Kidger Optics Associates

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"The Kidger Optics name was previously associated with Kidger Optics Ltd formed in 1982 by the late Michael Kidger and myself.

David Freeman joined Kidger Optics Ltd in 1984 as a salaried consultant working closely with both Michael and I on the development of the "SIGMA" optical design software. David also worked on optical design requirements for Kidger Optics' customers who sought optical design assistance from the company.

Kidger Optics Associates have many years of experience in serving the optical design community, and is very pleased to work with O&O mdc on this exciting Intraocular Lens (IOL) research giving benefit to so many people throughout the world."

Tina E Kidger

Optimisation of Aspheric IOLs:

1. Introduction

An IOL replaces the crystalline lens in the human eye when disease such as cataract reduces performance.

The IOL is in the posterior chamber of the anterior segment of the eye just behind the iris. In this study, the anterior chamber depth (ACD) of the IOL is assumed to be 4.96 mm. ACD is defined as the distance from the apex of the cornea lens to the edge centre line of an equi-convex IOL. An IOL lens typically is 6 mm diameter with an edge thickness of 0.3 mm and made from a flexible plastic material. Haptics attached to the edge of the lens help position it correctly within the eye.

The power of the IOL is selected to match both the power of the patient's cornea and the position of the retina to give a good image of objects at infinity. Surgeons calculate IOL power using mostly the "Holladay formula", using the "A constant" ratio based on the ACD of the IOL. An ACD of 4.96 matches an A constant of 118. Therefore for an "error free" IOL power calculation an equi-convex IOL is much more reliable as it is symmetrical.

The performance of the IOL "in situ" depends on the power and shape of the cornea, the position of the retina and the power, shape and aspheric profile of the IOL. The power of the IOL brings the image to a focus at the correct location. The shape and profile of the IOL affect image quality.

The IOL is surgically inserted and positioned to be nominally centred on and perpendicular to the optical axis. The positioning is subject to error and the IOL should ideally be designed to minimize the effects of decenter and tilt.

An IOL is MTF tested according to ISO 11979-2 Annex C by inserting it in a prescribed model eye. This model eye has very little resemblance to a human eye. The question arises – should the IOL be optimised to give best performance either in the ISO model eye or in a model eye that more closely matches the human eye. The results achieved may be significantly different.

2. IOL Performance

The on-axis performance of a perfectly centred, spherically surfaced IOL with positive dioptric power is affected by the lens shape i.e. by the ratio of the powers of the front and rear surfaces. The spherical aberration of the IOL is positive and is a minimum at a shape close to Convex-Plano.

If either of the IOL surfaces is given an axially symmetric aspheric profile then the third order spherical aberration of the IOL can be targeted on any specific value.

The cornea has residual positive spherical aberration that adds to the aberration from the IOL. The level of corneal aberration depends on the shape and power of the cornea and varies significantly from person to person and with the 'health' of the eye. The corneal radius is a maximum at its centre and flattens towards the outer edges. A study by Kiely PM, Smith G and Carney LG entitled "The mean shape of the human cornea" (Optica Acta 1982; 29; 1027-1040) found the central radius of curvature to be 7.72 ± 0.27 and the asphericity to be −0.26 ± 0.18 (see below for definition).

There is the option of over-correcting the IOL so that the cornea/IOL combination has zero spherical aberration; this is mostly intuitively done by surgeons when choosing IOLs for short-sighted patients. This can help improve resolution but the benefit will vary from one person to another due to the radius and shape variations of the cornea. It may affect perceived depth-of-focus. Another option is to design the IOL so that the cornea/IOL combination matches the spherical aberration in the emmetropic eye.

If the IOL is decentered or tilted then the off-axis aberration of the IOL can reduce resolution. The coma of the IOL dominates when the IOL is decentered. Both coma and astigmatism affect performance when the IOL is tilted.

The coma of the IOL is dependent on its shape and varies from negative when the lens is steeply meniscus towards the front to positive when the lens is steeply meniscus towards the rear. Its coma is zero at a shape close to Convex-Plano. The exact shape at which coma is zero is very close to the "best shape" where the IOL spherical aberration is a minimum. Correcting coma will reduce sensitivity to IOL decenter and will improve off-axis imaging.

The IOL is very close to the iris aperture. Consequently the astigmatism of the IOL is almost proportional to its power and there is little that can be done to significantly reduce it.

Choosing the shape of an aspheric IOL can almost counteract the effect of decenter, and improve the effect of tilt.

Recent publications have suggested that there is some advantage in asphering both surfaces of the IOL. In practice, there is very little such advantage. Both surfaces are very close to the aperture stop (the iris) and an aspheric on either surface can be used to correct spherical aberration and very little else.

3. Asphericity

This study is confined to axially symmetric aspheric surfaces with a profile that is a conic section. For ray-tracing purposes the optimum equation defining the sag z of the surface profile is

$$z = \frac{cr^2}{1 + \sqrt{1 - (1 + k)c^2 r^2}} \quad \text{or} \quad z = \frac{cr^2}{1 + \sqrt{1 - (1 - e|e|)c^2 r^2}}$$

where c is the curvature of the surface (reciprocal of radius), r is the distance from the axis and k is the conic constant that defines the asphericity. Alternatively, the asphericity is defined by the eccentricity e.

$k = 0$ or $e = 0$	spherical surface	$k = -1$ or $e = 1$	paraboloid
$k < -1$ or $e > 1$	hyperboloid	$0 \geq k \geq -1$ or $0 \leq e \leq 1$	prolate ellipsoid
$k > 0$ or $e < 0$	oblate ellipsoid		

IOL surfaces will be ellipsoidal or hyperbolical. Note that the cornea is also ellipsoidal with $k \approx -0.26$.

Such asphericals are adequate for correcting spherical aberration over the central 4 to 5 mm diameter of an IOL. However, to correct over a 6 mm diameter additional 6^{th} power and 8^{th} power figuring terms would be necessary.

4. IOL Shape

A macro has been written for an optical design software package that calculates the anterior and posterior surface radii of an IOL from the power (dioptres), diameter, edge thickness, IOL refractive index and the refractive index of the aqueous humour. The shape can be chosen from the following range.

> Convex-Plano, Equi-Convex, Plano-Convex, Fixed Posterior Radius, Fixed Anterior Radius, Fixed Power Ratio.

The Fixed Power Ratio specifies the ratio of the powers of the anterior and posterior surfaces.

The IOL Power is calculated from the equation given in ISO 11979-2 Annex A.

5. Aspheric IOL Optimisation

A second macro has been written to set up a model eye, insert an IOL (designed using the macro in Section 4) and then optimise its aspheric profile over an angular field of 5º according to conditions set by the user. The angular field represents the 1.5 mm diameter of the fovea. The optimisation maintains the IOL at a selected value of power, shape and edge thickness. The optimisation macro has three 'zoom' positions. The first zoom holds the nominal IOL perfectly centred and square to the optical axis. The second zoom decenters the IOL by 0.5 mm and the third tilts it by 5 degrees about its centre. The optimisation gives the best compromise over all three conditions.

A manufactured IOL will be tested (ISO 11979-2) over a 3 mm diameter pupil. However, the IOL design has been optimized over a larger pupil (between 4 and 4.5 mm) to avoid possible sharp changes in performance at the edge of the 3 mm aperture.

6. Optimisation Results

Optimising an IOL to give good performance with the ISO eye model is straightforward and successful. The spherical aberration can be completely corrected by the conic profile and the coma is corrected by choosing the lens shape. The results for a 20 dioptre lens are shown in Figure 1. The MTF graphs are 546.1 nm monochromatic calculations from 0 to 200 cycles/mm at best focus over a 3mm aperture on the lens. The top graphs are for the centred IOL, the middle graphs are for the IOL decentered by 0.5 mm and the lower graphs are for the IOL tilted by 5 degrees about its centre. The left hand, central and right hand graphs are for points on the lower edge, the centre and the upper edge of the fovea respectively.

Note that the monochromatic diffraction limited value of MTF is 0.67 at 100 cycles/mm and 0.36 at 200.

Figure 2 shows the result when the shape is constrained to be equi-convex. The coma cannot be completely corrected and the effect is evident when the lens is decentered and/or tilted.

Optimising an IOL to give good performance in a more realistic model eye is more difficult. I have selected a simplified Gullstrand model (Figure 3) with an aspheric added to the anterior corneal surface to emulate more closely the emmetropic eye. The eye lens has been removed and the IOL inserted in the posterior chamber at 4.96 mm ACD.

It is assumed that the IOL is correcting for a difference of corneal radius from the nominal. To simulate this, the IOL power is fixed, the distance from the front of the cornea to the retina is fixed and the corneal radius is allowed to vary during optimisation so that focus is restored. The distance from the apex of the cornea to the retina in the IOL/Gullstrand model will be constant 24.385 mm for IOLs with power between 18D and 24D and will be adjusted to higher or lower values outside this range to simulate the action of the human eye.

Figure 3 shows the performance of the IOL designed in Figure 1 (for best performance in the ISO eye model when analysed with the Gullstrand model). This shows that a lens optimised in the ISO model may not be ideal.

Figure 4 shows a 20D IOL with asphericity and shape optimised for best performance with the Gullstrand model. The correction is not perfect due to the effect of corneal aberrations but the result is quite good.

Figure 5 shows an equi-convex 20D IOL optimised in the Gullstrand model and again the lack of coma correction becomes evident when the lens is decentered. The result is only slightly inferior to the free shape design of figure 4.

Finally, Figure 6 shows the design of Figure 4 analysed in the ISO eye model.

7. Depth-of –Focus

A particular definition of DoF (Nio, Jansonius, Fidler, Norrby and Kooijman, "Spherical and irregular aberration are important for the optimal performance of the human eye", Ophthalmic and Physiological Optics, 2002, 22, 102-112) effectively defines it to be twice the positive dioptre focus change from the point where MTF is a maximum to the point where MTF has fallen to 50% of its maximum value.

Best focus and DoF are frequency dependent. For detecting edges the eye will focus for best MTF at low frequencies – around 10 cycles/mm on the retina. For reading newsprint, higher frequencies are important – around 40 cycles/mm or so. At higher frequencies MTF becomes progressively lower and few people have sufficient neural response to resolve frequencies beyond 100 cycles/mm on the retina. Nio et al suggested that DoF be quoted at 27.5 cycles/mm – being intermediate between typical edge detection and reading applications and giving a measurable neural response.

Figure 7 shows the on-axis, through-focus monochromatic MTF at 27.5 cycles/mm for a 20D dioptre aspheric IOL designed to give zero, 0.25, 0.50 or 1.00 wavelengths of residual third order spherical aberration at the retinal image. The aberration is measured over a 3mm beam diameter at the iris. MTFs are shown for beam diameters 3.0 , 4.0 and 5.0 at the iris (the beam diameters entering the eye are 3.4, 4.5 and 5.6 mm). In each case the 'zero' on the focus scale is the best focus at 3 mm beam diameter and 27.5 cycles/mm.

When the residual aberration is zero the best-focus MTF increases slightly with increasing beam diameter (due to reduced diffraction), the through-focus MTF is almost symmetric about best-focus and DoF is small. As aberration increases the best focus shifts forwards, the best focus is reduced and the depth of focus is increased. These effects are larger at larger beam diameters.

Table 1 lists the best-focus MTF and DoF as a function of both spherical aberration and beam diameter. Between zero and 0.25 wavelengths of aberration the differences of MTF and DoF are relatively small. The most noticeable effect is the shift of best-focus at larger beam diameters. From 0.25 to 0.50 wavelengths of aberration there is a noticeable gain of DoF at iris diameters greater than 4 but this is accompanied by reduced best-focus MTF and greater shifts of best-focus. Above 0.50 wavelengths the gain in DoF is large when the iris diameter is greater than 4 but the reduction in MTF is very pronounced.

The optimum level of spherical aberration is around 0.4 to 0.5 wavelengths – the level of aberration in an emmetropic eye!

8. Aspherics and Expansion

IOL design parameters are stated for the in situ condition i.e. in a hydrated state. During manufacture the IOL material is likely to be in a dry state. There is a significant expansion from the dry to the hydrated state (typically 10%) and this must be taken into consideration during manufacture.

All linear dimensions in the dry state should be a ratio 1/(1+e) smaller than the nominal design parameters where e is the fractional expansion. However, the conic constant used to define the aspheric surface (the *k*-value from section 3) is a dimensionless shape factor and is not scaled.

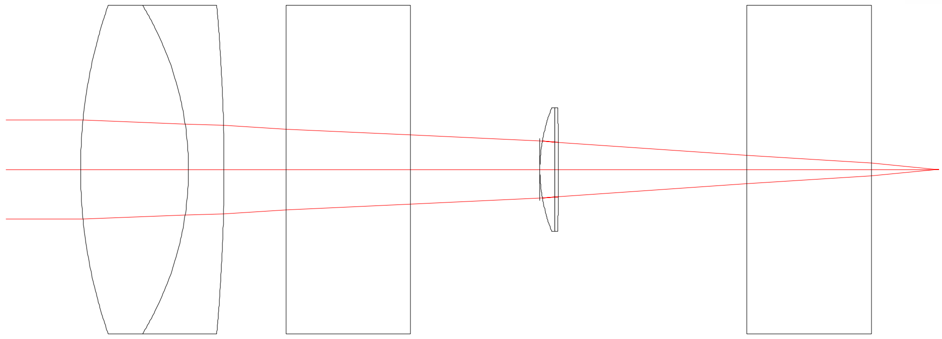
9. Conclusions

All the following conclusions are based on a 20D IOL.

1. It is possible to set up macros and optimisation files for automatic designs of IOLs.
2. The eye model used has an influence on the results.
3. An aspheric will correct spherical aberration of the IOL and of the cornea.
4. The shape of the lens can be used to correct coma.
5. Astigmatism cannot be corrected.
6. An asphericed free-shape IOL has good performance and reduced sensitivity to decenter and tilt.
7. An IOL optimised on the ISO 11979-2 eye model is not optimum when analysed with the Gullstrand eye model.
8. An IOL optimised with the Gullstrand Eye Model is nearly optimum when analysed with the ISO 1196798-2 eye model.
9. Performance over a pupil area larger than the 3mm test area will show greater variations between different shaped IOLs and between IOLs optimised on different eye models.
10. A conic section aspheric is sufficient to optimize performance over a 3 mm aperture.
11. Additional aspheric figuring terms will be needed to correct performance over apertures up to 6 mm.
12. Residual positive spherical aberration can substantially improve depth-of-focus when the iris is greater than 4 mm diameter but at the expense of reduced best-focus MTF.
13. The optimum level of residual spherical aberration is around 0.4 λ over a 3 mm aperture.
14. The conic constant defining an aspheric does not have to be scaled to allow for expansion from the dry to hydrated state.
15. Linear dimensions should be scaled to allow for expansion from dry to hydrated state.
16. Asphericing both surfaces is probably not beneficial.

David Freeman

For Kidger Optics Associates and O&Omdc



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2	S		-15.58000	5.21000	1.620317	8.000	SSK4
3	S		-90.20000	1.72000	1.694154	8.000	SF8
4	S		Plane	3.00000	1.000000	8.000	
5	S		Plane	6.00000	1.518721	8.000	BK7
6	EN		8.10170	6.25000	1.336000	3.000	AQUEOUS
7	S		-190.59918	0.89103	1.491500	3.000	IOL
8	SN		Plane	9.10897	1.336000	8.000	AQUEOUS
9	S		Plane	6.00000	1.518721	8.000	BK7
10	SU	Z	-12.50000	3.28117	1.000000	0.000	

CONIC SURFACE 6 CC = -0.397262 (ELLIPSE)

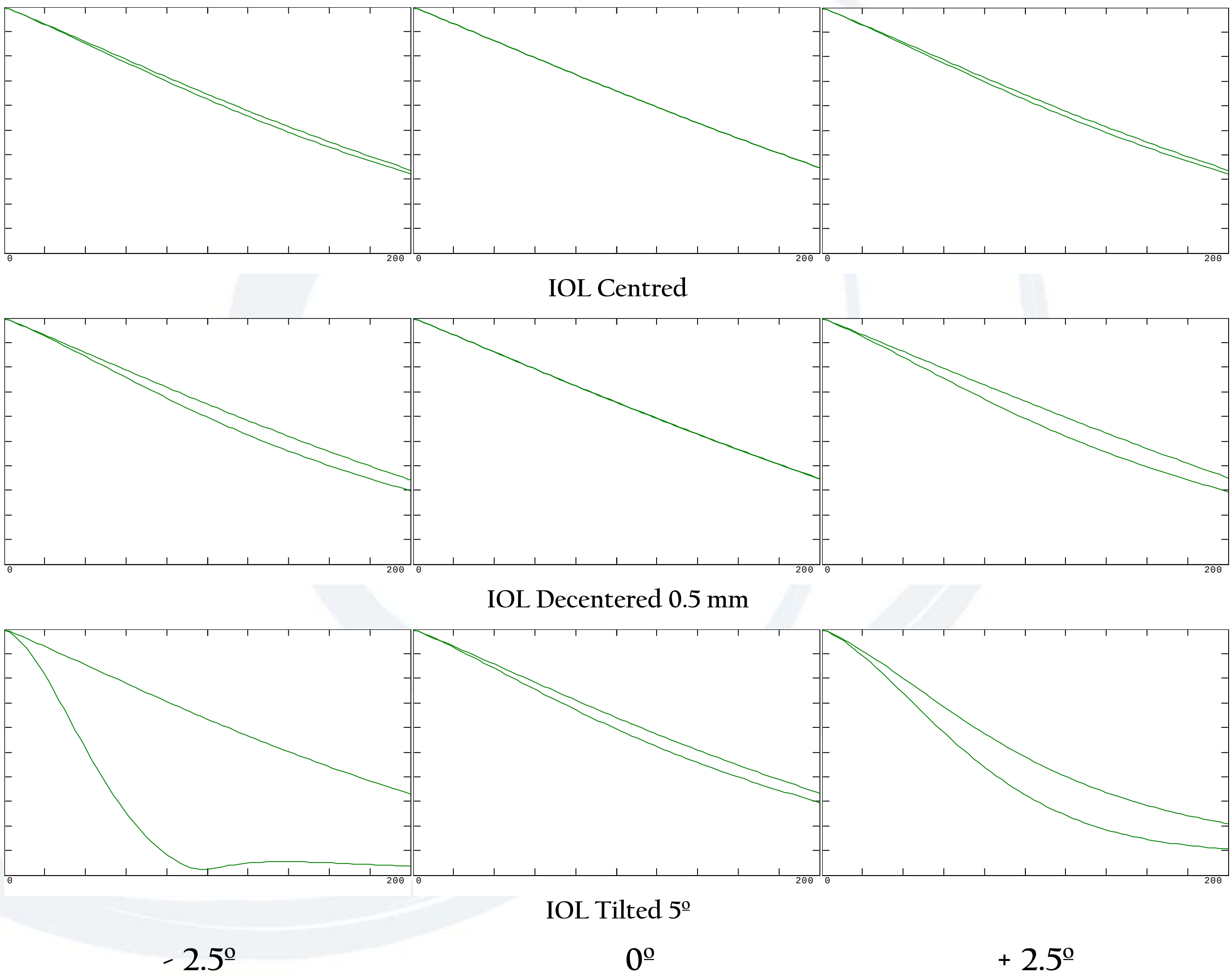
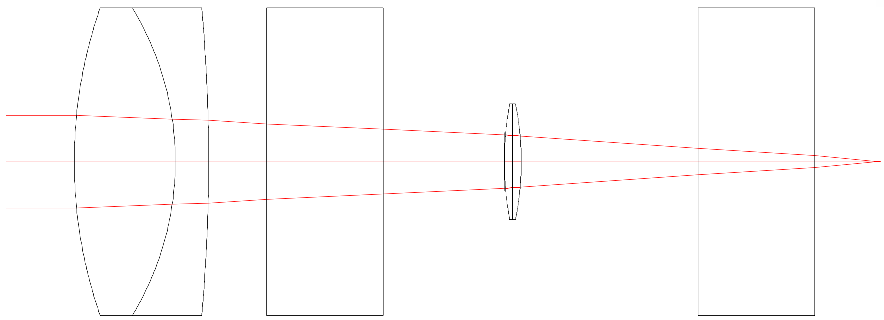


Figure 1. Free Shape 20D IOL Optimised with ISO 11979-2 Model Eye



SURFACES

#	SURF	SPACE	RADIUS	SEPN	INDEX1	CLR RAD	GLASS
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2	S		-15.58000	5.21000	1.620317	8.000	SSK4
3	S		-90.20000	1.72000	1.694154	8.000	SF8
4	S		Plane	3.00000	1.000000	8.000	
5	S		Plane	6.00000	1.518721	8.000	BK7
6	EN		15.50454	6.25000	1.336000	3.000	AQUEOUS
7	S		-15.50454	0.86951	1.491500	3.000	IOL
8	SN		Plane	9.13048	1.336000	8.000	AQUEOUS
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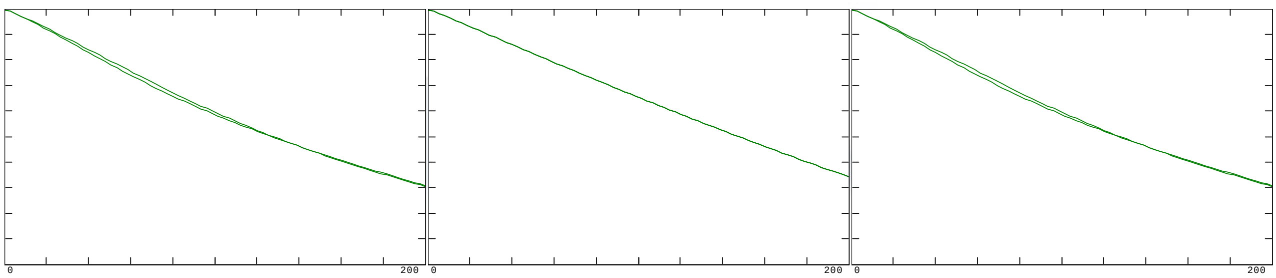
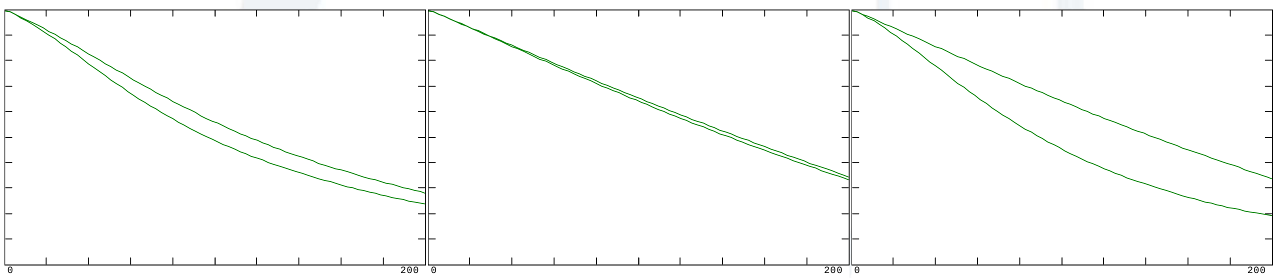
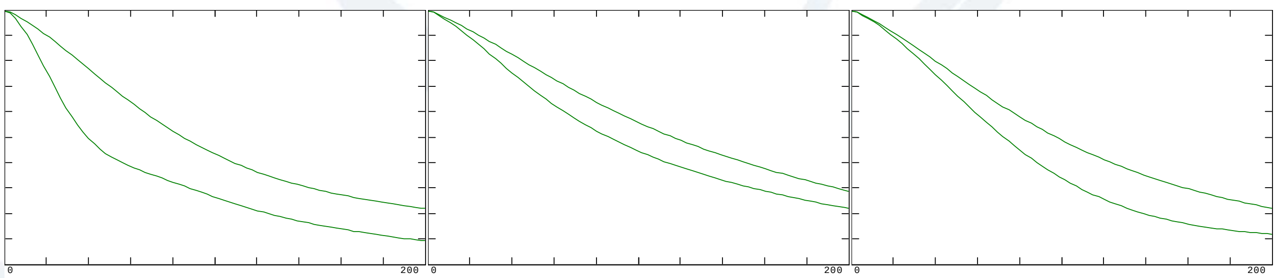


IOL Centred



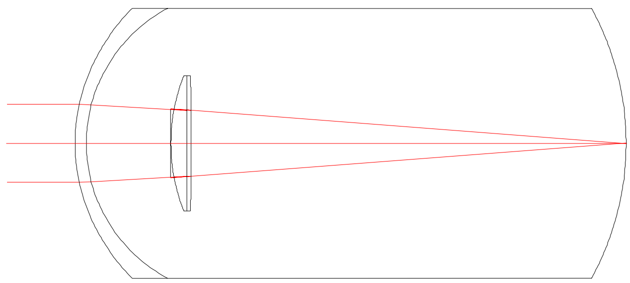
IOL Decentered 0.5 mm



IOL Tilted 5º

- 2.5º 0º + 2.5º

Figure 2. Equi-Convex 20D IOL Optimised with ISO 11979-2 Model Eye



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  2 S              6.80000    0.50000    1.376000   6.000   CORNEA
  3 EN             8.10170    3.74094    1.336000   3.000   AQUEOUS
  4 S           -190.59918    0.89103    1.491500   3.000   IOL
  5 SN     Z     -12.50000   19.25090    1.336000   6.000   AQUEOUS
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CONIC    SURFACE    3 CC =  -0.397262  (ELLIPSE)
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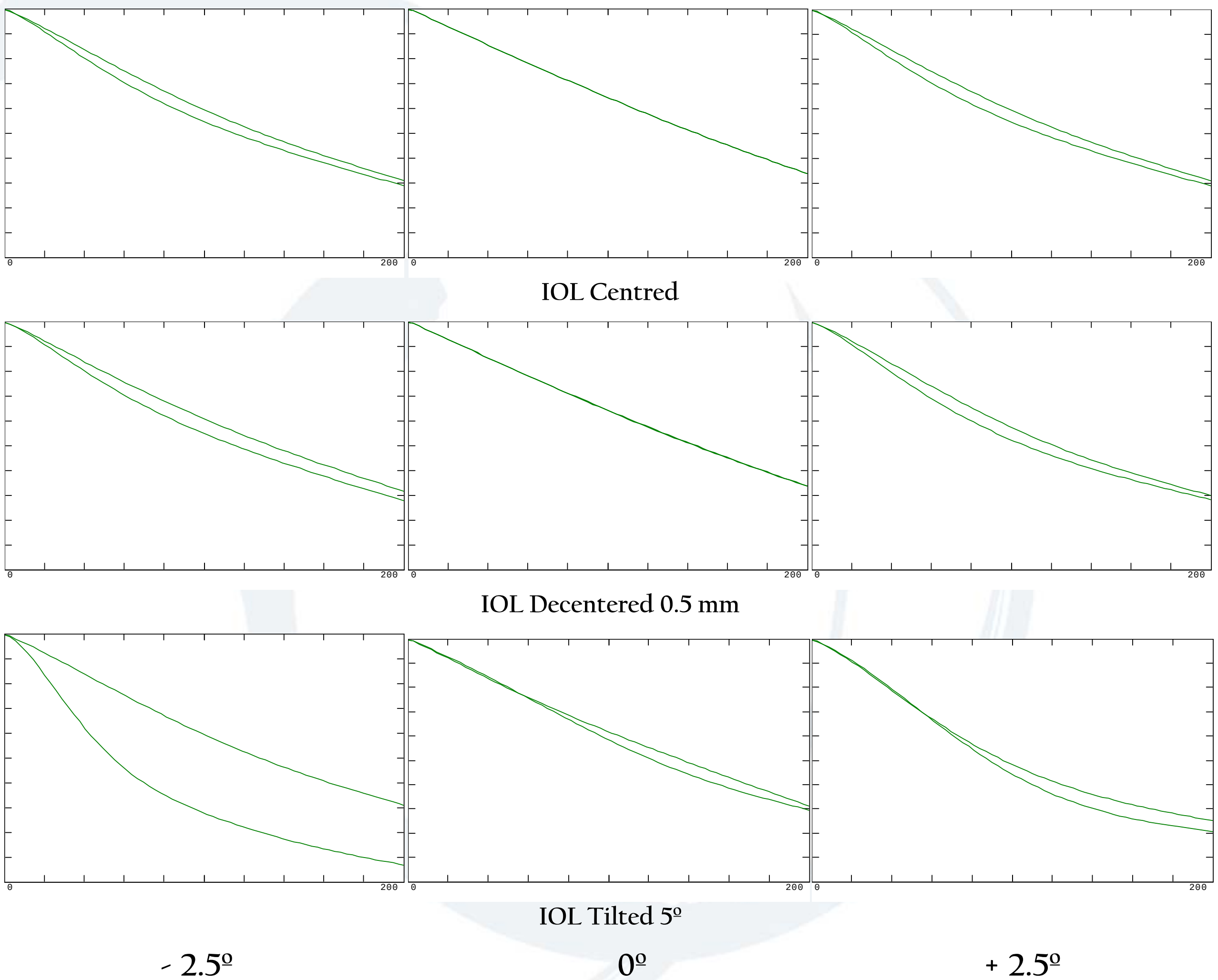
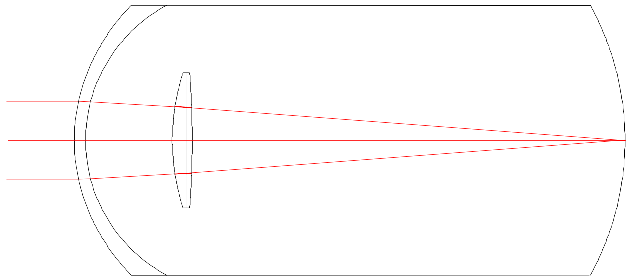


Figure 3. 20D IOL Design from Figure 1 Analysed with Gullstrand Model Eye



SURFACES

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3	EN		9.57851	3.84081	1.336000	3.000	AQUEOUS
4	S		-40.89809	0.87937	1.491500	3.000	IOL
5	SN	Z	-12.50000	19.16482	1.336000	6.000	VITREOUS

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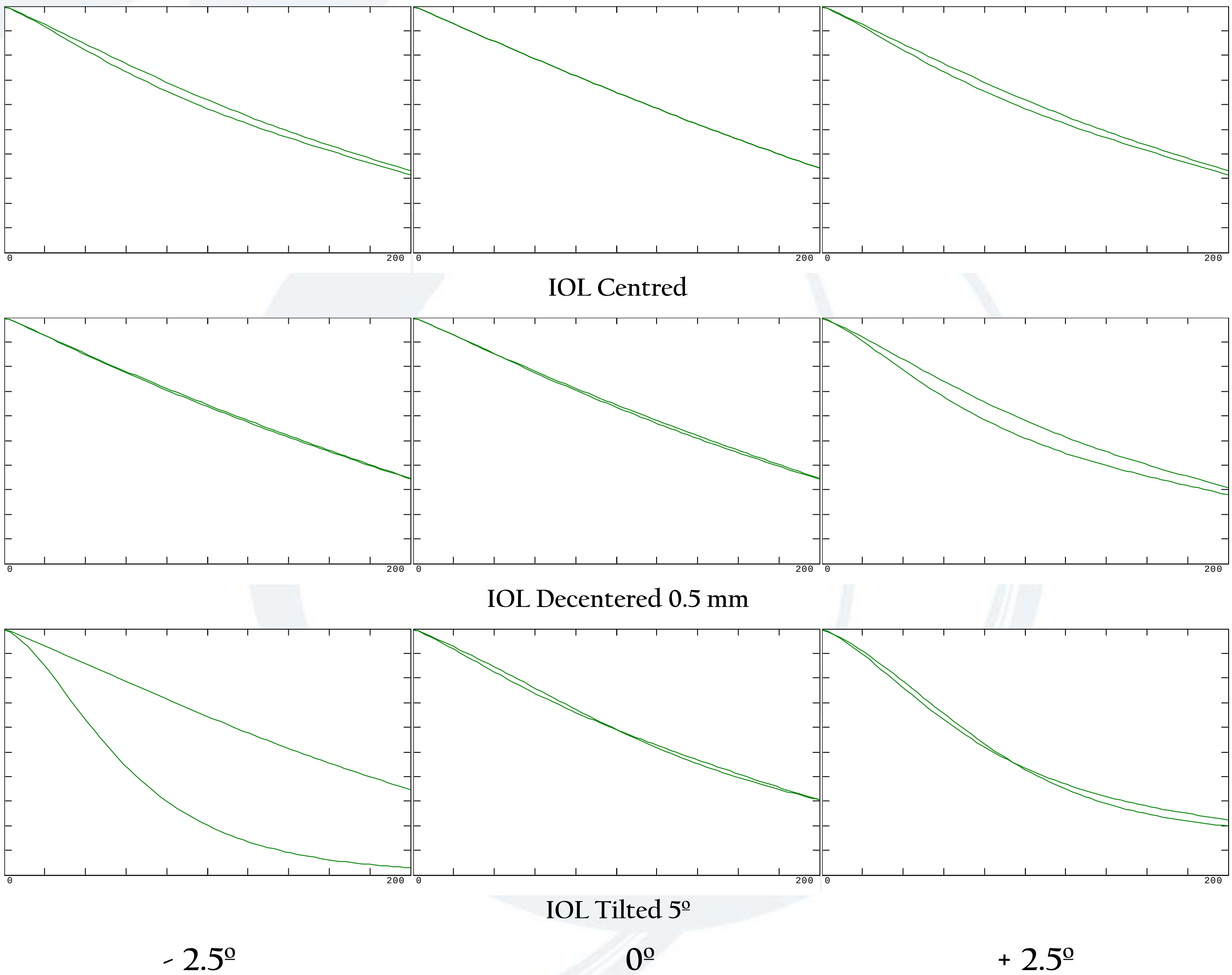
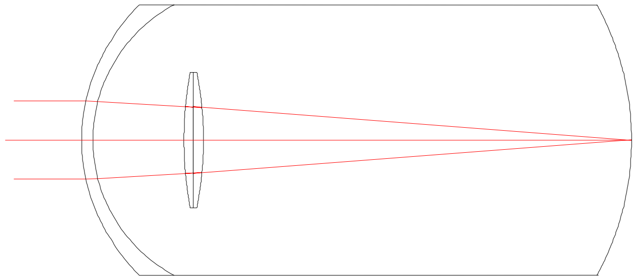


Figure 4. Free Shape 20D IOL Optimised with Gullstrand Model Eye



SURFACES

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2	S		6.80000	0.50000	1.376000	6.000	CORNEA
3	EN		15.50476	4.03776	1.336000	3.000	AQUEOUS
4	S		-15.50476	0.86524	1.491500	3.000	IOL
5	SN	Z	-12.50000	18.98200	1.336000	6.000	VITREOUS

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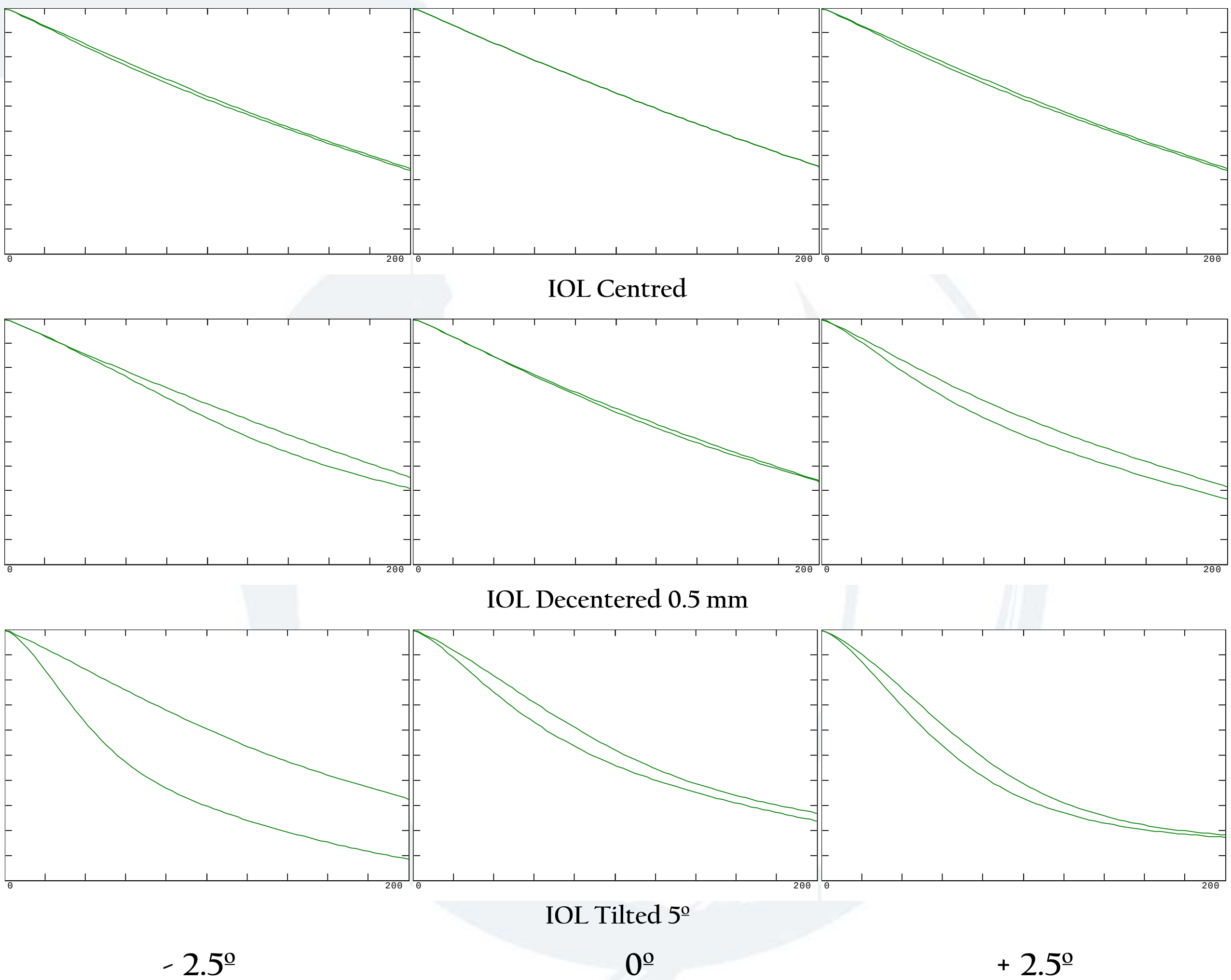
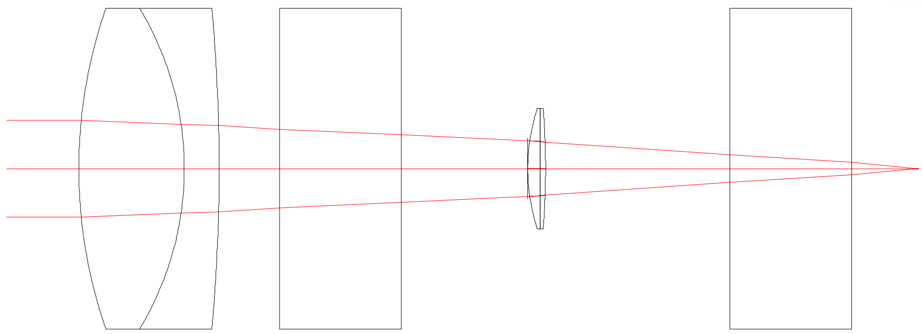


Figure 5. Equi-Convex 20D IOL Optimised with Gullstrand Model Eye



SURFACES

#	SURF	SPACE	RADIUS	SEPN	INDEX1	CLR RAD	GLASS
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2	S		-15.58000	5.21000	1.620317	8.000	A-SSK4
3	S		-90.20000	1.72000	1.694154	8.000	S-SF8
4	S		Plane	3.00000	1.000000	8.000	
5	S		Plane	6.00000	1.518721	8.000	S-BK7
6	EN		9.57851	6.25000	1.336000	3.000	User-AQUEOUS
7	S		-40.89809	0.87937	1.491500	3.000	User-IOL
8	SN		Plane	9.12063	1.336000	8.000	User-AQUEOUS
9	S		Plane	6.00000	1.518721	8.000	S-BK7
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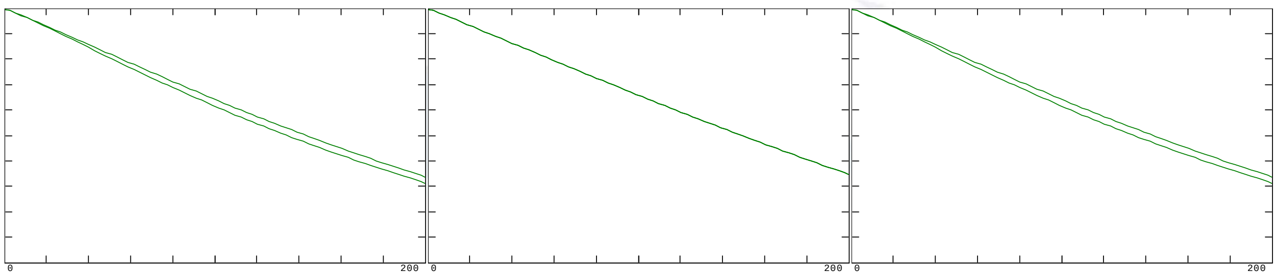
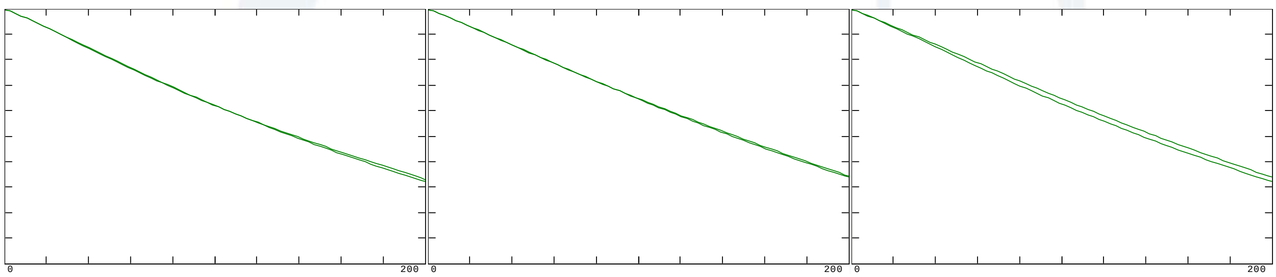
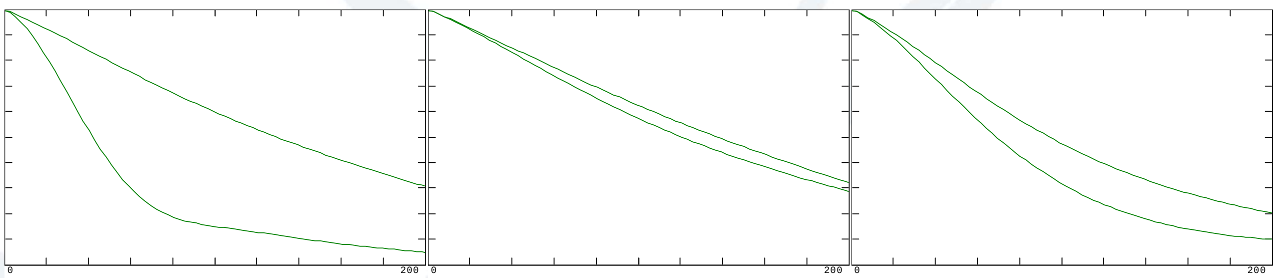


IOL Centred



IOL Decentered 0.5 mm



IOL Tilted 5º

- 2.5º 0º + 2.5º

Figure 6. 20D IOL Design from Figure 4 Analysed with ISO 11979-2 Model Eye

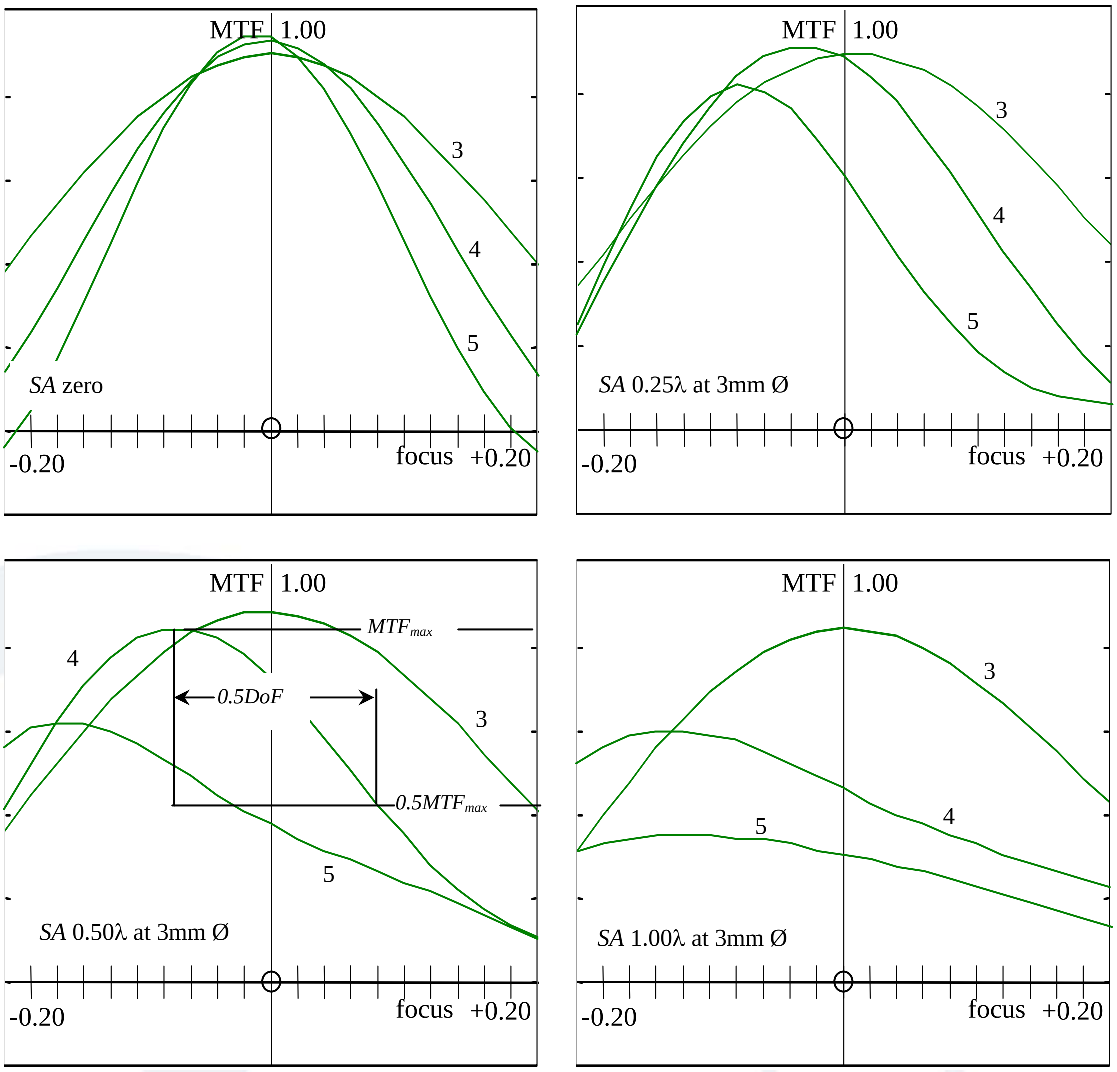


Figure 7. Effect of Spherical Aberration on Through-Focus MTF of a 20D IOL At frequency 27.5 cycles/mm (8 cycles/degree)

SA at 3.0 mm beam Ø	beam Ø 3.0 mm		beam Ø 4.0 mm		beam Ø 5.0 mm	
	MTF *best-focus*	*DoF*	*MTF* *best-focus*	*DoF*	*MTF* *best-focus*	*DoF*
zero	0.898	1.34	0.923	0.98	0.936	0.77
0.25 ▯	0.894	1.36	0.898	1.02	0.834	0.87
0.50 ▯	0.884	1.38	0.837	1.08	0.614	1.38
1.00 ▯	0.843	1.44	0.594	1.81	0.346	1.97

Table 1. Effect of Spherical Aberration on Best Focus MTF and Depth-of-Focus of a 20D IOL at 27.5 cycles/mm (8 cycles/degree)