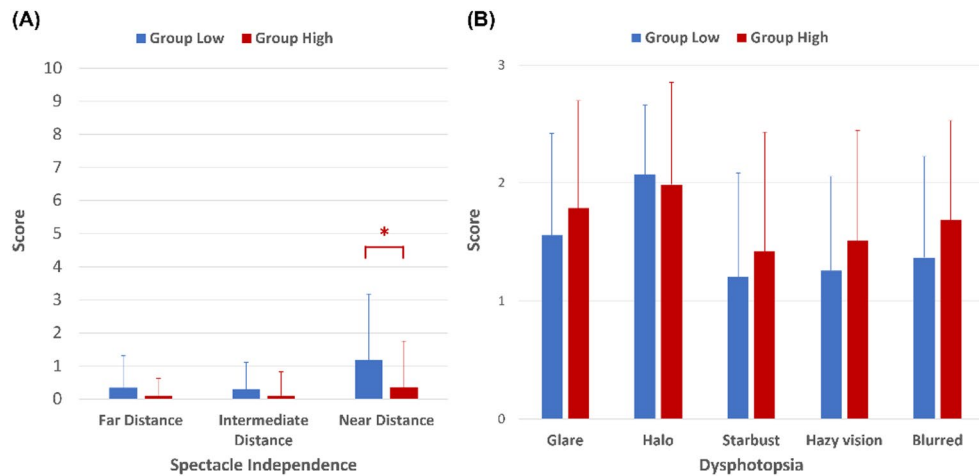


Fig. 8 Postoperative subjective satisfaction for spectacle independence (A) and dysphotopsia (B). Spectacle independence was rated on a 0–10 scale, where lower scores indicate less dependence on spectacles. Group Low = PanOptix® (low-water content); Group High = Clareon® PanOptix® (high-water content)



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and D.Y. Kim; Funding acquisition, Y.-S. Yoo, W.-J. Whang and D.Y. Kim All authors have read and agreed to the published version of the manuscript.

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Data availability The data presented in this study are available on request from the corresponding author.

Declarations

Conflict of interest The authors declare no conflicts of interest.

Ethical approval The study protocol was reviewed and approved by the St. Mary's Hospital Institutional Review Board (UC22RID10041).

Informed consent Informed consent for this retrospective study was waived.

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