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## ARTICLE

# Correlation with a multifocal intraocular lens of in vitro figures of merit with clinical visual acuity



Jérôme Loicq, PhD, Damien Gatinel, PhD, Nicolas Willet, PhD, Christophe Pagnouille, PhD, Maxime Dietens, Msc, Sarah Trigallez, Msc

**Purpose:** To assess the link between the in vitro optical properties of the PODFGF multifocal intraocular lens (IOL) and its visual acuity (VA) clinical performance.

**Setting:** The study was conducted at TUDelft (NL), ULiege (BE), the Rothschild Institute (FR), and Beaver-Visitec International (BE).

**Design:** The study analyzed 3 powers of the PODFGF IOL. The in vitro imaging quality was assessed using modulation transfer function (MTF) frequency sweep and through-focus MTF. Multiple figures of merit (FOMs), including MTF at 25-50-100 LP/mm, MTFa, and Strehl ratio, were extracted. Data acquisitions followed 2 ISO norms in green and white light conditions. The correlation with patients' clinical VA was evaluated.

**Methods:** The methodology had 2 parts: first, characterizing the in vitro properties of the IOL using FOMs, such as MTF, MTFa, and Strehl ratio, with multiple power samples (6 to 35 diopters). The second part analyzed the VA of 413 eyes implanted with FINE-VISION-HP (PODFGF). Over 2 years, subjective refraction,

uncorrected distance VA, corrected distance VA, uncorrected intermediate VA, distance-corrected intermediate VA, uncorrected near VA, distance-corrected near VA, defocus curve, photopic and mesopic contrast sensitivity, and rotational stability were analyzed.

**Results:** The correlation between in vitro MTFa evaluated from the experimental data on IOLs and the clinical VA performed on implanted patients leads to an accurate prediction of vision capabilities after surgery.

**Conclusions:** This study clinically demonstrates on a large patient cohort that MTFa complements single-frequency MTFs and establishes a mathematical link between MTF at 50 LP/mm, MTFa, and VA. In addition, it connects the 2 ISO model-eye standards and highlights the link between green and white light measurements in accurately predicting VA.

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Predicting the performance of an intraocular lens (IOL) before its implantation in the eye is crucial for the patient and the surgeon. To assess the in vivo capabilities of new IOLs, researchers invest significant effort in designing, prototyping, and testing techniques. As the final product's capabilities must be evaluated in the laboratory, the characteristics should closely match the implanted conditions. Since surgery is an invasive technique, it is often not possible to go back and forth between visual assessment and IOL optical properties. Therefore, lens choice must be made with high confidence.

The ultimate goal is to achieve the best visual comfort for the patient. The main figure of merit (FOM) used to assess this comfort is the patient's visual acuity (VA) after implantation. VA is a subjective perception of vision quality based on a rational measurement scheme.

In the laboratory, researchers rely on other FOMs such as the modulation transfer function (MTF) at single frequencies, the Strehl ratio, through-focus frequency sweep curves, and related integrated values over frequencies. As an example, the MTF at 50 ln/mm is vastly used in the community but does not reflect the overall performances of the IOL.

In the case of a multifocal IOL (mIOL), visual comfort leads to good VA across the optical axis from distant to near vision. Bridging the gap between laboratory measurements of in vitro behavior and the VA of pseudophakic patients is quite a challenge. From a research and innovation standpoint, identifying a set of FOMs that anticipate the quality of vision for patients at various focal distances can help to speed up the development of high-quality products.<sup>1</sup>

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The quality of vision of an implanted patient is influenced by multiple factors, including the intrinsic optical quality of the implanted IOL. However, vision is a complex process that involves the cornea, pupil, brain, binocular vision, and other contributors. To accurately evaluate IOL performance, a mix of objective and subjective quality metrics is required. Although the ISO standard recommends measuring the MTF of IOLs at single frequencies, this does not provide a complete picture of visual quality for pseudophakic patients. In addition, the complex classification of IOLs on the market can be confusing for users. Focusing on lens properties that affect patient performance may provide more useful information.<sup>2</sup>

To address these challenges, Alarcon et al. proposed a methodology in 2016 to predict through-focus VA using preclinical metrics.<sup>3</sup> Although ISO standards primarily focus on MTF at single spatial frequencies, integrated values of MTF over spatial frequencies can better predict VA associated with specific IOLs.<sup>4</sup> The use of integrated MTF values can better reflect the range of frequencies involved in vision and through-focus changes in VA.

Our work is inspired by the methodology proposed by Alarcon and Fidel Vega.<sup>3,5-7</sup> In this study, we extend the scope of the cited papers and we present a correlation matrix between experimental data and clinical VA under different illumination conditions and the 2 ISO standard model eyes. We use the case of the PODFGF IOLs and related VA once implanted in the patient eyes. PODFGF is a trifocal lens based on a double-diffractive pattern. Using the Lang/Alarcon/Vega approach, the IOL VA will be evaluated continuously through their 3 main foci: FAR, INTER, and NEAR. The analysis will be conducted on a large sample made of 3 distant diopters (D): 10 D, 20 D, and 35 D, to ensure statistical significance and representativeness.

In addition to MTF and VA, other factors, such as noise, affect the scene recognition and overall visual quality. For instance, researches show that a limited range of object spatial frequencies is necessary for letter identification, while noise in the 10 to 40 LP/mm range leads to less effective object recognition than in the 40 to 70 LP/mm range.<sup>8,9</sup> By considering multiple factors that affect visual quality, we can better understand the complex nature of vision and make more informed decisions regarding IOL development and their performance.

This study aims to establish an accurate correlation between the in vitro and in vivo FOMs, which will enhance our understanding and prediction of real-world performance. It aims to propose a connection between the 2 ISO model-eye standards. Furthermore, our study explores the relationship between measurements taken in green light and those acquired in white light although the ANSI standard and the Alarcon paper only described measurement in white light under the ISO model eye 2.

## METHODS

In this section, we outline the key elements of this study. First, we present the IOL sample sets being examined. Next, we describe the IOL, including its main characteristics and the principles behind its optical functioning. We also introduce the relevant FOMs

necessary to characterize the lens's behavior. Finally, we provide a detailed description of the experimental procedure and the data reduction.

## PODFGF IOL Under Study

This study focuses on the PODFGF IOL. Its commercial name is FINEVISION HP which is manufactured by the Physiol S.A./Beaver-Visitec International company. The PODFGF is a foldable mIOL made from yellow hydrophobic GFY raw material that contains 4.5% to 5.5% water and includes UV and blue-light filters. The haptic design is a double C-loop "POD" platform, and the optical design is based on an aspheric trifocal diffractive pattern for distance, intermediate, and near vision. The lens is intended for capsular bag implantation and is inserted with a non-preloaded injector. Compared with the well-known FINEVISION lens, FINEVISION HP is made from a higher index of refraction material.

The PODFGF IOL generates 3 foci, respectively, for distance, intermediate, and near vision on the retina. Distance vision is provided by the refractive behavior of the lens, while intermediate and near vision is achieved by an additional diffractive lens system with power additions of 1.75 D and 3.5 D, respectively.

The shape of the diffractive lenses enables smart management of light intensity on each focus. The height of the diffractive structure is critical in determining diffraction efficiency. The zeroth order of the 2 diffractive lenses transmits light for distance vision, while the first diffraction order of each lens focuses light for intermediate and near vision. In addition, the second diffraction order associated with the intermediate focus is located at the near vision location and increases the useful light to that focus.

## Sample Set

To cover the entire range of optical powers of IOLs produced by Beaver-Visitec International/Physiol S.A., tests were performed on 3 lots, each comprising 10 PODFGF IOLs. The 3 lots represent low ( $\leq 15.0$  D), medium (15.5 to 25.0 D), and high ( $> 25$  D) power IOLs that are currently being marketed. All tested IOLs were intended for human eye implantation and had undergone the complete manufacturing process. Before any optical measurement, the IOLs were stored and relaxed (without any holder) in an aqueous solution (0.9% NaCl) at room temperature for at least 24 hours. The optical performance of the IOLs was measured in vitro with the OptiSpheric IOL PRO 2 test bench produced by Trioptics. The average measured spherical aberration at 3 mm of the PODFGF IOL is (0.027, 0.039, 0.023)  $\mu\text{m}$  for the (10 D, 20 D, 30 D) IOL, respectively.

## Imaging Quality

The imaging quality of any optical imaging system is determined by at least 2 complementary components: the quality of focus and the amount of light energy conveyed in each focus. Therefore, the quality of focus must be evaluated and the radiometric behavior. The relative quantity of energy contained in the different foci strongly depends on the diffractive shape of the lens.

Imaging quality refers to the optical resolution achieved by an optical system. The higher the resolution, the better the imaging quality. The relationship between the distribution of light on the focal plane, called the point spread function (PSF), and the receptor system, the retina, must be assessed. The PSF includes all aberrations and the effects of the diffraction both of which affect the image formation. In the spatial frequency domain, the PSF is associated with the MTF, which is the modulus of the optical transfer function, itself the Fourier transform of the PSF. The MTF represents the ability of an imaging system to reproduce in the image plane, the spatial frequencies contained in the object volume. The MTF is also understood as the contrast function depending on spatial frequency. Therefore, MTF is a powerful FOM for assessing the imaging quality of any imaging optical system.

However, it does not directly reflect the system's light transmission efficiency, known as throughput. Throughput accounts for factors such as reflection, transmission, absorption, scattering, and, in diffractive lenses, diffraction efficiency.

Figure 1 presents the experimental MTF acquired on one of the PODFGF lenses under study with a distant power of 20 D. The surface plot in Figure 1a shows the through-focus frequency-sweep MTF. Figure 1b presents the same set of data on a color-coded MTF. The zones corresponding to the distant, intermediate, and near focuses are clearly visible. These zones extend along the frequency axis.

### Figure of Merits

The evaluation of the imaging quality of an IOL is built with multiple FOMs. Most of in vitro FOMs are based on the experimental frequency-sweep MTF obtained from PSF measured along the optical axis. Single-frequency MTF, MTFa, and Strehl ratio are deduced from the MTF frequency sweep. From an optical standpoint, these FOMs are usually sufficient to define the quality of an imaging system because they include all aberrations related to the lens.

The MTF is the modulus of the Fourier transform of the PSF, known as the impulse function of the optical system. The MTF converts the light energy distribution into a spatial frequency-dependent number which describes how the contrast of a scene is transferred through the imaging system at a given frequency. In case of an IOL, the ISO guidelines usually require the evaluation of the

MTF at single frequencies: 25 LP/mm, 50 LP/mm, and 100 LP/mm, assuming that these frequencies characterize enough human vision.

However, MTF frequency sweep of an IOL has a complex dependency with the spatial frequency, which is not necessarily monotonously decreasing, as shown in Figure 1c and d. Providing that, relying only a single-frequency MTF to evaluate lens behavior creates wrong interpretation due to lack of information on its overall performance with multiple frequencies.

As the patient's vision needs multiple spatial frequencies to reproduce the diversity of the observed scenes, IOLs must be design in such a way that most of the spatial frequencies contained in the object domain can be reproduced accurately in the image space.

By consequence, characterizing the IOLs at only a few single frequencies is not enough to cover the entire spatial spectrum of vision. To evaluate the quality of an IOL placed in an eye, the use of quantities that reproduce VA should be stimulated. This is why MTFa, Strehl, and visual Strehl are introduced. Recent works have defined these new FOMs, which integrate broader aspects of the lens's optical properties.<sup>3</sup>

A. Single frequencies correspond to the MTF value at a given frequency. Usually, the 25, 50, and 100 LP/mm are used.

B. MTFa corresponds to the integrated value of the MTF curve between frequency 0 LP/mm and 50 LP/mm:

$$\text{MTFa} = \iint_0^{50} \text{MTF}(f_x, f_y) df_x df_y \quad (1)$$

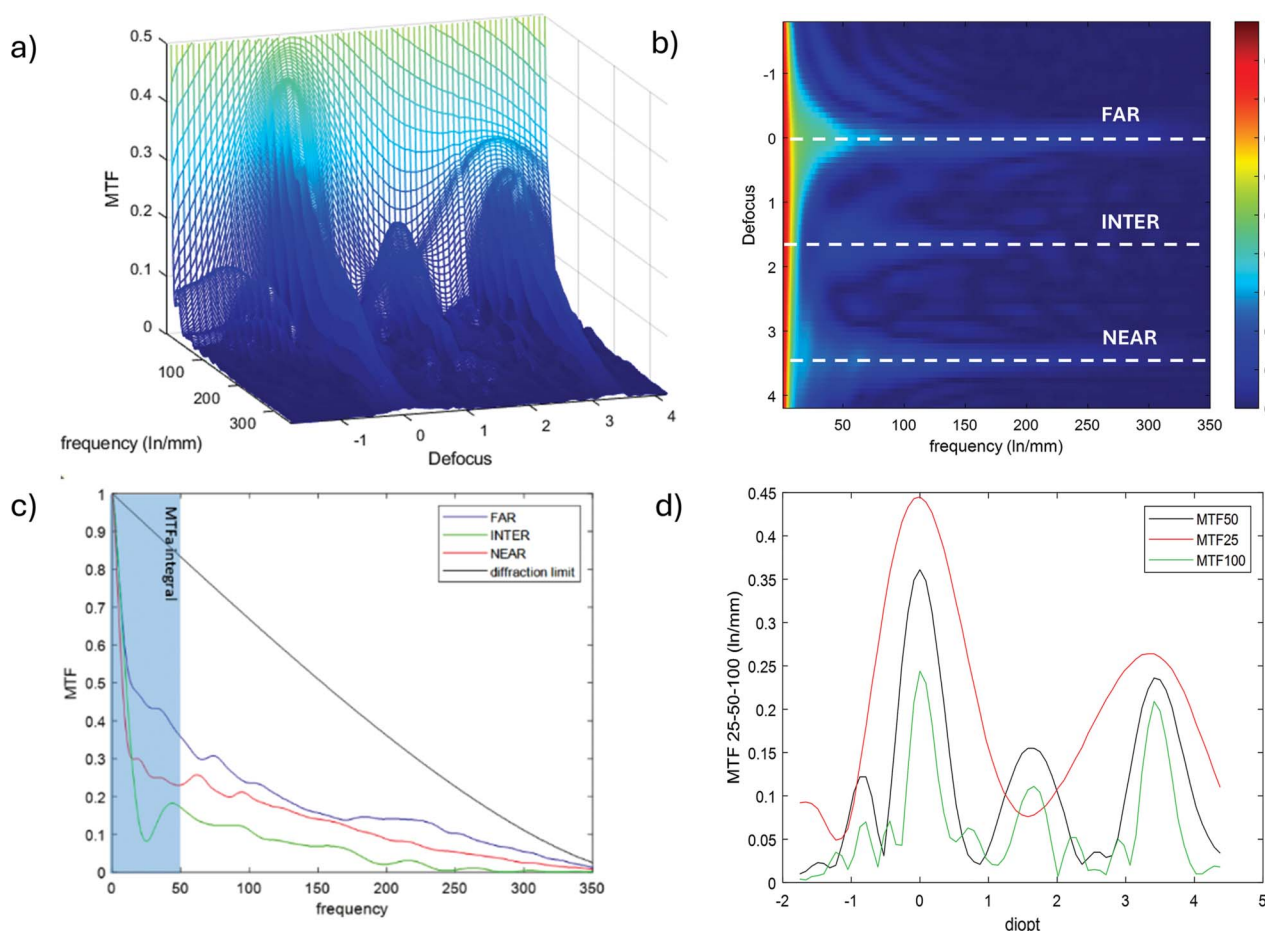


Figure 1. Experimental dataset of the MTF frequency sweep along the optical axis (defocus) associated with the PODFGF-20 D (graphs a and b). Graph c represents the frequency sweep for the same sample at the best focus (dashed lines in graph b). Graph c displays MTF through-focus curves at 25, 50, and 100 LP/mm spatial frequencies. The shaded zone in b and c corresponds to the integration area for the MTFa. The measurements were acquired under 3 mm pupil aperture, in green light with an ISO1 cornea. MTF = modulation transfer function

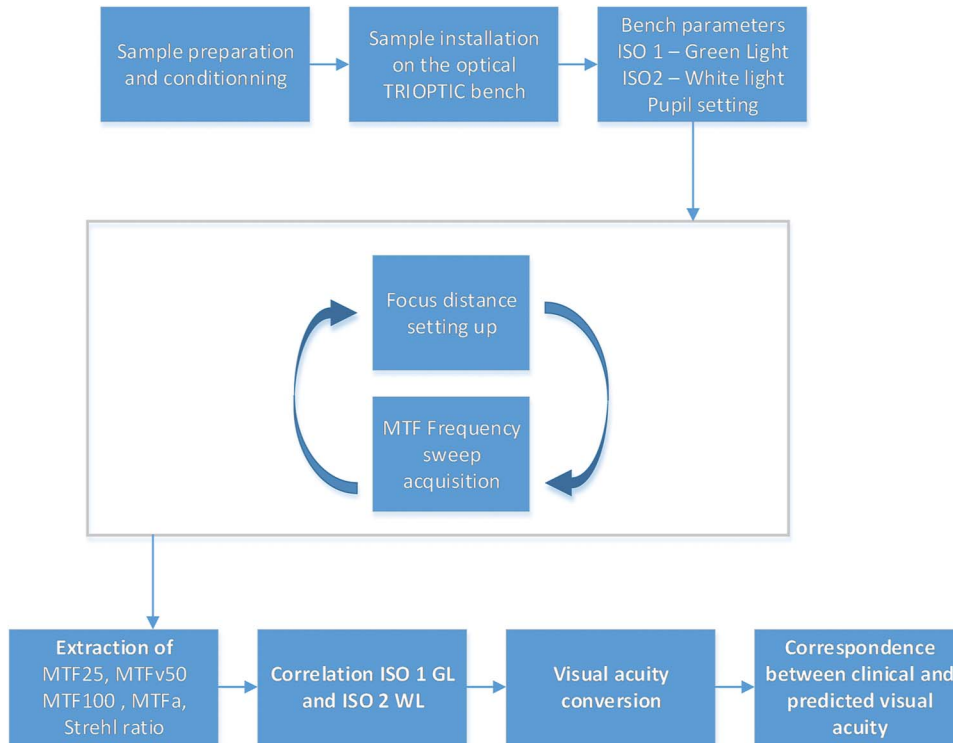


Figure 2. Experimental data acquisition and analysis process.

C. Strehl ratio measures the quality of an imaging system compared with its diffraction limit. Mathematically, it corresponds to the ratio of the integrated MTF to the related diffraction limited MTF.

$$SR = \frac{\left( \iint MTF(f_x, f_y) df_x df_y \right)}{\left( \iint MTF_{\text{diffract}}(f_x, f_y) df_x df_y \right)} \quad (2)$$

D. Visual Strehl is the Strehl ratio integral limited to the range [0; 50] LP/mm.

Figure 1b shows the experimental MTF variation with the frequency (horizontal axis) and the through-focus (vertical axis). Light blue zones represent the influence of each focus. In graph-c, the 3 curves represent the MTF-frequency sweep acquired at each of the best foci, while the black line is the diffraction limit. The shaded area represents the MTFa integration zone. The use of integrated MTF smoothens its variation. As it will be demonstrated later, MTFa will result to a FOM predicting better the VA of patient once the lens is implanted in eyes. In addition, clinical VA is a crucial in vivo FOM used to assess the performance of IOLs after implantation. It provides a comprehensive evaluation of the lens's optical behavior. The objective of this study was to establish an accurate correlation between the in vitro and in vivo FOMs, thus enabling a better understanding and prediction of the performances in the real world.

### Measurements and Analysis Procedure

Figure 2 displays the procedure we used in this study, including experimental data acquisition under multiple illumination condition and clinical VA.

**Sample Preparation and Conditioning** All of the measured IOLs in this study were specifically designed for implantation in the human eye and underwent a complete manufacturing process at Beaver-Visitec International/Physiol S.A. Before optical measurements, each lens was stored and allowed to relax in an aqueous solution (0.9% NaCl) at room temperature for at least 24 hours.

**Sample Installation on the Optical Trioptics Bench** The IOL samples are placed on a holder designed for routine measurement of the through-frequency MTF. The MTF measurements are acquired using the Trioptics optical bench.

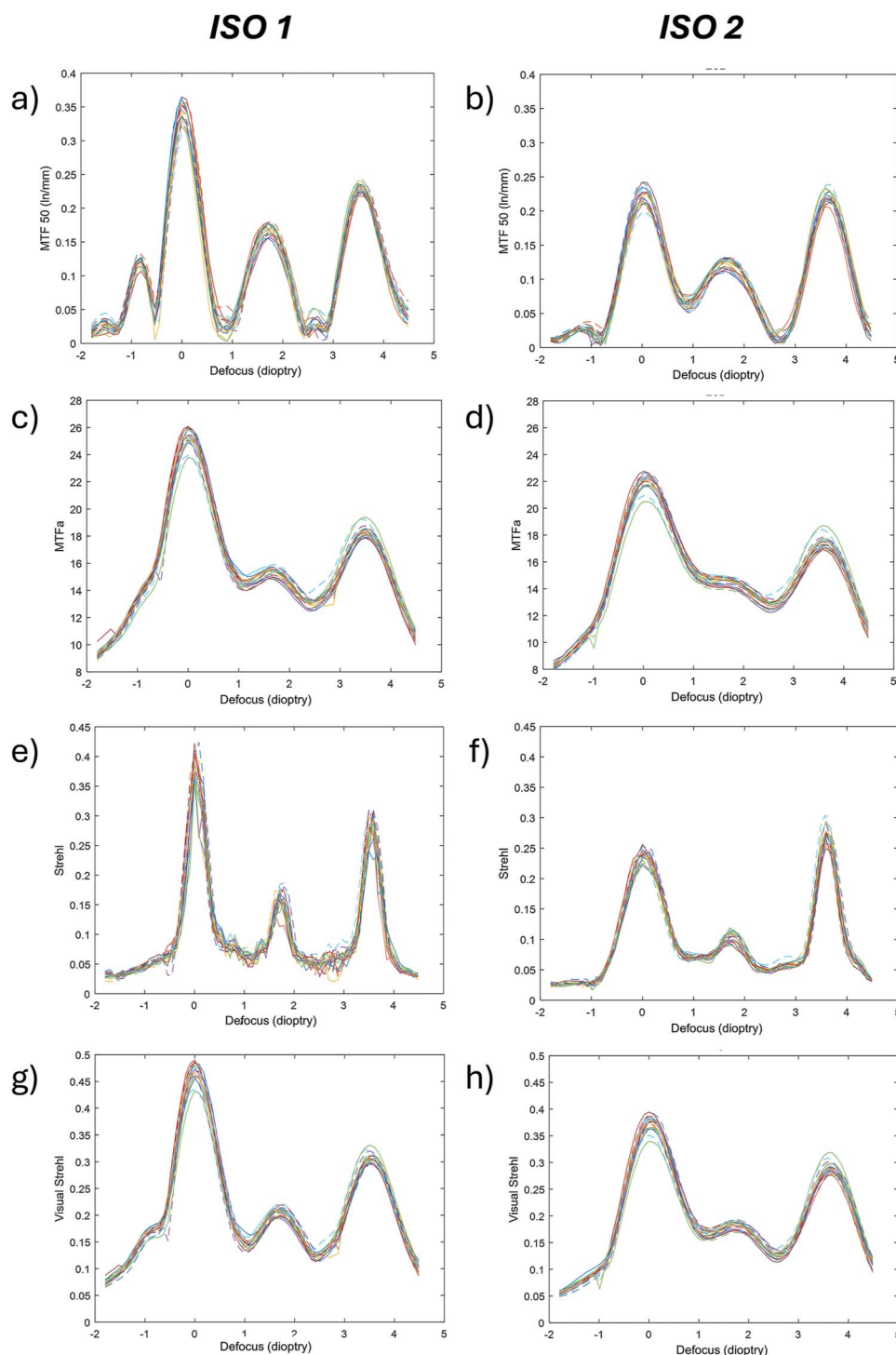
**Bench Parameters** The MTF was evaluated under different experimental conditions, including a 3 mm pupil size and the independent use of 2 ISO corneas. The aberration-free cornea (ISO 1) was used under green light (552 nm), while the aberrated cornea (ISO 2) was used under white light, reproducing the photopic response of the eye. The spherical aberration of the cornea ISO2 model eye is set at 0.28  $\mu\text{m}$  on the Trioptics bench.

**Through-Focus MTF and Frequency Sweep** The through-focus MTF is obtained with the acquisition of the MTF frequency sweep all-along the optical axis. Through-focus MTF characterizes the focusing properties of the lens about defocus. In multifocal lenses, the image quality is best at the main focal points: distance, intermediate, and near vision.

**Figure of Merit** From the MTF frequency sweep obtained following the previous item procedure, the described FOMs are extracted following their equations. As an example, the single-frequency MTF50 (50 LP/mm) highlights 3 main peaks (Figure 3a). Each of them is associated with the main foci of the trifocal lens. An identical procedure is applied for the 2 other single frequency usually used, MTF25 (25 LP/mm) and MTF100 (100 LP/mm). Based on the measurements presented in Figure 1, integration over a frequency domain allows for the extraction of the MTFa, Strehl ratio, and visual Strehl ratio.

**FOM Correlation** The objective of this task is to assess the relationships between the various FOMs. The defocus is the common variable between the different FOMs. Providing that corresponding FOMs at each defocus value are made in correspondence with each together. Finally, correlations and trends are determined between the different FOMs under the 2 ISO corneas.

**VA Correlation** After evaluating the implanted PODFGF IOLs clinically, the average VA was obtained. The correlation between VA and the FOM was then assessed, and trends determined.



**Figure 3.** Based on the frequency sweep MTF (PODFGF lenses at 20 D) measured along the optical axis as presented in Figure 1, the MTF value at 50 LP/mm is extracted and presented as a function of defocus. The measurements are made using the ISO1 standard under green light (a), while the data under white light are obtained using the ISO2 standard (b). The aberration contained in the ISO2 cornea tends to smooth the curves and reduces the MTF values. Multiple curves are associated with multiple samples measured. In this case, the PODFGF lens designed for 20 D is presented. Identically, the MTF frequency sweep acquired along the focus allows for the extraction of the MTFa (graphs c and d), Strehl ratio (graphs e and f), and visual Strehl ratio (graphs g and h). Multiple samples are measured for statistical analysis purposes. MTF = modulation transfer function

## RESULTS

### Through-Focus

Following the procedure described above, multiple PODFGF IOLs at different distant powers (10 D, 20 D, and 35 D) were characterized on the Trioptic bench. The sample sets include 10 lenses per reference. From the MTF frequency sweep acquired along the optical axis, MTF through-focus dependencies are obtained. MTFa, Strehl ratio, and visual Strehl are deduced with equations 1 and 2.

In Figure 3a and b, graphs display the MTF through-focus curves for each of the lenses at 20D. The left graph shows the ISO1 curves in green light and 3 mm aperture, while the right one displays the MTF50 under white light and ISO2 cornea at 3 mm aperture condition. In both ISO conditions, the 3 focal peaks are visible. Considering the FWHM of each of the foci, the ISO2 condition under white light generates larger peaks because of the spherical aberration of that artificial cornea. The increase of the peak width goes

Parameter	PODFGF
Patient	220
Eyes	413
Sex(F/M)	63.6/36.4
Age (y)	63.3 ± 8.4 (44 , 84)
IOP (mm Hg)	15.97 ± 3.11 (9, 29)
Sphere (D)	1.12 ± 2.21 (-8.5, 8)
Refractive cylinder (D)	-0.58 ± 0.54 (-3.5, 0)
SE (D)	0.83 ± 2.21 (-8.75, 7.75)
Monocular UDVA (logMAR)	0.45 ± 0.3 (-0.12, 1.34)
Monocular CDVA (logMAR)	0.12 ± 0.17 (-0.24, 1)
K1 (D)	43.03 ± 1.44 (36,97, 46,68)
K2 (D)	43.61 ± 1.44 (37,51, 47,24)
Corneal astigmatism (D) - DeltaK	0.58 ± 0.31 (0, 1.77)
AL (mm)	23.42 ± 1.02 (20.44, 27.86)
LT (mm)	4.41 ± 0.44 (3.29, 6.24)
ACD (mm)	3.12 ± 0.41 (1.99, 4.29)
WTW (mm)	12.08 ± 0.39 (11, 13.29)
Spherical IOL power (D)	22.3 ± 3 (11.5, 33)
UDVA (logMAR)	0.45 ± 0.3 (-0.12, 1.34)
CDVA (logMAR)	0.12 ± 0.17 (-0.24, 1)
DCIVA (logMAR)	0.34 ± 0.28 (-0.22, 1.2)
DCNVA (logMAR)	0.34 ± 0.28 (-0.2, 1.2)

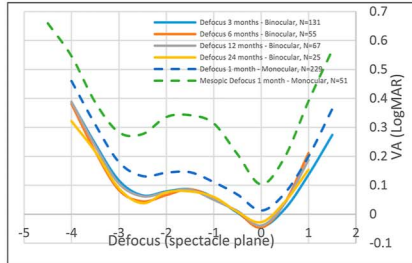
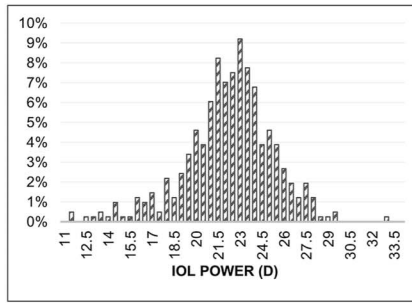


Figure 4. Left: IOL power distribution implanted into eyes (indicates the nb of eyes and patients). Right: Average VA of the population of eyes implanted with PODFGF and following the distribution described at left.

from 0.1 to 0.5 dioptry. In addition, white light illumination condition leads to additional chromatic aberrations which widen the peaks. This effect is equally visible on the graphs in Figure 3d, f, and h. MTFa, Strehl ratio, and visual Strehl are compared under both illumination conditions and ISO cornea: Figure 3a, c, e, and g for ISO1 and Figure 3b, d, f and h for ISO2. As the peaks widen, their maximal values decrease. This is explained by light energy spreads around the focal points, leading to lower contrast.

**Patient Sample Description**

In this study, 220 patients were implanted with a total of 413 eyes between 2018 and 2021. The patients of the cohort

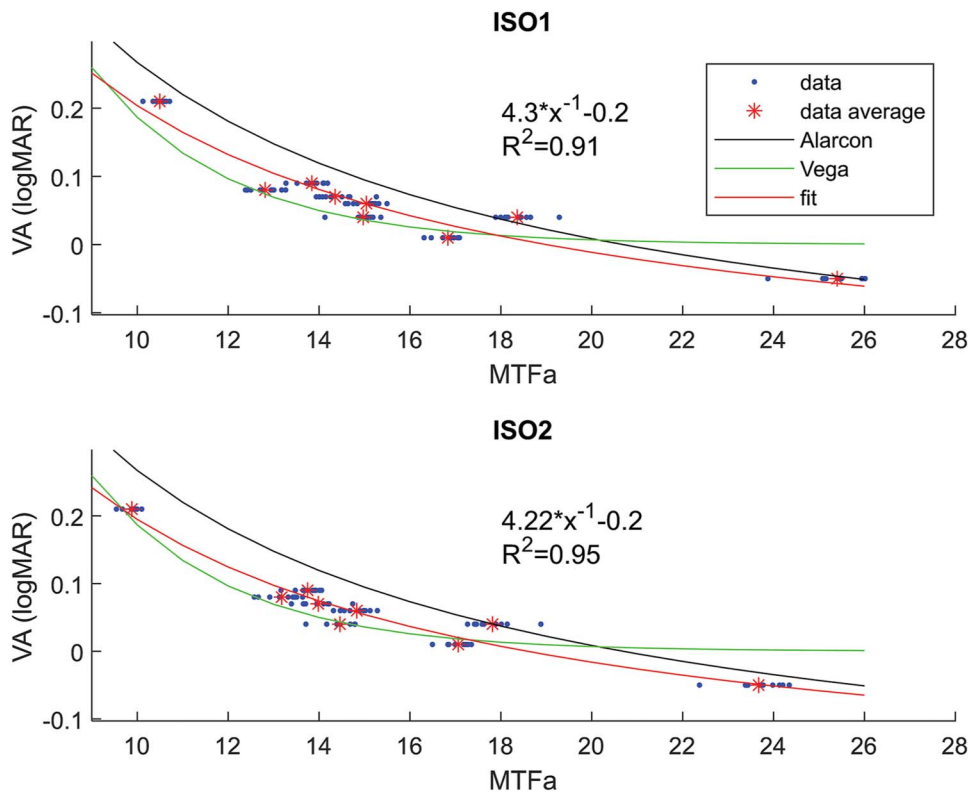
were implanted with PODFGF. The female/male ratio was 63.6%/36.4%. The average patient age was 63.3 ± 8.4 years (ranging from 44 to 84). The preoperative characteristics of the patient cohort are presented in Figure 4 (left).

The distribution of the IOL power implanted into the eyes is shown in Figure 4 (upper right). For each patient, the VA was monitored during the 2 first years after their implantation. The average VA acuity is presented in Figure 4 (bottom right). The patient pupil size was not controlled during clinical testing.

The clinical study results illustrate the changes in VA relative to the defocus curve over time. The curves were obtained at different time intervals after implantation, and

Table 1. Correlation coefficient between figures of merit in the condition of the ISO1 standard (upper). The same correlation in ISO2 is represented in bracket (). Correlation coefficient of the same figure of merit in both ISO conditions (bottom).						
ISO1 (ISO2)						
	MTF 25	MTF 50	MTF 100	MTFa	Strehl ratio	Visual Strehl ratio
MTF 25	1					
MTF 50	0.87 (0.76)	1				
MTF 100	0.73 (0.46)	0.83 (0.82)	1			
MTFa	0.89 (0.9)	<b>0.95</b> (0.63)	0.71 (0.28)	1		
Strehl ratio	<b>0.93</b> (0.54)	0.85 (0.73)	0.77 (0.81)	0.83 (0.3)	1	
Visual Strehl ratio	<b>0.95</b> (0.98)	<b>0.94</b> (0.79)	0.72 (0.46)	<b>0.98</b> (0.93)	<b>0.91</b> (0.54)	1
ISO1 vs ISO2						
	MTF 25	MTF 50	MTF 100	MTFa	Strehl ratio	Visual Strehl ratio
MTF 25	<b>0.99</b>					
MTF 50		0.65				
MTF 100			0.52			
MTFa				<b>0.98</b>		
Strehl ratio					0.55	
Visual Strehl ratio						<b>0.95</b>

MTF = modulation transfer function  
 Bolded values correspond to values above 0.9.



**Figure 5.** The couples of experimental values ( $MTF_a(\text{defoc}_i)$ ,  $VA(\text{defoc}_i)$ ) under ISO1 and ISO2 conditions are shown as blue dots. The red stars represent the average over 10 lenses per dioptre. The black and green lines correspond to the Alarcon and Vega models, respectively, while the red curve has a similar expression to the Alarcon model with the parameters adjusted to better fit the data. MTF = modulation transfer function

the data were collected under both monocular and binocular conditions for comparison. As anticipated, the binocular defocus curves demonstrated higher performance efficiency than the monocular defocus curves. As the VA acuity seems to be stabilized after 6 months, we will use the 6-month binocular defocus curves as the in vivo reference for establishing the relationship between in vitro FOM and the defocus curve.

### Trends and Correlations

The following section aims at establishing the correlations between the different FOMs acquired during the lens characterization process. Our ultimate goal is to develop a precise and efficient method of characterizing lenses that is closely linked with the final FOM, that is, the patient's VA. In a production chain, a minimal number of parameters should be verified to reduce costs while maintaining sufficient quality management. It is essential to determine the optimal number of parameters to be checked to achieve this goal. In addition, the right measurement strategy can save significant time and money, especially in the development of new products. Evaluating the final results of the implanted lens in the eye can provide a clearer direction and improve developers' confidence.

On an experimental bench, IOL MTF properties are acquired under 2 cornea conditions: unaberrated (ISO1) and aberrated (ISO2) with different wavelengths and ranges of FAR power at 3 mm aperture. ISO2 characterization is typically conducted under white light to simulate normal illumination conditions, while ISO1 characterization is

performed under single-frequency illumination. Vega et al. used an aberration-induced artificial cornea (ISO2) to simulate the averaged human spherical aberration. In our case, we will compare the effects of both aberration conditions because the ISO1 is more representative of the intrinsic IOL's optical properties. To be as close to the real conditions as possible, we routinely select the aberrated cornea under white light illumination. However, an unaberrated cornea illuminated with monochromatic light provides a better understanding of the intrinsic optical behaviors of the lenses. All experimental results were obtained with a 3 mm pupil aperture.

### FOM Correlation

In the following section, we will examine different correlation configurations and identify the optimal configuration for accurately characterizing and anticipating the VA of the patient. Owing to the numerous possible combinations of FOMs to characterize the lens, we have chosen to present only the most relevant correlations, which are presented in Supplemental Figures 1, 2, and 3 (available at <http://links.lww.com/JRS/B353>, <http://links.lww.com/JRS/B354>, <http://links.lww.com/JRS/B355>). Some combinations exhibit poor correlation properties, such as in Supplemental Figure 4 (available at <http://links.lww.com/JRS/B356>). All the combinations followed the same data analysis and processing as described in the previous section, with MTF frequency sweep curves acquired along the optical axis and defocus parameter. To establish a relationship between 2 FOMs, the values obtained at a single

defocus are compiled to create pairs of X and Y values, such as

$$[X, Y]_{i,j,k} = \left[ \text{FoM}_{i,j,k}^a(d), \text{FoM}_{i,j,k}^b(d) \right]$$

where  $\text{FoM}^{a,b}$  is one of the FOMs (MTF 25, 50, and 100, MTFa, Strehl, or Vis Strehl),  $i$  is the index associated with the lens sample number related to the inventory,  $j$  is the index relative to the dioptre of the lens,  $k$  is the focus of interest (far, inter, and near), and  $d$  is the defocus.

After obtaining the  $[X, Y]$  pairs for each combination of FOMs, they are plotted on a graph and linear correlation is analyzed. The resulting correlation coefficients are calculated and presented in Table 1. By examining the correlation coefficients, we can determine the best configuration for an optimal characterization and anticipation of the patient's VA because the next step is to make the relevant correlation with the VA.

The correlation coefficients  $R^2$  for all FOM combinations are reported in Table 1 (upper) for the ISO1 standard condition, ISO2 condition is in bracket. Table 1 (bottom) presents the cross-correlation coefficient between ISO1 and ISO2.

### Correlation With the VA

Our aim is to establish a relationship between MTFa and other FOM with the defocus curve. To do this, we needed to eliminate the common variable between the in vivo and in vitro curves, which is the dependency on the defocus parameter. For each value of the defocus curve, a pair of values ( $\text{MTFa}(\text{defoc}_i), \text{VA}(\text{defoc}_i)$ ) were recorded and stored in a mathematical vector. The sampling was adjusted to the largest. In this case, it is the VA sampling at 0.5D, commonly used in VA studies.

To establish an accurate correspondence between the in vivo and in vitro data, we chose to scale both defocus dependencies to be in the spectacle plane. The result of the scaling process is shown in Supplemental Figure 5 (available at <http://links.lww.com/JRS/B357>). The horizontal axes of the MTFa, Strehl, visual Strehl, and MTF50, 25, and 100 curves have been scaled down by a factor of 0.71. This adjustment aligns the peak positions of the curves, allowing for direct comparison of their respective maxima.

The couples of values  $(\text{MTFa}, \text{VA})_i$  for each defocus value were plotted (Supplemental Figure 5, available at <http://links.lww.com/JRS/B357>). Depending on the selected spatial frequency, the through-focus characteristics can differ significantly. As already stated, it can result in a loss of information.

The couples  $(\text{MTFa}, \text{VA})_i$  are reported in Figure 5 for both illumination conditions and model eye cornea. The blue dots represent data collected from 30 lenses, with 10 lenses for each diopter value (10 D, 20 D, and 30 D). The primary source of dispersion on the MTFa values is not related to the diopter values. Instead, it is more closely associated with the variations among the lens samples.

We used Matlab and nonlinear fitting toolbox to process the correlations between the VA and the MTFa. The result of our fitting is presented in Figure 5 by the red curve "fit" and is based on the Alarcon equation<sup>3,7</sup>:

$$\text{VA}(\text{MTF}_a) = a(\text{MTF}_a)^{-1} + b$$

The "Alarcon" and "Vega" models are also represented in Figure 5 as a reference. The parameters and the equations are reproduced from the related publications.<sup>3,7</sup> In our model, we chose the same mathematical expression as the Alarcon equation, which allows us to reach negative values of VA, whereas the Vega model does not. Our fitting parameters are slightly different. We also found that the correlation was better within ISO2 condition than ISO1.

### DISCUSSION

The main objective of this study was to establish a direct correlation between in vitro measurements and in vivo results. This link is crucial to assess the impact of changes in the design of IOLs some of which may have a significant effect on a patient's vision, and manufacturers aim to anticipate such effects. Vision and scene recognition are complex processes involving subjective and objective factors, making it necessary to choose the best set of FOMs. We found that multiple and complementary FOMs need to be used, and in this regard, the frequency through-focus sweep-MTF generates the most powerful set of data. MTF incorporates the effects of IOL aberrations and the related impact on image quality, making it a standard of measurement. FOMs, such as MTFa, Strehl ratio, and the single-frequency MTF at 25, 50, and 100 LP/mm, are extracted from the MTF curves.

For characterizing patient vision, the most useful FOM is VA, which is obtained through clinical studies. The trends are evaluated using statistical methods with a large number of patients and with different periods of time used to quantify the vision capabilities. Our study begins with evaluating the trends between different FOMs. Table 1 (upper) presents the correlation between FOMs under the ISO1 and ISO2 standards, respectively. Our analysis shows that only linear relationships were identified. Furthermore, Table 1 (bottom) exhibits the cross-correlation properties between the ISO1 and ISO2 cornea, evaluating the transition from one to the other. Notably, the MTF at 100 LP/mm generated poor correlations with any of the other FOMs in both ISO standards, while MTF 50 and MTF25 yielded significantly better coefficients, particularly for spatial-frequency integrated FOMs such as MTFa and Strehl. In the ISO1 condition, the best correlation was observed between MTF50 and MTFa, from single-frequency MTF to spatial-frequency integrated FOMs.

Finally, we performed a correlation between MTFa and VA. Alarcon and Vega studies have demonstrated that MTFa is the best FOM to be correlated with VA. In that case, the relationship is not linear, showing a dependence in  $(\text{MTF}_a)^{-1}$  with VA. As Alarcon studies suggest, the correlation coefficient between VA and MTFa was better in the ISO2 condition. We came to the same conclusion, even if the fitting parameters presented in International Organization for Standardization and Vega et al. are slightly different than ours.<sup>4,7</sup> Nevertheless, the dependency of the VA with  $\text{MTF}_a^{-1}$  is confirmed.

Regarding the main goal of the study—to establish an accurate correlation between the in vitro and in vivo FOMs and to link these correlations between the 2 ISO model-eye standards under green light and white light—we deduced the following sequence. Three steps are required to achieve this link. An in vitro single-frequency FOM measured in ISO 1 will be linked to the average VA as follows: (1)  $(MTF50)_{ISO1} \rightarrow (MTFa)_{ISO1}$ , (2)  $(MTFa)_{ISO1} \rightarrow (MTFa)_{ISO2}$ , and (3)  $(MTFa)_{ISO2} \rightarrow VA$ .

As a consequence, an in vitro MTF at a single frequency (50 lines/mm) measured under the ISO 1 standard is linked to VA through a change of variable from ISO 1 to ISO 2 using the MTFa FOM. The MTFa is then accurately linked to VA, confirming the deduced dependency presented in Alarcon et al. in white light under ISO2 model eye.<sup>5</sup>

However, compared with the state of the art, our study adds the correlation link between the 2 ISO standards and the 2 illumination conditions. It also demonstrates that with a single-MTF value at 50 lines/mm, measured under ISO 1 with green light, the prediction of VA can be achieved.

The relationship between in vitro characterization of IOL and their impact on patient vision is a complex one. Many components have to be considered, including the eye's natural aberrations and the brain's processing of visual information. The evaluation of IOL performance requires multiple FOM due to the multifrequency nature of vision. Although previous studies have primarily focused on through-focus MTF at 50 LP/mm, this approach is limited because vision involves multiple spatial frequencies. To address this limitation, frequency-integrated FOMs such as MTFa, Strehl ratio, and visual Strehl parameters have been developed to provide a more comprehensive evaluation of IOL performance. On the other side, VA is another important factor in assessing patient vision.

Our study was conducted on patients implanted with PODFGF IOL and focused on the correlation between multiple FOMs measured on the optical bench and VA. Our results support previous studies that demonstrate a strong correlation between MTFa and VA. In addition, we sought to create a direct link between MTF50 LP/mm FOM and VA through the ISO standard.

MTF50 is a commonly used FOM that provides information on the IOL's spatial resolution, but it may not be sufficient to fully characterize the IOL's optical quality. Other FOMs, such as MTFa and Strehl ratio, may provide additional information that is important for assessing the IOL's visual performance.

Integrating over a larger spatial frequency band may provide a more representative measure of the IOL's visual performance because it takes into account a wider range of spatial frequencies that are relevant to human vision. After evaluating the implanted PODFGF IOLs clinically, the average VA was obtained. The correlation between VA and the FOM was then assessed, and trends determined the importance of considering multiple FOMs and integrating frequency ranges that correspond to the best visual agreement to comprehensively evaluate IOL performance.

## WHAT WAS KNOWN

- The ISO standard for assessing IOLs primarily focuses on single-frequency modulation transfer function (MTF) values. However, this method does not fully capture the IOL's optical quality or how it affects VA across multiple spatial frequencies.
- Previous studies suggested that integrated MTF values provide a more comprehensive prediction of VA because they take into account a wider range of spatial frequencies relevant to human vision.
- Predicting the VA of patients with mIOLs is challenging because of the complex interplay between the IOL's optical properties and other visual factors, including the cornea, pupil size, and neural processing.

## WHAT THIS PAPER ADDS

- This study develops a correlation between in vitro figures of merit (MTF, Strehl ratio, and visual Strehl) and clinical VA after implantation of PODFGF IOLs. This provides a stronger foundation for predicting patient outcomes based on laboratory tests.
- The work demonstrates that frequency-integrated metrics such as MTFa (average MTF) are more reliable than single-frequency MTF values for predicting visual performance because they better represent the multifocal properties of the lenses.
- A specific methodology for characterizing IOL performance was proposed, which establishes stronger correlations between in vitro MTF measurements and in vivo patient VA, helping to bridge the gap between laboratory testing and real-world outcomes.

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