Quality of images with toric intraocular lenses

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Purpose: To objectively evaluate the image quality obtained with toric intraocular lenses (IOLs) when misaligned from the intended axis.

Setting: University Eye Clinic and the Department of Industrial and Information Engineering, University of Trieste, Trieste, Italy.

Design: Experimental study.

Methods: An experimental optoelectronic test bench was created. It consisted of a high-resolution monitor to project target images and an artificial eye. The system simulates the optical and geometric characteristics of the human eye with an implanted toric IOL. A 3.00 diopters corneal astigmatism was simulated. Images reproduced by the optical system were captured according to different IOL axis positions. The quality of each image was analyzed using the visual information fidelity (VIF) criterion. The VIF reduction was calculated at each IOL rotational step.

Results: A 5-degree IOL axis rotation from the intended position determined a decay in the image quality of 7.03%. Ten degrees of IOL rotation caused an 11.09% decay of relative VIF value. For a 30-degree rotation, the VIF decay value was 45.85%. Finally, the image decay with no toric correction was 56.70%.

Conclusions: The more the objective quality of the image decays progressively, the further the axis of the IOL is rotated from its intended position. The reduction in image quality obtained after 30 degrees of toric IOL rotation was less than 50% and after 45 degrees, the image quality was the same as that of no toric correction.

Astigmatism is one of the main causes of poor refractive outcomes after cataract surgery.[1] Remaining astigmatism, despite a perfect surgery, might affect both quality of vision and spectacle independence leading to unsatisfactory postoperative outcomes.[2] Toric intraocular lenses (IOLs) have been designed for both restoring visual acuity deteriorated by cataract and correcting corneal astigmatism, thereby leading to good spectacle independence for distance and, using multifocal technology, for near vision. Toric IOLs were first realized by Shimizu et al.[3] to correct preexisting corneal astigmatism.[4,5] Since then, it has been recognized that an accurate alignment of a toric IOL is a crucial prerequisite to achieving the intended reduction of astigmatism at the time of cataract surgery.[6,7] Felipe et al.[8] analyzed changes in the eye's refractive properties when a toric IOL rotates and concluded that toric IOL rotations less than 10 degrees are not obstacles for a satisfactory astigmatism correction. Alpins[9] applied a vector calculation to analyze the loss of astigmatic effect with misalignment and found a sinusoidal relationship between the amount of axis rotation and the loss of astigmatic effect, with a 15-degree misalignment showing a 13.4% loss of astigmatic effect, a 30-degree misalignment resulting in a 50% loss of astigmatic effect; however, it was not until a 45-degree misalignment that there was a total loss of astigmatic effect. The purpose of this study was to evaluate the quality of images obtained when a toric IOL rotates to different axis positions away from the intended axis.

MATERIALS AND METHODS

An optoelectronic test bench was created at the University Eye Clinic laboratories of Trieste in cooperation with the Department of Engineering and Architecture of the same University. This test bench was created by reproducing the optical conditions as closely as possible to those of a human eye.[10,11] The core of the system is an electrooptomechanical device that mimics the optics and

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geometry characteristics of the human eye referring to the Gullstrand model[12] and International Organization for Standardization 11979-2 norm.[13] It consists of a case containing a saline solution with a proper refractive index (1.334, close to that of aqueous and vitreous humors). Figure 1 shows the most relevant parts of the system; the parameters were designed as follows:

Artificial Cornea

The artificial cornea is an aberration-free poly(methyl methacrylate) lens with a 1.490 refractive index.

Iris

To mimic the eye's pupil behavior, a sliding bar having holes of different sizes is mounted behind the cornea. By sliding this frame, one can apply 6 different pupil diameters, from 2.0 mm to 8.0 mm.

Intraocular Lens Holder

A circular housing of 13.0 mm diameter allows the IOL haptics to be held down by a circular magnetic clip. This design enables the optic part of the IOL to be perfectly centered on the system optic axis. Moreover, the IOL holder allows longitudinal and rotational movements of the artificial lens.

Output Window

It consists of a thin optical glass located where the image is focused, corresponding to the retinal position.

Relay Optic and Camera

A monochrome charge-coupled device (CCD) camera is mounted at the end of the system. It acquires the images produced by the device at the level of the optical glass simulating the retinal position. A relay optic is necessary to adapt the CCD spatial resolution to that of the human fovea.

All the components of the artificial eye are mounted on a rail for a perfect alignment.

All movements are controlled by a computer and are adjustable in a micrometric way because of a motorized microsystem. Different motors control both the anteroposterior and lateral movement of the IOL, its rotation, the different pupil diameters, and the anteroposterior displacement of the optical glass that simulates different axial lengths (ALs). It is possible to move the IOL along the longitudinal axis with a maximum range of ± 2.0 mm with respect to the predefined position. It is possible to also rotate the IOL 45 degrees clockwise and counterclockwise around the eye's principal axis to assess the effect of IOL misalignment on retinal image formation. Finally, it is also possible to move the output window with a range of ± 5.0 mm, thus simulating a distance from the cornea to the retina from 20 to 30 mm.

A test image is positioned on a screen in front of the artificial cornea and the image reproduced by the system, including the toric IOL, is acquired by the monochrome CCD camera mounted at the end of the optical bench. A structured image was chosen as a test image (a woman's face) rather than a standard pattern image. This allowed evaluation of the quality of complex images, such as those that form in real life, using dedicated software.

The quality of images was assessed using the visual information fidelity (VIF) criterion for full-reference image quality assessment. In full-reference quality-assessment methods, the quality-assessment algorithm has access to a "perfect version" of the image against that it can compare with a "distorted version." The VIF method was derived from a statistical model for natural scenes, a model for image distortions, and a human visual system model in an information–theoretic framework. The quality-assessment method used in the present study was developed at the Laboratory for Image & Video Engineering (LIVE) at the University of Texas at Austin. Its Matlab implementation is also available on the LIVE website[A] and it works in the wavelet domain.[14] Sheikh and Bovik[15] provide further documentation. This method is an extension of the image quality measurement based on natural scene statistics.[16]

The VIF method explores the connections between image information and visual quality. Specifically, the reference image is modeled as being the output of a stochastic natural source that passes through the human visual system channel and is processed later by the brain. The information content of the reference image is quantified as being the mutual information between the input and output of the human visual system channel. This is the information that the brain could ideally extract from the output of the human visual system. The same measure is then quantified for the (distorted) test image.[B] Precisely, the VIF is a single quality/distortion value and it is defined as the ratio of the test image information (numerator of VIF) to the reference image information (denominator of VIF). If all information about the reference image has been lost in the test distorted image, then the VIF value is zero. It is vice versa if the test image is not distorted at all so that it represents a perfect copy of reference image; VIF is equal to unity. Therefore, in the presence of a certain distortion between reference and test images, the VIF value will always fall in the 0 to 1 range. The innovation of this quality-assessment method is that the VIF also has the ability to predict whether the visual image quality has been enhanced by a contrast enhancement operation. If the test image has a superior visual quality in respect to the reference image as a consequence of a linear contrast enhancement, the VIF value will be greater than 1. The performance of this algorithm was validated with an extensive subjective psychometric study involving 779 images and several human observers, showing that this method outperforms recent state-of-the-art image quality-assessment algorithms by a sizeable margin.[16,17] The VIF performs better than (or at par with)

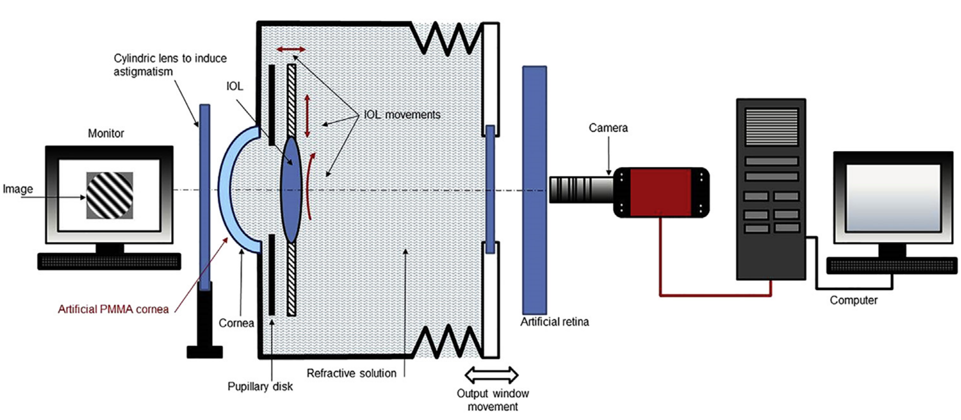

Figure 1. Optoelectronic system scheme. From left to right: high-resolution monitor, astigmatism inducing lens, artificial eye with IOL support, CCD camera, computer. The system allows to perform movements controlled by the computer: sliding of the perforated plate to simulate 6 different pupillary openings, longitudinal IOL movement of ± 2.0 mm, transverse IOL movement of ± 1.0 mm, rotational IOL movement of ± 45 degrees, window displacement of ± 5.0 mm (CCD = charge-coupled device; IOL = intraocular lens; PMMA = poly[methyl methacrylate]).

many image quality-assessment methods in cross-distortion validation as well as individual distortion types.[15,18,19]

Under experimental conditions when the image is perfectly focused, the VIF values vary between 0.25 and 0.40 (unpublished data). This is because the image is displayed through a liquid-crystal display screen refracted through the lens system, acquired by a CCD camera and realigned by the software. These steps produce an information loss. The VIF value also varies depending on the image used and the pupillary diameter chosen. In this study, the Acrysof IQ toric IOL (SN6AT6, Alcon Laboratories, Inc.) with a spherical equivalent (SE) of 21.0 diopters (D) and a cylindrical power of 3.75 D was tested. The biometric SRK/T formula[20] was used to calculate the IOL power corresponding to the AL of the system.

A 3.00 D corneal astigmatism was simulated by placing a cylindrical lens just in front of the artificial cornea. This value was chosen because 3.75 D of cylinder on a toric IOL was calculated to correct 3.00 D on the corneal plane. Ten different images were acquired for each IOL position. In the first set, the axis of the toric IOL corresponded to the axis of the astigmatism and this image is considered as the baseline. Subsequently, an IOL rotation of 5 degrees, 10 degrees, 15 degrees, 20 degrees, 25 degrees, 30 degrees, 35 degrees, 40 degrees, 45 degrees, and 90 degrees were induced and the images were captured, stored, and analyzed by the software. All images were obtained with a 3.0 mm pupil diameter to avoid higher-order aberrations attributable to larger diameter pupils. The comparison and VIF calculation were performed between the base image (obtained with axis in the correct position) and each of the images obtained after IOL axis rotation (those images are called "derived").

Image quality can be reduced by IOL decentration and pupillary diameter, but also by IOL design.[21] The AL and the pupil diameter can both be modified on the optoelectronic test bench to verify the possible influence of light and aberration onto the image quality. In addition, the amount of corrected astigmatism and the IOL power can be varied to evaluate the impact of a magnification effect on visual quality. Those eventualities were not evaluated in this study and could be evaluated in complementary studies.

The optomechanical model eye uses an aberration-free cornea. The Acrysof IQ toric IOL design presents a negative spherical aberration to correct the positive aberration of an average cornea. That might cause induced negative spherical aberration in this system; however, its value is not affected by the rotation of the IOL.

RESULTS

Using the toric IOL, the results showed a progressive deterioration of image quality correlated to the increase of the angle between the intended position and the rotated axis. Table 1 and Figure 2 show the values of VIF and VIF relative reduction. Table 1 also shows the differences between consecutive VIF values.

The VIF decay curve obtained (Figure 2) did not show a regular trend. The decay of the image quality was different for every 5-degree rotational step. In particular, the curve seemed to be steeper in the interval between 15 degrees and 20 degrees with no linear progression.

A small amount of IOL axis rotation induced a low image quality decay, whereas rotations greater than 10 degrees affected the image quality more. However, the data demonstrated that 30 degrees of toric IOL rotation reduced the image quality less than 50% and 45 degrees of toric IOL rotation reduced the image quality to the same as no toric correction at all. This was contrary to suggested 100% reduction of image quality caused by toricity of IOL at 30 degrees misalignment and paralleled the vectorial 50% astigmatic loss at 30 degrees and the 100% loss at 45 degrees.

Table 1. Visual information fidelity values and VIF reduction from reference image values for each 5-degree rotation step.

IOL Rotation (°)	VIF Value		
	Mean ± SD	Reduction ($n10^2$)*	Percentage†
0	0.2929 ± 0.0028	0.00	100.00
5	0.2723 ± 0.0022	2.06	92.97
10	0.2604 ± 0.0020	1.19	88.91
15	0.2377 ± 0.0021	2.27	81.15
20	0.1914 ± 0.0021	4.63	65.35
25	0.1741 ± 0.0023	1.73	59.44
30	0.1586 ± 0.0017	1.55	54.15
35	0.1478 ± 0.0022	1.08	50.46
40	0.1354 ± 0.0023	1.24	46.23
45	0.1253 ± 0.0022	1.01	42.78
90	0.0860 ± 0.0024	3.91	29.36
No correction	0.1269 ± 0.0019	—	43.30

VIF = visual information fidelity
*Reduction for each step
†Percentage of current VIF value compared with original VIF value

DISCUSSION

Corneal astigmatism management has become crucial in modern practice cataract and refractive surgery because roughly 50% of the white population have at least 1.0 D of astigmatism.[22] Cataract patients are even more demanding regarding spectacle independence after surgery to improve their quality of vision and toric IOLs are currently 1 of the main options for astigmatism correction during cataract surgery.[23] Although several studies already focused on visual outcome after toric IOL implantation,[24] very few have analyzed toric IOLs' optical performance in an experimental environment.[21,25] Most previous studies analyzed contrast sensitivity indices such as the modulation transfer function to study the IOL optical performance, even though contrast sensitivity is just 1 of the features of human sight.[26]

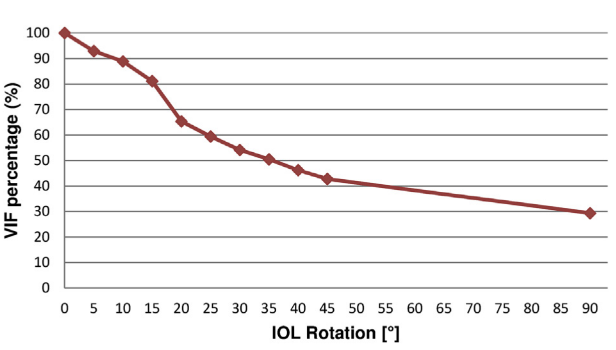

Figure 2. The VIF decay trend graph. The curve does not show a regular trend; the decay of the image quality is different for every 5-degree rotational step. (IOL = intraocular lens; VIF = visual information fidelity).

Our study describes a new and more complete method to assess the image quality transmitted by toric IOLs. An essential prerequisite to achieving the correction of astigmatism after cataract surgery is an accurate alignment of the toric IOL. Indeed, images transmitted through an astigmatic cornea are corrected by the toric IOL as much as the axis of the IOL corresponds to the steep meridian of the corneal astigmatism. Toric IOL rotations or misalignments cause an important deterioration of image quality. Alpins[9] performed a scalar comparison of the prevailing astigmatism between remaining astigmatism magnitude and the preoperative cylinder associated with toric IOL rotation. A rotational error of 10 degrees determines a resultant astigmatism that is 35% of the preoperative astigmatism. This resultant astigmatism increases to 52% of the total astigmatism to be corrected when the rotation is 15 degrees. The prevailing astigmatism magnitude is equal to the preoperative cylinder with a 30-degree rotation. These findings were substantially confirmed by many works in the literature, such as those by Felipe et al.[8] and Langenbucher et al.,[27] and lead to the generalized statement that approximately 3% of cylinder corrective power is lost for every 1 degree of off-axis rotation.

A well-positioned toric IOL nullifies the preoperative astigmatism through a vector equal and opposite. The toric IOL rotation causes an astigmatism reduction at the intended meridian, which could be evaluated through a vectorial calculation. The flattening effect is a parameter (surgically induced astigmatism cosine [2θ]) to evaluate how effective astigmatism treatment has been and the flattening index is the relationship between flattening effect and the targeted change in astigmatism. Alpins[9] studied the effect of misaligned astigmatism treatment on the flattening index and found that the loss of effect at 30 degrees off axis is 50% and at 45 degrees off axis is 100%. Our results show lower VIF reductions in the 0 degree to 10 degrees and in the 20 degrees to 30 degrees IOL rotational intervals, and a greater one in the 10 degrees to 20 degrees interval, leading to the conclusion that greater than 10 degrees is crucial for the loss of image quality. Furthermore, the data we collected showed a VIF decay trend as a toric IOL rotates from its intended position consistent with the sigmoidal flattening index decay curve.

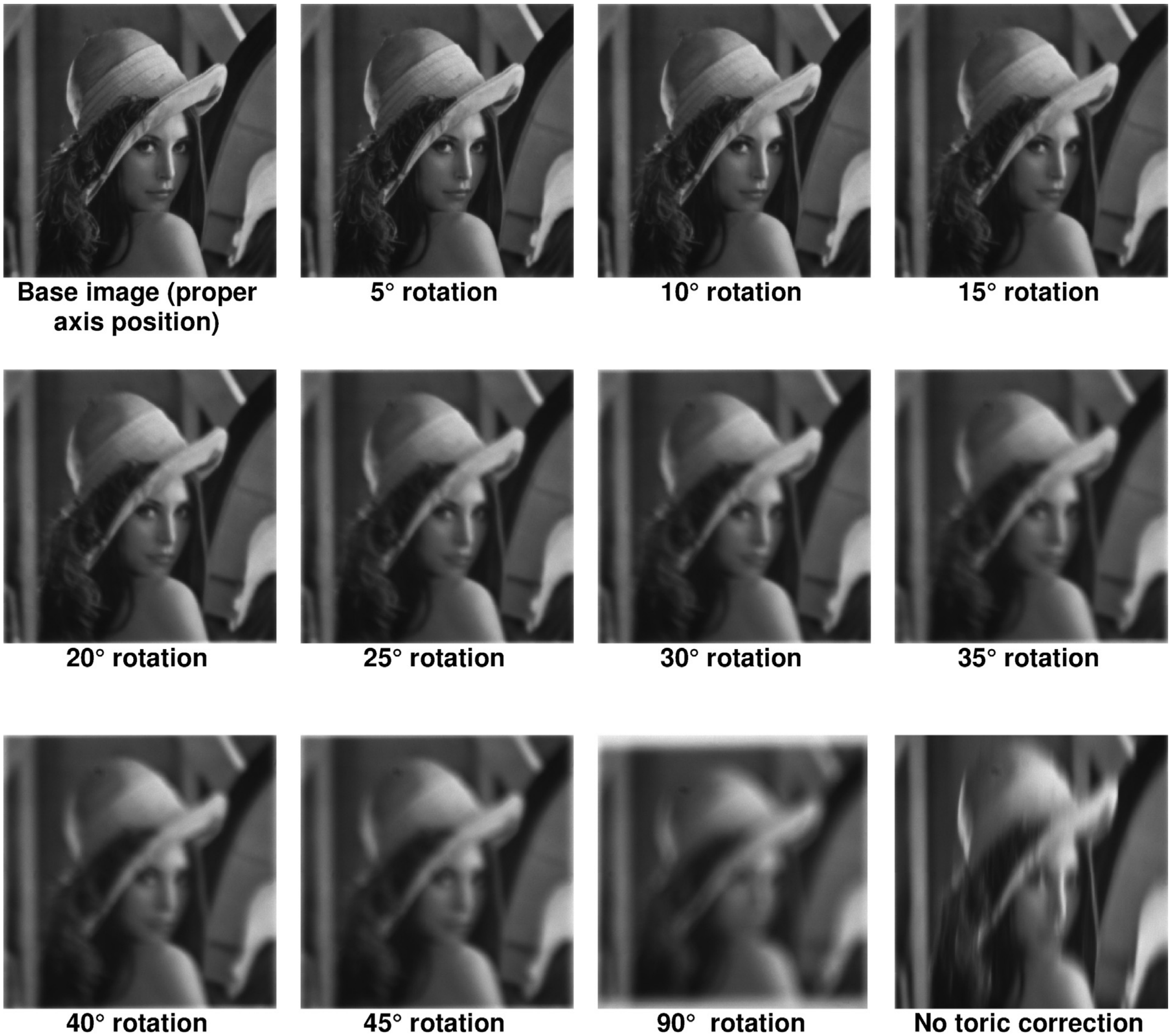

Figure 3. Reference image deterioration induced by toric IOL rotation. It is possible to observe the difference between image quality at 30 degrees rotation and without astigmatism correction. *Image source: Playboy (1972), photo by Dwight Hooker.*

Our study objectively analyzed the variations of the image quality after toric IOL rotations: within 30 degrees of rotations the image quality is not compromised as much as a previous study suggested.[26] Assuming that each 3-degree of rotation corresponds to 10% of the loss of astigmatic change in magnitude, a rotation of 30 degrees would lead to a loss of 100% of astigmatic reduction, affecting the quality of vision as much as a rotation of 30 degrees in the opposite cyclical direction where the astigmatism magnitude has not changed. But with rotation at 30 degrees from the intended axis, the effective flattening (flattening effect/target-induced astigmatism vector) is only 50% and measuring the astigmatism at the preoperative meridian would show 50% of it remaining.

However, our results show a VIF mean value of 0.1253 for an IOL rotation of 45 degrees that is comparable to the VIF value of 0.1269 found with no toric correction, suggesting that quality of imagine decay follows the trend of flattening index. Although the 45-degree rotation and the no toric correction image in Figure 3 appear quite different, they have a similar VIF value because VIF is an index of the information loss during image transmission. The 2 images are different but their loss of information is comparable. We can thus state that the loss of astigmatic correction is not linear with toric IOL rotation. Our results agree with Alpins'[8] and Alpins et al.'s[28] findings.

In conclusion, the decay trend of the image quality after the rotation of a toric IOL is not comparable to the scalar comparison between postoperative and preoperative prevailing astigmatism. In particular, for IOL rotation within 10 degrees, the image quality seems to not be consistently affected, whereas the highest decay occurs for rotation ranging between 10 degrees and 20 degrees, suggesting an IOL repositioning for rotations of more than 10 degrees. Furthermore, our data showed an image quality reduction for toric IOL rotations consistent with the trend of flattening index where a 45-degree misalignment causes a 100% loss of any toric correction.

WHAT WAS KNOWN

- Toric IOL rotation from its intended axis affects the quality of images.
- The loss in correction is known to be vectorial in nature as a sigmoid curve governed by the formula cosine (2θ).

WHAT THIS PAPER ADDS

- The optoelectronic test bench permitted objective quantification of the image deterioration induced by the rotation of the IOL axis.
- A small amount of IOL axis rotation induced a low image quality decay, whereas rotations greater than 10 degrees affected the image quality more.
- Scalar comparison of misaligned IOLs compared with aligned toric IOLs was linear and overestimated the actual loss of image quality.

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