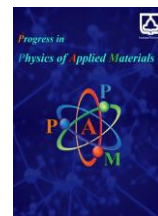




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Influence of Intraocular Lens Material Constants on Retinal Image Quality: A Physics-Based Modeling and Ray-Tracing Study

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ABSTRACT

The optical performance of intraocular lenses (IOLs) depends on both geometrical characteristics and material properties. This study evaluated how the refractive index and Abbe number of different IOL materials could affect on-axis retinal image quality using Zemax OpticStudio. A pseudophakic eye model was used to simulate IOLs made from polymethyl methacrylate (PMMA), hydrophilic acrylic, hydrophobic acrylic, silicone, Collamer, polyisobutylene-based polymer, and a gradient-index (GRIN) lens. The optical performance of IOLs was analyzed using the modulation transfer function (MTF), retinal spot diagram, and the Strehl ratio. Higher Abbe numbers resulted in larger MTF values, smaller retinal spot sizes, and higher Strehl ratios by decreasing chromatic aberration, while the refractive index alone had little influence. In addition, the effects of pupil diameter, IOL decentration, and tilt on image quality were evaluated to examine the robustness of each design under clinically relevant conditions. The GRIN IOL achieved the best overall performance among the evaluated lenses but was the most sensitive to pupil dilation and IOL decentration. However, manufacturability, the effects of scattering, absorption, and surface reflections were not included and should be investigated experimentally in future studies.

1. Introduction

Intraocular lenses (IOLs) are among the most successful implantable biomedical devices, widely used for visual rehabilitation after cataract extraction and, increasingly, for refractive lens exchange [1]. Their optical performance depends not only on lens geometry and surface design, but also strongly on the intrinsic properties of the material from which they are fabricated. Therefore, material selection has become a central consideration in modern IOL design, particularly with the emergence of premium IOL technologies intended to optimize postoperative visual performance [2]. Real-world visual outcomes are influenced by additional factors, including IOL decentration and tilt, capsular bag changes, and light scatter that may develop over time [3,4].

Conventional IOL materials include polymethyl methacrylate (PMMA), hydrophobic acrylic, hydrophilic acrylic, Collamer, and silicone, each with characteristic optical and mechanical properties [5,6]. PMMA was the first widely used IOL material and is characterized by excellent optical clarity and long-term material stability; however, its rigid nature requires implantation through relatively large incisions, which may increase surgically induced astigmatism and delay wound healing. The introduction of foldable materials such as silicone and acrylic polymers enabled IOL implantation through small corneal incisions, significantly improving surgical efficiency and reducing postoperative recovery time [7]. Collamer lenses are made from a collagen-copolymer material that combines high optical transparency with excellent biocompatibility. Their

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flexibility allows implantation through small corneal incisions, supporting minimally invasive cataract surgery [6].

Hydrophobic acrylic lenses, in particular, have become widely adopted in contemporary cataract surgery because they combine foldability with a relatively high refractive index and favorable capsular biocompatibility. Hydrophilic acrylic lenses, which contain a higher water content, are typically more flexible and easier to inject but may differ in long-term optical stability and capsular interactions [8,9]. Another important innovation in IOL design is the development of gradient-index (GRIN) intraocular lenses. Unlike conventional lenses with a uniform refractive index, GRIN-IOLs possess a refractive index that gradually varies from the center toward the periphery of the optic. This internal refractive index distribution enables more physiologic light focusing and can help reduce optical aberrations, particularly spherical aberration. GRIN technology aims to more closely mimic the optical properties of the natural crystalline lens, potentially improving image quality and visual performance after cataract surgery [10].

Material properties also affect surgical and postoperative behavior, including foldability, incision size, and mechanical handling during implantation. Furthermore, biological interactions between the lens material and ocular tissues influence posterior capsule opacification (PCO) rates [11,12]. Material-related phenomena such as glistenings in some hydrophobic acrylic lenses and calcification in certain hydrophilic acrylic materials may also affect long-term optical quality [13,14]. Therefore, while refractive index and Abbe number are important for understanding optical performance, the overall success of an intraocular lens in modern cataract surgery also depends on surgical practicality, biocompatibility, and long-term stability.

Optical modeling provides a practical and rigorous approach for evaluating such materials before IOL fabrication or clinical use [15]. Among the available optical design platforms, Zemax OpticStudio is one of the most widely used tools for ocular ray tracing and retinal image analysis, including wavefront analysis, modulation transfer function (MTF) evaluation, and point spread function (PSF) calculation [16-18]. The classic eye model introduced by Liou and Brennan remains one of the most influential physiological schematic eye models for optical analysis because it incorporates realistic anatomical dimensions [19]. Several studies have used ray-tracing simulations to evaluate IOL performance and its effects on retinal image quality [20].

These simulations have demonstrated that IOL design parameters significantly influence optical aberrations and the MTF of the pseudophakic eye [16,21]. In addition to lens geometry, the optical properties of IOL materials have also been investigated [22,23]. Studies have shown that hydrophobic and hydrophilic intraocular lens materials [24], silicone [25], and acrylic polymers [7,26] differ in refractive index and chromatic dispersion, which may influence chromatic aberration and retinal image contrast. Biocompatible materials such as polyisobutylene-based

polymers were also introduced and evaluated in rabbits [27].

The purpose of the present study is therefore to investigate the optical performance of commonly used intraocular lens materials by simulating their properties using optical design software. Specifically, the modulation transfer function and retinal spot diagrams of representative hydrophobic acrylic, hydrophilic acrylic, PMMA, Collamer, polyisobutylene-based polymer, silicone, and GRIN-IOL materials are evaluated using Zemax OpticStudio software. In addition, the study investigates the independent effects of chromatic dispersion by comparing materials with different Abbe numbers at a fixed refractive index, as well as the effect of refractive index variation while maintaining a constant Abbe number. Through these simulations, the study aims to clarify the role of intrinsic material properties in determining retinal image quality and to provide further insight into the relationship between IOL material characteristics and visual performance in modern cataract surgery.

2. Materials and Methods

2.1. Design and Optical Modeling Strategy

This study was designed as a computational optical analysis of a pseudophakic eye model to investigate the effect of IOL material properties on retinal image quality along the optical axis. The simulations were performed in Zemax OpticStudio using sequential ray tracing, which is appropriate for modeling the eye as an ordered optical system composed of successive refractive surfaces and transparent media. Within this framework, the cornea, aqueous humor, pupil, crystalline lens or implanted IOL, vitreous humor, and retinal image surface were defined in their physiological order and analyzed under controlled optical conditions [28,29].

The schematic eye model used in this study was based on the anatomically accurate Liou-Brennan model [19]. According to this model, the dimensions of the simulated ocular components, including surface curvatures, axial thicknesses, inter-surface distances, and asphericities, were selected according to the reported anatomical parameters of the human eye. The optical properties of the ocular media, including refractive indices and dispersion characteristics (Abbe numbers), as well as the gradient refractive-index (GRIN) profile of the crystalline lens, were assigned according to the Liou-Brennan eye model [19, 30].

Our main objective was to compare the optimized optical performance of different intraocular lens materials. Six homogeneous IOL materials were investigated: Collamer, hydrophilic acrylic, hydrophobic acrylic, PMMA, polyisobutylene-based polymers, and silicone. These materials represent a broad spectrum of clinically established biomaterials with high biocompatibility and distinct mechanical properties. PMMA serves as the rigid historical control, while hydrophilic and hydrophobic acrylics represent the most common materials in modern foldable IOLs. Silicone is highly flexible, and polyisobutylene-based polymers represent modern high-stability alternatives. Collamer is selected due to its unique

collagen-copolymer structure. Also, these materials exhibit a diverse range of refractive indices ($1.43 \leq n \leq 1.55$) and chromatic dispersion properties ($42 \leq V \leq 58$), enabling a systematic assessment of their optical performance and aberration characteristics [31–35].

For each homogeneous IOL material, the anterior and posterior radii of curvature were independently optimized. Therefore, a single fixed lens geometry was not used to compare the different materials. Instead, each material was allowed to achieve its own optimized combination of surface curvatures within the same eye model. This strategy was adopted because the refractive index of the IOL material affects the surface curvature required to achieve the desired optical power and performance.

In addition to the homogeneous IOLs, a gradient-index intraocular lens (GRIN-IOL) was proposed as an advanced design framework. The concept of the GRIN IOL is inspired by the natural crystalline lens, which has a spatially varying refractive-index distribution rather than a uniform refractive index. The gradient-index structure of the crystalline lens contributes to ocular power, internal ray bending, and aberration control [36–40]. Therefore, a GRIN-IOL may provide additional degrees of freedom for optical optimization, offering greater flexibility in optimizing on-axis retinal image quality compared with conventional homogeneous IOLs.

2.2. Base Pseudophakic Eye Model

The base pseudophakic eye model was implemented as a rotationally symmetric sequential optical system based

on the Liou–Brennan eye model. The model consisted of the object space, input beam, cornea, aqueous region, pupil, IOL, vitreous region, and retinal image surface. All dimensions were defined in millimeters. The corneal geometry, aqueous region, pupil position, vitreous region, and retinal surface were kept constant for all IOL material configurations.

The anterior corneal surface had a curvature radius of 7.770 mm, a thickness of 0.550 mm, a refractive index of 1.38, an Abbe number of 50.2, a semi-diameter of 5.000 mm, and a conic constant of -0.180. The posterior corneal or aqueous interface had a curvature radius of 6.400 mm, a thickness of 3.160 mm, a refractive index of 1.34, an Abbe number of 50.2, a semi-diameter of 5.000 mm, and a conic constant of -0.600.

The pupil was positioned posterior to the aqueous region and was used as the aperture stop of the system. In the first configuration, the pupil semi-diameter was 1.250 mm, corresponding to a pupil diameter of 2.50 mm. The IOL was placed posterior to the pupil and was modeled using two refractive optical surfaces. The vitreous region was assigned a refractive index of 1.34 and an Abbe number of 50.2. The retinal image surface was modeled as a curved surface with a curvature radius of -12.000 mm. A curved retinal image surface was employed, as retinal curvature plays a critical role in determining the spatial distribution of ray interception, field curvature, spot size, and overall image formation within schematic eye models [16–19].

Table 1. Optical parameters of the base pseudophakic eye model.

Surface	Optical element	Radius of curvature (mm)	Thickness (mm)	Refractive index / Abbe number	Semi-diameter (mm)	Conic constant
OBJ	Object plane	Infinity	1000.000	—	0.000	0.000
1	Input beam	Infinity	50.000	—	1.448	0.000
2	Cornea	7.770	0.550	1.38 / 50.2	5.000	-0.180
3	Aqueous region	6.400	3.160	1.34 / 50.2	5.000	-0.600
4	Pupil	Infinity	0.000	1.34 / 50.2	1.250	0.000
5	IOL anterior surface	Variable	1.590	IOL material	3.000	0.000
6	IOL posterior surface	Variable	2.430	Vitreous	3.000	0.000
7	Vitreous region	-8.100	16.239	1.34 / 50.2	5.000	0.960
IMA	Retina	-12.000	—	—	5.000	0.000

The same base eye model (as reported in Table 1) was used for all optimized IOL material configurations. Therefore, the differences observed between material configurations were attributed to the interaction between material refractive properties and optimized IOL surface curvatures rather than to changes in the surrounding ocular geometry.

2.3. Cataractous Crystalline Lens Gradient-Index Model

Before replacing the crystalline lens with an IOL, the cataractous crystalline lens was represented using a gradient-index model. This step was involved because in the Liou–Brennan eye model, the natural crystalline lens is not optically homogeneous. Its refractive index varies both radially and axially, and this internal refractive-index

distribution contributes to ocular power and aberration balance [36-41]. The crystalline lens surfaces were modeled using the Gradient 3 formulation in Zemax OpticStudio.

The baseline crystalline-lens GRIN profile was taken from the Liou-Brennan model, in which the anterior lens nucleus was represented by $n_0 = 1.368$. To simulate cataract-like nuclear sclerosis, n_0 was increased to 1.44,

consistent with a higher peak refractive index in the human lens nucleus [42]. The remaining GRIN coefficients were kept unchanged to isolate the effect of refractive-index elevation on image quality. This increase in refractive index is expected to degrade optical quality, potentially leading to increased image blur and reduced retinal image contrast. The Gradient-index coefficients of the cataractous crystalline lens model are presented in Table 2.

Table 2. Gradient-index coefficients of the cataractous crystalline lens model.

Surface	Optical element	Radius of curvature (mm)	n_0	n_{r2}	n_{r4}	n_{r6}	n_{z1}	n_{z2}	n_{z3}
6	Anterior crystalline lens	12.4	1.44	-1.978E-003	0.000	0.000	0.049	-0.015	0.000

For a rotationally symmetric gradient-index medium, the radial coordinate is defined as $r = \sqrt{x^2 + y^2}$, where x and y are the transverse coordinates. The local axial coordinate is denoted by z . The refractive-index distribution was described using radial and axial polynomial terms as [29].

$$n = n_0 + n_{r2}r^2 + n_{r4}r^4 + n_{r6}r^6 + n_{z1}z + n_{z2}z^2 + n_{z3}z^3 \quad (1)$$

In this expression, n_0 is the base refractive index. The coefficients n_{r2} , n_{r4} , and n_{r6} describe radial changes in the refractive-index distribution, while n_{z1} , n_{z2} , and n_{z3} describe axial changes. The radial terms define how the refractive index varies from the optical axis toward the lens periphery, while the axial terms describe its variation along the optical axis through the thickness of the lens.

A negative value of n_{r2} indicates that the refractive index decreases as the radial distance from the optical axis increases. This behavior is consistent with the general refractive-index distribution of the natural crystalline lens, in which the central region typically has a higher refractive index than the peripheral cortex [36-38]. The axial terms describe the anterior-to-posterior variation in refractive index and can influence longitudinal ray propagation, optical path length, and spherical aberration.

The radial derivative of the refractive-index distribution is [29].

$$\frac{\partial n}{\partial r} = 2n_{r2}r + 4n_{r4}r^3 + 6n_{r6}r^5 \quad (2)$$

The axial derivative of the refractive-index distribution is defined by [29].

$$\frac{\partial n}{\partial z} = n_{z1} + 2n_{z2}z + 3n_{z3}z^2 \quad (3)$$

These derivatives describe the spatial rate of change of the refractive-index distribution. In a homogeneous optical medium, rays are refracted only at optical surfaces. In a gradient-index medium, rays are also continuously refracted inside the volume of the medium because the refractive index changes with position. The general ray equation in a gradient-index medium can be expressed as [43]:

$$\frac{d}{ds} \left(n \frac{dr}{ds} \right) = \nabla n \quad (4)$$

where s is the path length along the ray, r is the ray position vector, and the gradient of n represents the spatial variation of refractive index. This equation shows that a gradient-index optical element provides an internal mechanism for controlling ray propagation in addition to surface refraction.

2.4. IOL Geometry and Optical Representation

After cataract extraction, the crystalline lens was replaced by an intraocular lens (as shown in Fig. 1). The homogeneous IOLs were modeled as monofocal refractive lenses with two optical surfaces: an anterior IOL surface and a posterior IOL surface. The central IOL thickness was kept constant at 1.590 mm for all material configurations. The optical semi-diameter assigned in Zemax was 3.000 mm.

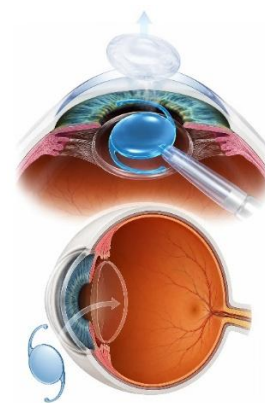


Fig. 1. Schematic representation of cataract extraction and intraocular lens implantation.

As depicted in Figure 2, the physical IOL consisted of a central optical zone and peripheral haptics. The optic diameter was approximately 6 mm, and the overall IOL diameter was approximately 13 mm. In the optical simulation, only the central refractive optical zone was included in the ray-tracing path. The haptics were not modeled as refractive surfaces because their primary role is mechanical stabilization of the IOL inside the capsular bag rather than retinal image formation.

The paraxial power of a refractive surface is given by [44]:

$$\Phi_i = \frac{n_{i+1} - n_i}{R_i} \quad (5)$$

where Φ_i is the refractive power of the surface. n_i and n_{i+1} are the refractive indices before and after the surface, and R_i is the radius of curvature of that surface.

For a thick IOL, the equivalent paraxial power can be approximated as [44]:

$$\Phi_{IOL} = \Phi_1 + \Phi_2 - \frac{t}{n_{IOL}} \Phi_1 \Phi_2, \quad (6)$$

where Φ_1 and Φ_2 are the anterior and posterior surface powers, t is the central IOL thickness, and n_{IOL} is the refractive index of the IOL material. This relationship explains why different IOL materials require different optimized curvatures. When the refractive index changes, the curvature required to produce the same refractive effect also changes.

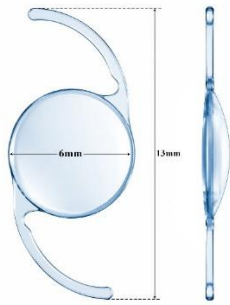


Fig. 2. Representative geometry of the intraocular lens. The central optic provides the refractive optical zone, while the haptics provide mechanical stabilization.

2.5. IOL Material Properties

Six homogeneous IOL materials were evaluated in this study: Collamer, hydrophilic acrylic, hydrophobic acrylic,

PMMA, polyisobutylene-based polymer, and silicone. Each material was modeled as a homogeneous, isotropic, and optically transparent medium. The optical material properties included in the simulation were refractive index and Abbe number.

The refractive index determines the bending of light at the IOL surfaces. For a given optical power, a material with a higher refractive index can generally achieve the required focusing effect with lower curvature or reduced thickness. The Abbe number describes chromatic dispersion and is defined as [34,35]:

$$V_d = \frac{n_d - 1}{n_F - n_C} \quad (7)$$

where n_d , n_F and n_C are the refractive indices at the Fraunhofer d , F , and C spectral lines, respectively. A higher Abbe number indicates lower chromatic dispersion, while a lower Abbe number indicates stronger wavelength-dependent refractive variation [34,35,39].

Chromatic dispersion is relevant in IOL design because wavelength-dependent refraction can contribute to longitudinal chromatic aberration and reduce polychromatic retinal image quality. However, the final optical performance of a pseudophakic eye is determined by the combined effects of material dispersion, IOL curvature, corneal aberrations, pupil size, retinal image position, and residual spherical aberration [31-38].

We used the Zemax Model Glass representation, in which the wavelength-dependent dispersion is defined from the refractive index at d -light (n_d , 587.56 nm) and the Abbe number (V_d). Based on these inputs, Zemax automatically interpolates the refractive index at the simulated wavelengths using the Schott dispersion model. The specifications of the selected IOL materials used in our simulation are presented in Table 3 [26,40,41].

Table 3. Specifications of the Evaluated IOL Materials.

Material Class	Common/Trade Name Examples	Chemical compositions	Refractive index (n)	Abbe number (V)	References
Collamer	Staar Surgical, AG	polyHEMA hydrogel (30% water) + 0.3% porcine collagen + covalently bonded UV-blocking chromophore	1.43	45	[6]
Hydrophilic acrylic	Hydrophilic-copolymer (e.g. Centerflex, Akreos)	hydroxyethylmethacrylate (polyHEMA) + hydrophilic acrylic monomer	1.43	58	[45]
Silicone	PDMS, PDMDMS	poly(dimethylsiloxane), poly(dimethyldiphenylsiloxane)	1.43	42	[45], [46]
PMMA	Polymethyl methacrylate	polymerization of methacrylic acid	1.49	58	[47]
Polyisobutylene-based polymer	xPIB IOL (e.g. Eyedea)	Crosslinked polyisobutylene based on SIBS	1.52	50	[27]
Hydrophobic acrylic	Hydrophobic-copolymer (e. g. AcrySof, Alcon Laboratories, Sensar, AMO)	copolymers of acrylate and methacrylate derived from PMMA	1.55	55	[45]

2.6. Material-Specific Optimization Procedure

For each candidate IOL material, the lens design was re-optimized by varying only the anterior and posterior surface radii, while the IOL thickness, diameter, conic constants, and all other ocular model parameters were kept constant to isolate the effect of material properties. The effective IOL optical power was constrained to remain constant at about 19 D, ensuring that differences in optical performance arise from material properties rather than variation in lens power. This approach reflects clinical and industrial IOL design practice, in which a change in material refractive index is generally accompanied by a redesign of the lens surface curvatures to preserve the intended dioptric power.

The optimization was performed using Zemax OpticStudio in Sequential mode using the local optimizer. The merit function was designed to minimize the polychromatic RMS spot radius at the retina for a single on-axis field point (0°). Wavelengths were set to $F = 486.13$, $d = 587.56$, $C = 656.27$ nm. The dispersion curves for the respective IOL materials were automatically computed by Zemax using the specified dispersion formula and the standard interpolation algorithms. To ensure balanced representation across the visible spectral range and

uniform evaluation of the polychromatic performance, the three wavelengths were assigned equal spectral weights of 1.0 (1:1:1 ratio) in the Zemax Wavelength Data editor. Monochromatic evaluations were also performed at the d-line (587.56 nm) to assess monochromatic wavefront aberrations and spherical aberrations.

The retina was modeled as a curved surface with a radius of -12 mm, and its position was fixed to represent optical performance at a constant axial length. The pupil diameter was set to 2.5 mm. The merit function included the XNEG, XXEG, and OPDX operands. XNEG and XXEG were employed as geometrical constraints to control the minimum and maximum edge thicknesses of the IOL, respectively, thereby ensuring physically feasible lens geometries during optimization. Optical performance was evaluated using 54 OPDX operands, which calculated the optical path difference relative to the diffraction centroid. These operands were distributed across three pupil rings and six radial arms and were evaluated at three design wavelengths, resulting in 54 OPDX operands. This sampling scheme enabled optimization of the spot radius relative to the diffraction centroid across the pupil aperture and the selected wavelengths. The optimized IOL surface radii obtained for each material are presented in Table 4.

Table 4. Optimized IOL radii after material-specific optimization.

Material	Optimized anterior radius	Optimized posterior radius
	R_{front} (mm)	R_{back} (mm)
Collamer	5.684	-38.020
Hydrophilic acrylic	5.790	-31.613
Silicone	5.856	-40.373
PMMA	10.986	-26.627
Polyisobutylene	13.190	-31.327
Hydrophobic acrylic	14.771	-39.577
GRIN-IOL ($n = 1.43$)	15.234	-39.287

The optimized radii in Table 4 show that all IOL configurations converged to a biconvex-like sign pattern under the Zemax sign convention, with positive anterior radii and negative posterior radii. This indicates that the optimized designs preserved the general geometrical form expected for a refractive IOL under anterior-to-posterior light propagation.

Among the homogeneous IOLs, lower-index materials such as Collamer, hydrophilic acrylic, and silicone required smaller anterior radii, which correspond to stronger anterior surface curvature. In contrast, higher-index materials such as hydrophobic acrylic, PMMA, and polyisobutylene were optimized with larger anterior radii, indicating weaker anterior curvature for achieving the required focusing behavior. The posterior radius remained negative for all material configurations, but its magnitude changed depending on the material and the optimization result.

The proposed GRIN-IOL showed the largest anterior radius while maintaining a negative posterior radius. This suggests that the GRIN-IOL did not rely only on strong surface curvature for focusing. Instead, its internal

gradient-index distribution provided an additional mechanism for controlling ray propagation and optical power. Therefore, the optimized radii support the idea that both surface curvature and refractive-index distribution contribute to the final optical behavior of the proposed GRIN-IOL.

2.7. Optical Performance Metrics

After optimization, the optical performance of each IOL configuration was evaluated using the MTF, RMS spot radius, and Strehl ratio. These metrics were selected because they describe complementary aspects of image formation. MTF evaluates contrast transfer, RMS spot radius assesses geometrical ray concentration, and spherical aberration characterizes pupil-dependent wavefront distortion [31,32,39,46].

2.7.1. Modulation Transfer Function

The optical transfer function was defined as the normalized Fourier transform of the point spread function defined by [15,48,49]:

$$OTF(f_x, f_y) = \frac{\iint PSF(x, y) \exp[-i2\pi(f_x x + f_y y)] dx dy}{\iint PSF(x, y) dx dy} \quad (8)$$

where $PSF(x, y)$ is the point spread function at the retinal image plane and f_x and f_y are spatial frequencies.

The modulation transfer function was defined as the magnitude of the optical transfer function, [15,48,49]:

$$MTF(f_x, f_y) = |OTF(f_x, f_y)| \quad (9)$$

MTF was computed using the Fast Fourier Transform (FFT) MTF analysis in Zemax OpticStudio. A higher MTF value indicates better contrast transfer at the retinal image plane. Since MTF is affected by defocus, diffraction, spherical aberration, chromatic dispersion, pupil diameter, and retinal image-plane position, it was used as the main objective metric for comparing the optimized IOL designs under identical eye-model conditions [48,49].

2.7.2. RMS Spot Radius

The RMS spot radius was used to quantify the geometrical spread of rays at the retinal image plane, [50]:

$$RMS_{spot} = \sqrt{\frac{1}{N} \sum_{i=1}^N [(x_i - \bar{x})^2 + (y_i - \bar{y})^2]} \quad (10)$$

where N is the number of traced rays. x_i and y_i are the coordinates of the i -th ray intercept, and $\bar{x}$ and $\bar{y}$ are the centroid coordinates of the ray distribution.

A smaller RMS spot radius indicates tighter focusing and reduced geometrical blur. This metric is useful for comparing the focusing behavior of different optimized IOL configurations, especially when the goal is to determine how material-dependent curvature optimization affects retinal ray concentration.

2.7.3. Strehl ratio

The Strehl ratio (SR) is a dimensionless parameter widely used to quantify the optical quality of an imaging system by comparing its performance with that of an ideal diffraction-limited system. It is defined as the ratio of the peak intensity of the aberrated point spread function (PSF) to the peak intensity of the diffraction-limited PSF under identical conditions, [51]:

$$SR = \frac{I_{peak, aberrated}}{I_{peak, diffraction-limited}} \quad (11)$$

where $I_{peak, aberrated}$ is the maximum intensity of the Huygens PSF in the presence of aberrations, and $I_{peak, diffraction-limited}$ is the corresponding peak intensity for an ideal optical system. The Strehl ratio was calculated from the Huygens PSF plot in Zemax OpticStudio at an on-axis field angle of 0° , using the F, d, and C wavelengths (486.1, 587.6, and 656.3 nm, respectively) with equal spectral weights.

2.8. Proposed GRIN-IOL Framework

A GRIN-IOL is proposed as an advanced design framework. Unlike a homogeneous IOL, which has a constant refractive index throughout the optical zone, a GRIN-IOL has a spatially varying refractive-index profile (as shown in Fig. 3). This structure can potentially control ray propagation through both surface refraction and internal refractive-index gradients.

This design is motivated by the optical behavior of the natural crystalline lens. The crystalline lens contributes to the total optical power of the eye not only through the curvature of its anterior and posterior surfaces but also through its internal gradient-index structure [38-40]. Therefore, replacing a cataractous crystalline lens with a GRIN-IOL may provide an additional mechanism for controlling aberrations and improving retinal image quality.

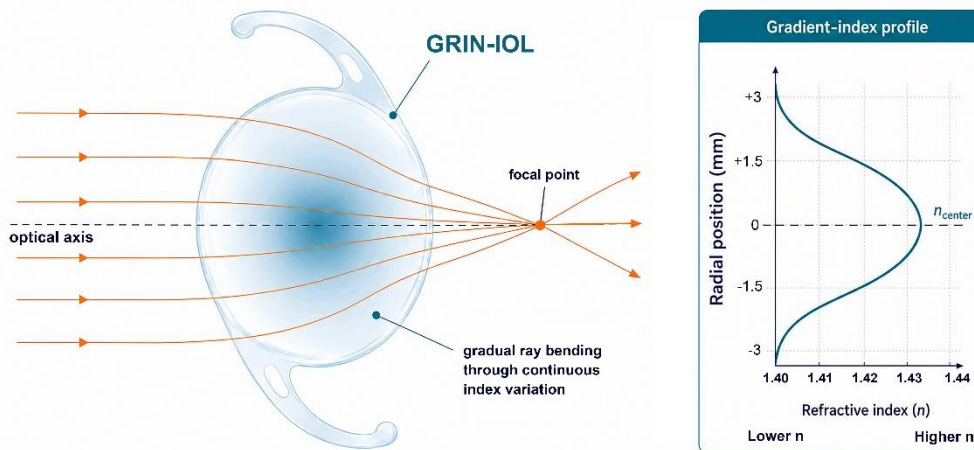


Fig. 3. Conceptual schematic of the proposed GRIN-IOL.

Fig. 3 illustrates the conceptual structure of the proposed GRIN-IOL and the corresponding radial refractive-index profile. In this design, the refractive index is higher near the central optical zone and decreases toward the peripheral region of the lens. This spatial variation of refractive index allows the rays to bend gradually inside the IOL rather than only at the anterior and posterior surfaces. Therefore, the GRIN-IOL provides an

additional internal optical mechanism for controlling ray propagation, focusing behavior, and retinal image quality.

The proposed GRIN-IOL can be described using the same polynomial coefficient structure used for the patient crystalline lens model. In this formulation, the refractive index itself is expressed as a function of radial and axial coordinates, [29,52]:

$$n(r, z) = n_0 + n_{r2}r^2 + n_{r4}r^4 + n_{r6}r^6 + n_{z1}z + n_{z2}z^2 + n_{z3}z^3. \quad (12)$$

For future GRIN-IOL optimization, the design-variable vector can be written as, [52]:

$$\mathbf{x}_{\text{GRIN}} = [R_{\text{front}}, R_{\text{back}}, n_{r2}, n_{r4}, n_{r6}, n_{z1}, n_{z2}, n_{z3}] \quad (13)$$

Table 5 presents the final optimized Gradient 3 parameters of the proposed GRIN-IOL model. In this optimization, the base refractive indices n_0 were kept fixed and were not treated as optimization variables. Only the anterior and posterior surface radii and the selected gradient-index coefficients were varied during optimization. All other eye-model parameters were kept constant to isolate the effect of the GRIN-IOL surface geometry and internal refractive-index distribution.

The coefficients reported as zero were kept inactive in the final model and were not included as higher-order gradient terms. Therefore, the optimized GRIN-IOL profile was determined by the surface curvatures, the selected radial gradient coefficient, and the selected axial gradient coefficients. This configuration allowed the IOL to control ray propagation through both surface curvature and internal refractive-index variation, unlike homogeneous IOLs, which primarily rely on surface refraction.

2.9. Comparative Simulation Protocol

To ensure a fair comparison, all optimized IOL configurations were analyzed using the same base eye model and simulation conditions. The corneal parameters, aqueous chamber, pupil position, pupil size, vitreous region, retinal curvature, and IOL thickness were fixed. Only the IOL material and the optimized IOL radii were changed between configurations.

For each material-specific IOL design, the recorded outputs included the optimized anterior and posterior IOL radii, MTF, representative spot diagram, and Strehl ratio. These outputs were selected to evaluate the relationship between material-dependent curvature optimization and on-axis retinal image quality. The RMS spot radius was used to quantify geometrical image blur, the MTF was used to assess contrast transfer, and the Strehl ratio was used to evaluate the proximity of the optical system to the diffraction-limited condition for the optimized IOL design. The same wavelength setting, field configuration, aperture conditions, and MTF analysis type were applied to all material configurations.

The simulations were performed under polychromatic illumination using three wavelengths of 0.486, 0.587, and 0.656 μm , corresponding approximately to the Fraunhofer F , d and C spectral lines, respectively. These wavelengths were selected to account for chromatic dispersion effects through the refractive index and Abbe number of each IOL material. MTF, RMS spot radius, and Strehl ratio were extracted from the corresponding Zemax analysis outputs for each optimized IOL configuration and are compared in the Results section.

3. Results and Discussion

Fig. 4 shows the retinal spot diagrams obtained for the different IOL materials under identical imaging conditions. In the silicone IOL (Fig. 4a, $n = 1.43$, $V \approx 42$), the polychromatic spot is relatively broad and elongated, yielding an RMS spot radius of 12.698 μm , which reflects the combined effect of residual spherical aberration and the relatively strong dispersion of this material. Substituting silicone with Collamer (Fig. 4b, $n = 1.43$, $V \approx 45$) slightly improves the overlap of the three wavelength components and reduces the RMS radius to 11.927 μm , consistent with the modest increase in Abbe number and the corresponding reduction in longitudinal chromatic aberration.

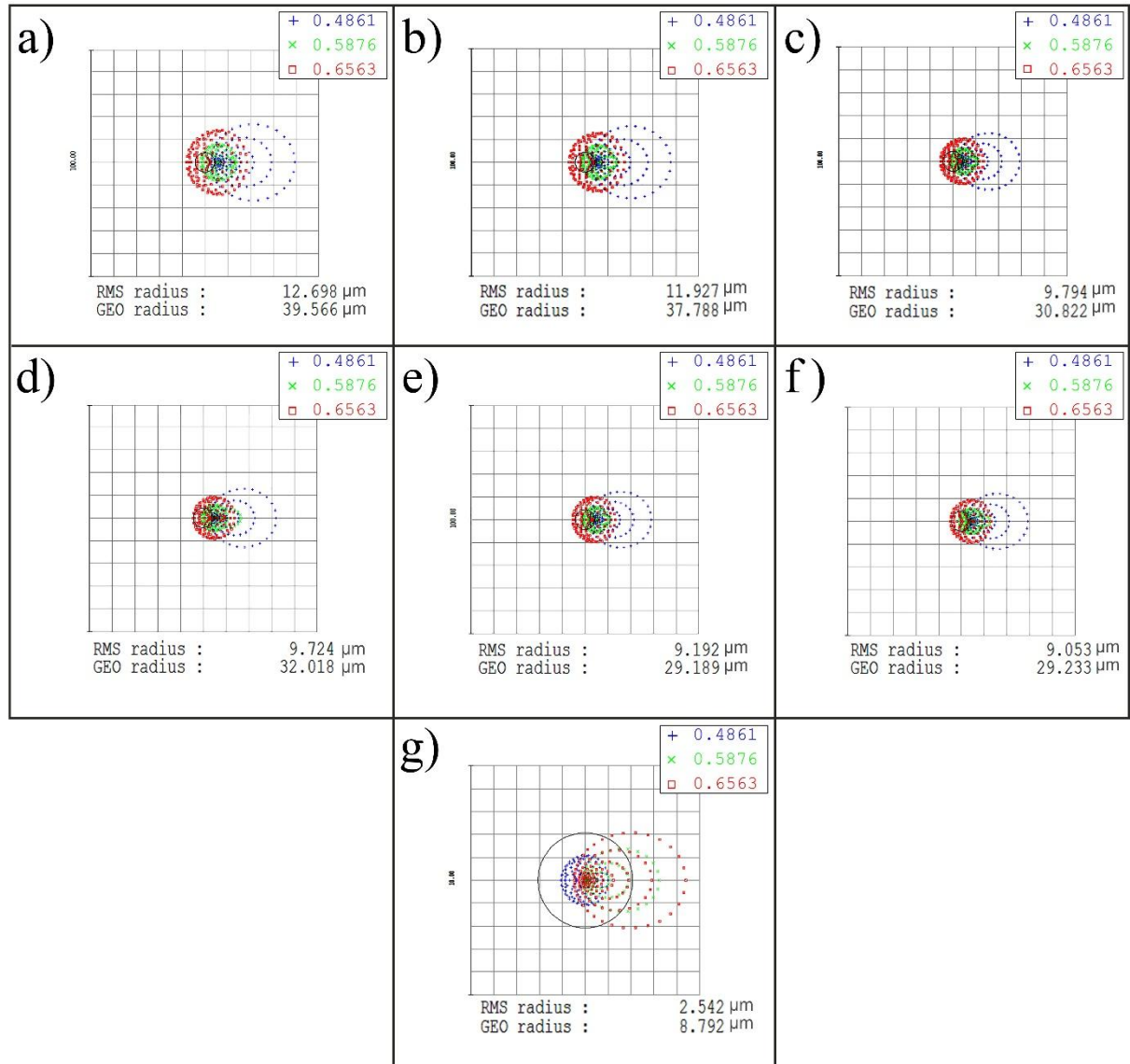
A more marked contraction of the spot is observed when a polyisobutylene-based polymer material is used (Fig. 4c, $n = 1.52$, $V \approx 50$): the higher refractive index allows the same optical power to be achieved with weaker surface curvatures, which alleviates geometrical aberrations and decreases the RMS spot radius to 9.794 μm . The hydrophilic acrylic lens (Fig. 4d, $n = 1.43$, $V \approx 58$) performs at a similar level, with an RMS radius of 9.724 μm . In this case, the relatively moderate index is compensated by the high Abbe number, which effectively suppresses chromatic blur so that the three monochromatic foci largely overlap.

The hydrophobic acrylic design (Fig. 4e, $n = 1.55$, $V \approx 55$) exhibits a further, albeit small, improvement: the spot distribution becomes more compact and symmetric, and the RMS radius drops to 9.192 μm . Among the homogeneous materials, the best performance is obtained with PMMA (Fig. 4f, $n = 1.49$, $V \approx 58$), where the combination of relatively high index and high Abbe number yields the tightest cluster of rays and the lowest RMS radius, 9.053 μm . This result is in line with the long-standing use of PMMA as a reference material for monofocal IOLs.

By contrast, the GRIN-IOL (Fig. 4g, on-axis $n \approx 1.43$) shows a qualitatively different behavior. The introduction of a radially varying refractive-index profile collapses the polychromatic spot so that the three wavelengths become almost indistinguishable in the image plane, and the RMS spot radius is substantially reduced to 2.542 μm . This corresponds to roughly a fourfold reduction compared with the PMMA lens and indicates that the GRIN profile simultaneously mitigates primary spherical aberration and the residual longitudinal chromatic aberration. Overall, the spot-diagram analysis demonstrates that changing the bulk material from silicone to high-index, high-Abbe polymers yields only incremental gains in image quality (from $\sim 13 \mu\text{m}$ down to $\sim 9 \mu\text{m}$ RMS), whereas implementing an appropriate GRIN design places the system close to the diffraction-limited regime, with micrometer polychromatic spot sizes.

Table 5. Gradient-index coefficients of the proposed GRIN-IOL model.

Surface	Lens region	Radius of curvature (mm)	n0	nr2	nr4	nr6	nz1	nz2	nz3
6	Anterior GRIN region	15.234	1.43	-1.990E-003	0	0	-0.064	0.077	0
7	Posterior GRIN region	-39.287	1.407	1.988E-003	0	0	0.012	9.011E-003	0

**Fig. 4.** Retinal spot diagrams of intraocular lenses made from different materials: a) silicone, b) Collamer, c) polyisobutylene-based polymer, d) hydrophilic acrylic, e) hydrophobic acrylic, f) PMMA, and g) GRIN-IOL.

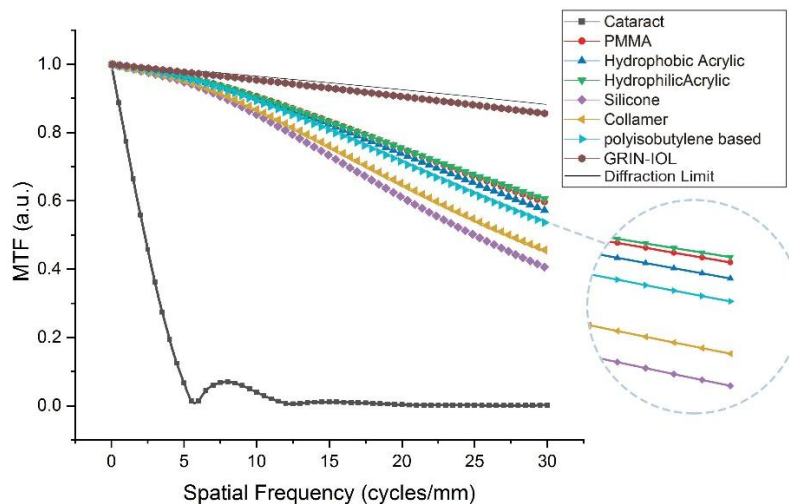


Fig. 5. Resulting FFT MTF of IOLs made from different materials compared with a cataractous eye.

The FFT MTF is a measure of an optical system's ability to transfer contrast at different spatial frequencies from the object to the image. Higher MTF values indicate better retinal image quality, higher contrast, and improved visual performance. Fig. 5 illustrates the MTF across a spatial frequency range of 0 to 30 cycles/mm, comparing the cataractous eye with various IOL materials. The cataractous crystalline lens (black squares) exhibits a significant degradation in contrast, with the MTF dropping to near-zero values at approximately 5 cycles/mm. It should be noted that this reduction in optical quality is not driven by physical light scattering (which was not explicitly modeled in our ray-tracing simulation). Instead, the degraded MTF and contrast sensitivity are caused by wavefront distortions, elevated spherical aberrations, and refractive power shifts arising directly from the pathological alterations in the lens's refractive index distribution, which effectively block high-frequency visual information from reaching the retina.

Upon replacement with IOLs, a significant restoration of image contrast is observed. Among the conventional homogeneous materials, PMMA and Hydrophilic Acrylic (red circles and green downward triangles) demonstrate the highest performance, while silicone (purple rhombuses) shows the most rapid decline in modulation. However, the most striking result is the performance of the GRIN Hydrophilic IOL (brown hexagons).

The GRIN-IOL maintains high and stable MTF across the entire evaluated spectrum, significantly outperforming all other materials. While the best homogeneous lenses (PMMA/Hydrophilic) drop to a modulation of approximately 0.6 at 30 cycles/mm, the GRIN design improves a modulation level above 0.85, providing the patient with a level of image sharpness and contrast sensitivity that closely mimics a healthy crystalline lens. The diffraction-limited MTF reaches approximately 0.9, which is very close to the values obtained for the GRIN-IOL.

The Strehl ratio is a key metric in optical engineering that quantifies how closely an optical system approaches the performance of an ideal, aberration-free system. It is defined as the ratio of the peak intensity of the actual point spread function (PSF) to that of an ideal, diffraction-limited optical system under identical conditions. Higher Strehl

ratio values indicate better optical performance, lower wavefront aberrations, and improved on-axis retinal image quality, while a Strehl ratio of 1 represents a perfect diffraction-limited system. Fig. 6 summarizes the optical performance of the different IOL materials in terms of the Strehl ratio. Among the homogeneous designs, the silicone lens exhibits the lowest Strehl ratio, 0.122, indicating a point-spread function that is strongly degraded with respect to the diffraction-limited reference. Replacing silicone with Collamer leads to a slight increase in Strehl to 0.139, consistent with the modest reduction in longitudinal chromatic aberration obtained with this material.

A more noticeable improvement is observed for the polyisobutylene-based polymer IOL, whose Strehl ratio reaches 0.173. The higher refractive index of this polymer allows the same dioptric power to be achieved with flatter surfaces, which partially alleviates residual spherical aberration and brings the peak intensity of the PSF closer to the ideal case. The hydrophobic acrylic lens further increases the Strehl ratio to 0.202, reflecting the combined benefit of high refractive index and reasonably high Abbe number in controlling both monochromatic and chromatic aberrations.

Among the conventional homogeneous materials, the highest Strehl ratio was obtained for the hydrophilic acrylic design, with a value of 0.243, followed closely by PMMA with a Strehl ratio of 0.227. Although the absolute differences between these polymers are moderate, the improvement from silicone to hydrophilic acrylic represents approximately a two-fold increase in the Strehl ratio, which is consistent with the reduction in the reported RMS spot radius.

The present study evaluates only the optical effects of refractive index and chromatic dispersion. Under these idealized conditions, materials with higher Abbe numbers demonstrated reduced chromatic aberration and improved polychromatic image quality. However, clinical studies frequently report superior visual outcomes with hydrophobic acrylic IOLs due to factors not included in the optical model, such as reduced posterior capsule opacification, lower incidence of long-term opacification, and improved capsular biocompatibility. Therefore, the

optical superiority predicted by the simulation should not be interpreted as overall clinical superiority.

The GRIN-IOL achieved a polychromatic Strehl ratio of 0.748. Although this value is slightly below the conventional criterion for diffraction-limited performance (Strehl ratio ≥ 0.80) [48], it indicates high optical quality and performance approaching the diffraction limit. The radially varying refractive-index profile efficiently compensates for residual primary spherical aberration and reduces chromatic blur, resulting in a point spread function with a substantially higher peak intensity than those of the homogeneous IOL designs.

To quantify the impact of the refractive index gradient on image quality, we evaluated the primary spherical aberration using the Seidel aberration analysis in Zemax OpticStudio. The conventional homogeneous lens materials (Silicone and Collamer) exhibited a primary spherical aberration coefficient of 0.0025. In contrast, the proposed GRIN-IOL design achieved a reduction of this coefficient to 0.0018. This quantitative decrease in spherical aberration is consistent with the improved MTF and Strehl ratio performance, confirming that changing only the bulk material composition yields incremental gains in image quality, whereas introduction of a properly tailored GRIN profile produces a substantial enhancement, elevating the IOL performance toward near-diffraction-limited imaging conditions.

To investigate the effects of refractive index and Abbe number of IOL materials on on-axis retinal image quality independently, the MTF was plotted for a constant refractive index of 1.55 and variable Abbe number of 37 to 58 (as shown in Fig.7a), and also for a constant Abbe number of 46 and variable refractive index of 1.43 to 1.55 (as shown in Fig.7b). To distinguish the independent effects of refractive index (n) and Abbe number (V) on on-axis retinal image quality, when one parameter (n or V) was varied while the other was held constant, the IOL geometry was re-optimized at each step. Specifically, the anterior and posterior radii of curvature of the IOL were re-optimized using the merit function, incorporating the specified operands, to maintain the target optical power and ensure the system remained in focus on the retina. Therefore, the results presented in Fig. 7 represent the independent effects of the refractive index and the Abbe number after geometrical compensation.

A quantitative sensitivity analysis was additionally performed by plotting the MTF at 30 cycles/mm as a function of Abbe number at constant refractive index (inset of Fig. 7a) and as a function of refractive index at constant Abbe number (inset of Fig. 7b). The resulting trends showed that the MTF exhibited a greater sensitivity to changes in the Abbe number than to comparable changes in refractive index, supporting the conclusion that the Abbe number plays a more significant role in determining the intrinsic optical performance of IOL.

Materials with higher Abbe numbers exhibited higher MTF values at high spatial frequencies, smaller retinal spot sizes, and higher Strehl ratios due to reduced chromatic

aberration. Therefore, from a purely optical perspective, IOL materials with higher Abbe numbers, such as PMMA and hydrophilic acrylic, are predicted to provide better retinal image quality than materials with lower Abbe numbers, such as silicone [28,53]. Nevertheless, clinical material selection must also consider factors not included in the optical model, such as posterior capsule opacification, glistening, biocompatibility, and long-term material stability, which may favor hydrophobic acrylic IOLs despite their lower Abbe numbers. Furthermore, wavelength-dependent absorption, bulk scattering, surface-reflection losses, and microscopic material inhomogeneities were not explicitly modeled. Therefore, the calculated image-quality metrics describe the idealized refractive performance of the simulated IOLs under uniform, homogeneous, and lossless material assumptions.

Since aberrations depend strongly on pupil diameter, simulations were performed at additional pupil sizes (2.5 to 6 mm) to evaluate the robustness of each material (as depicted in Fig. 8). As can be seen, the optical performance of all six homogeneous IOL materials exhibited a noticeable decline in MTF values as the pupil dilated.

As shown in Fig. 8, while the GRIN-IOL achieves the highest absolute optical quality at smaller pupil sizes, it exhibits a steeper rate of MTF decline during pupil dilation compared to the homogeneous designs. Conversely, lower-index materials, such as silicone and Collamer, demonstrate more stable performance, characterized by a significantly shallower slope of MTF degradation as the pupil size increases.

However, high-performance optical designs, particularly GRIN lenses, are inherently sensitive to positional misalignments. To assess the impact of realistic surgical conditions, a sensitivity analysis evaluating the MTF of the proposed design under tilt and decentration was performed. Misalignments were evaluated over clinically relevant ranges: radial decentration up to 0.6 mm and tilt angles up to 5° . While homogeneous IOLs primarily experience an increase in off-axis coma and astigmatism when displaced, the GRIN IOL exhibits a compound optical response due to the simultaneous shift of both surface geometry and the internal refractive-index distribution relative to the eye's visual axis.

As observed in Fig. 9, the simulation results indicate that for minor misalignments within typical surgical tolerances (decentration ≤ 0.3 mm and tilt angle $\leq 2^\circ$), the GRIN IOL retains superior overall MTF values compared to homogeneous designs, effectively preserving retinal image quality.

However, as tilt angle exceeds 3° or decentration exceeds 0.4 mm, the asymmetric phase errors introduced by the displaced GRIN profile lead to a steeper rate of MTF degradation relative to its aligned baseline. This sensitivity underscores the importance of precise capsular bag positioning and highlights a key design trade-off between peak optical performance and tolerance to surgical displacement.

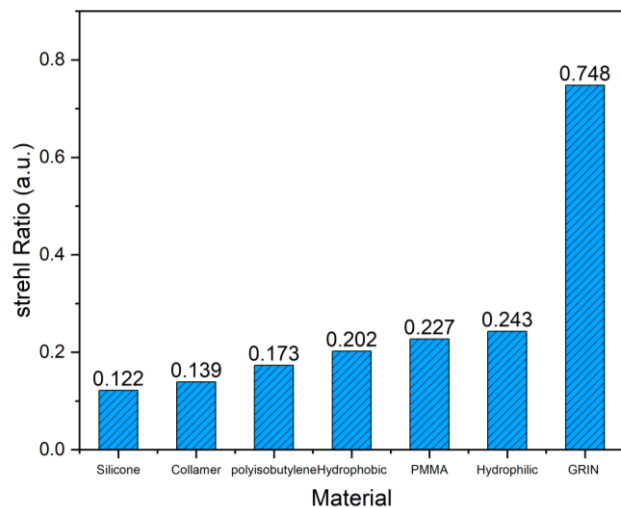


Fig. 6. Comparison of the Strehl ratio of IOLs made from different materials.

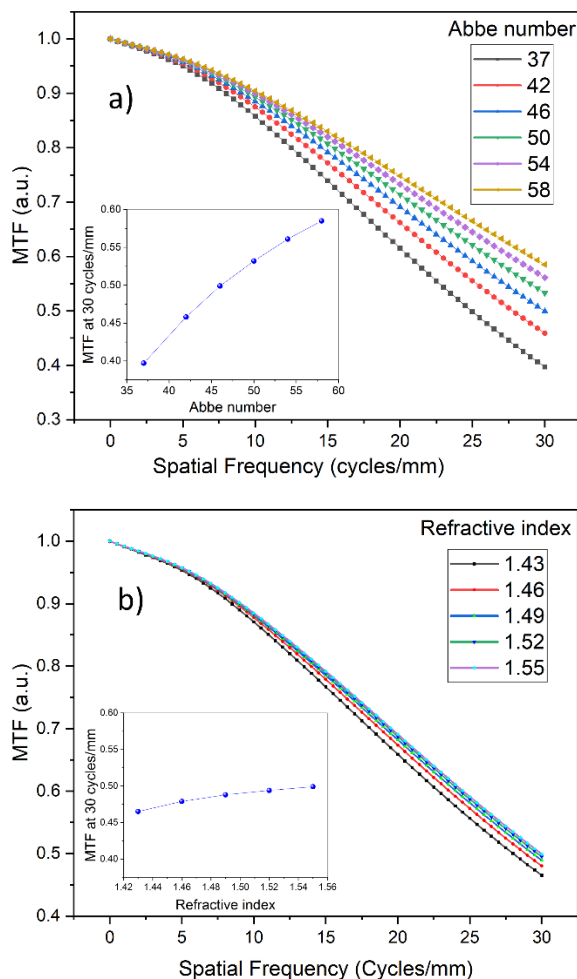


Fig. 7. MTF for a) constant refractive index and variable Abbe number, b) constant Abbe number and variable refractive index.

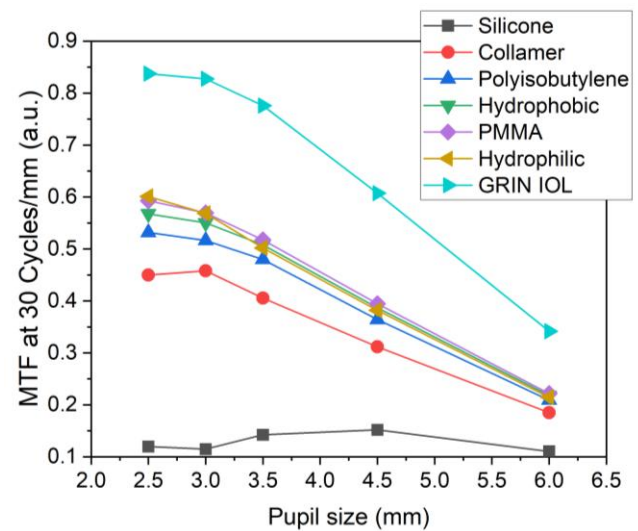


Fig. 8. MTF value at 30 cycles/mm for increasing pupil diameter.

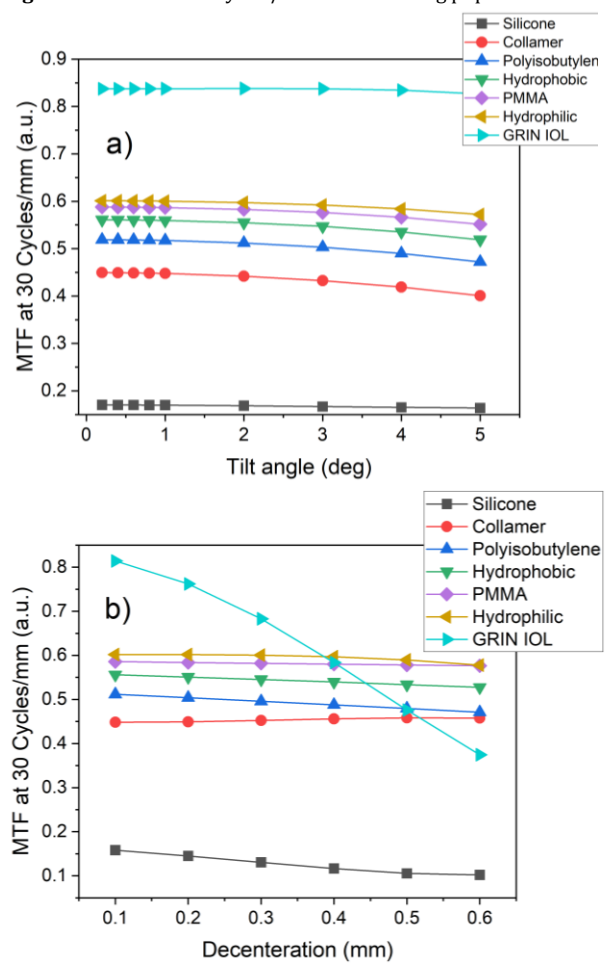


Fig. 9. MTF value at 30 cycles/mm for different IOL configurations under a) tilt and b) decentration.

4. Conclusions

This study investigated the effects of refractive index and Abbe number of IOL materials on on-axis retinal image quality using Zemax ray-tracing simulations. The results demonstrate that the Abbe number affects optical performance much more strongly than the refractive index. Materials with higher Abbe numbers exhibited better MTF, smaller retinal spot sizes, and higher Strehl ratios, primarily due to reduced chromatic aberration, while variations in the refractive index had little effect on on-axis retinal image quality. Among all IOL materials investigated, the GRIN-lens provided the best overall optical performance, with simultaneous reduction in both monochromatic and chromatic aberrations. Conventional homogeneous materials with higher Abbe numbers, such as PMMA and hydrophilic acrylic, also demonstrated superior intrinsic optical performance compared with materials with lower Abbe numbers.

Although these findings provide valuable insight into the role of material properties in IOL optical performance, the simulations considered only the intrinsic optical characteristics of the lens materials. Clinical factors such as biocompatibility, posterior capsule opacification, glistening, long-term material stability, and surgical considerations were not included in the pseudophakic eye model and should therefore be considered when selecting an IOL for clinical use.

Furthermore, the simulated IOLs should be regarded as benchmark material models within a common monofocal pseudophakic optical framework rather than as exact replicas of commercially marketed IOLs. Future studies could incorporate specific commercial IOL geometries and product-level comparisons, together with customized design optimizations, to provide a more comprehensive evaluation of next-generation IOLs.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' Contribution Statement

Conceptualization and study design: (R.M. and M.R.), Data collection and experimentation: (R.M. and M.R.), Data analysis and interpretation: (R.M. and M.R.), Manuscript writing and editing: (R.M. and M.R.), Supervision and project administration: (M.R.).

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