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# **Design and Evaluation of Refractive Multifocal Intraocular** Lenses Implanted within the Human Eye

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Abstract. In this paper, optimum design of three classic model have been proposed, for refractive multifocal intraocular lenses (singlet, doublet, triplet-MIOLs) implanted within human eye (Liou & Brennan model). The analysis were carried out with ZEMAX-EE optical software through the polychromatic functions; MTF, PSF, spot diagram and (longitudinal-, Sphero-) chromatic aberration in addition to comparison with healthy eye. Due to good biocompatibility, AR40N Allergan and AcrySof SA60AT were used to design refractive MIOLs in unique and / or dual combination. Correction of the spherical aberration and longitudinal chromatic aberration (LCA) within 5° of visual field and 4 mm of pupil diameter were performed over the spectral region (455-655 nm). Result indicate that for all MIOLs proposed design (pseudophakic eye) sharp vision was achieved for a set of distances within range  $(25-10^8 \text{ cm})$  but still much less than in healthy eye and pseudophakic eye with triplet-MIOLs implanted was the best model.

Keywords: Refractive intraocular lens; classic intraocular lens implant; image quality of eye; Multifocal IOLs.

## 1. Introduction

In an aging society, the most frequent causes of blindness is crystalline lens cataracts or opacification which leads to significant degradation in the retinal image and decreasing the patients vision quality [1,2]. Since 1949, until now the removal surgery of opaque crystalline lens and replacing it with an intraocular lens (IOLs) "artificial lens" was the most effective method for cataract treatment[3-6]. In the mid-20 century Sir Ridley [7, 8] developed the first artificial intraocular. PMMA material was used for the first IOLs which the implantation necessary required relatively large incision of the eye balls. Since this time high biocompatibility and flexibility new IOL materials were developed for IOL manufacture[9-11]. Due to new IOL advent technology the popular IOLs lens was foldable silicone or acrylic lenses [12] which need small enough incision to implanted. Wide review of applied manufacture materials, IOLs different category and design principles was described by Zeng and Fang [13]. The retinal image quality of IOL depends on many optical parameters and features. The most important parameter is the refractive index of material lens[12] and power of focusing, which depends on radius of curvatures, thickness (IOL shape). Nowadays multifocal intraocular lenses (MIOLs) are widely use with one implant for the pseudophakic patient to replace the opaque crystalline lens, as well for presbyopia correction [14]. Refractive separated MIOLs zones was illustrated in Figure1 [15].

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Figure 1. Diagram of refractive zones of the MIOLs [15].

Recently, Al-Hamdani and Hashim [16] adopting Zemax-EE (2005)software and the Liou and Brennan human eye model to design polythiourethane contact lens and study the effect of Polychromatic Light on human eye image performance. The analysis also present conduct quantitative comparisons for different diameters of pupil entrance and the criteria for degradation of retinal image was MTF, blur spot size (RMS) and the type and amount of aberrations(monochromatic and polychromatic).

In this article, doublet and triplet proposed MIOLs of two material were presented to correct chromatic and spherical aberrations as high order aberrations. Further multi-focus refractive MIOLs also investigated.

## 2. Material and Method

With the aid of ZEMAX-EE software, Liou & Brennan eye models (Pseudophakic eye models) was used to design and analysis the quality of retinal image formed by the implanted MIOLs [17]. Table 1 summarized eye model parameters of optical surface. This model acquires wide acceptance as one of the best approaches to the visual system of the human eye [12].

Surface	Comment	<b>Radius</b> (mm)	Thickness (mm)	Glass Refractive	Abbe	<b>Diameter</b> (mm)	Conic	
				<b>555</b> nm	number			
OBJ	Object	Infinity	Infinity	-	-	0	0.00	
1	Anterior	7.77	0.50	1.376	50.23	10	-0.18	
2	cornea Posterior cornea	6.40	3.16	1.336	50.23	10	-0.60	
STO	Pupil	Infinity	0	1.336	50.23	2.5	0	
3	Lens- front	12.40	1.59	Grad A	-		-0.94	
4	Lens- back	Infinity	2.43	Grad P	-	10	0.00	
5	Vitreous	-8.10	16.27	1.336	50.23	10	0.96	
IMA	Retina	-12.00	-	-		10	0	

**Table 1**. Parameters of optical surface of the Liou & Brennan eye model [16].

\* Where OBJ, STO and IMA are object, stop and image surfaces.

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This model assumes that the crystalline lens is composed of anterior and posterior as a two parts with gradient (variable) refractive index. The distribution of gradient index and index in anterior  $(n_A)$  and posterior parts  $(n_P)$  are given by the following equations [17]:

$$[n_A(z,r)] = 1.368 + 0.049057z - 0.015427z^2 - 0.001978r^2,$$
(1)

And gradient index in the posterior part by[17]:

$$[n_P(z,r)] = 1.4078 - 0.006605z^2 - 0.001978r^2,$$
<sup>(2)</sup>

Adopting Liou &Brennan model the dispersion relation described for entire eye media is [17]:

$$n(\lambda) = n_{555} + 0.0512 - 0.1455\lambda + 0.0961\lambda^2$$
(3)

where (z, r) are the cylindrical-coordinates with the z-axis oriented along the visual-axis of the model eye and  $n_{555}$  is index of refraction for the wavelength equal to 0.555 µm.

In order to design refractive MIOLs, refractive index and chromatic dispersion (determined by Abbe number) of materials must be employed. The used two materials are:

- The first material is acrylic (AR40N Allergan) with index  $n_{(1)} = 1.47$  and Abbe number  $V_d$  (1) = 71 [18]. This material classified as relatively low dispersion material.
- The second one is more dispersive; acrylic (AcrySof SA60AT) with  $n_2 = 1.55$  and  $V_d$  (2) = 37[19].

The optimum performance of different MIOLs were studied and evaluate with the aid of ZEMAX-EE software accessed using a merit function defined as[20].

$$MF = \left[\frac{1}{N} \sum_{j=1}^{N} \left[\frac{f(\lambda_i) - f_j}{\Delta f_j}\right]^2\right]^{1/2}$$
(4)

Further the spectral sensitivity curve in bright illumination (photopic state) [21, 22] of human eye (pseudophakic eye). The characteristics of retina image were calculated for the input pupil of 4mm diameter and 5° X-field. The data of human eye spectral sensitivity are presented in Table 2.

 Wavelength (mm)
 0.455
 0.505
 0.605
 0.655

 Spectral sensitivity
 0.0746
 0.4027
 0.8658
 0.4569
 0.0568

Table 2. Human eye different wavelengths spectral sensitivity

#### 3. Results and Discussion

Optimum result of classic refractive MIOLs of the three types [singlet; doublet & triplet] implanted in pseudophakic eye are presented in Tables (3-5).

Table 5. Optical Surface Data Parameters For Singlet MIOLS Refractive									
Element	Radius (mm)	Thickness (mm)	diameter (mm)	Refractive index	Abbe number				
Anterior Surface	6.00	0.90	6.00	1.470	71.00				
Posterior Surface	-6.00	2.43	6.00	1.336	50.23				

 Table 3. Optical Surface Data Parameters For Singlet MIOLs Refractive

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	Even Aspheric Coefficients							
Element	Conic constant	2 <sup>th</sup> order	4 <sup>th</sup> order	6 <sup>th</sup> order	8 <sup>th</sup> order			
Anterior Surface	-1.222E+8	-0.12379	-0.016639	-5.017E-4	-2.921E-4			
Posterior Surface	-5.9580	-0.12801	-0.016800	-4.927E-4	-1.852E-4			

						<b>Even Aspheric Coefficients</b>		
Element	Radius (mm)	Thickness (mm)	diameter (mm)	Refractive index	Abbe number	<b>Conic</b> constant	4 <sup>th</sup> order	6 <sup>th</sup> order
Anterior	12.44	0.60	3	1.470	71.00	-18.0	-8.339E-4	9.280E-5
Surface								
Intermediate	-5.92	0.60	3	1.550	37.00	0.0	0	0
Surface								
Posterior	-8.91	2.43	3	1.336	50.23	5.2	1.781E-4	1.789E-4
Surface								

Table 5. Optical Surface Data Parameters For Triplet MIOLs Refractive

			diameter (mm)	<b>Refractive</b> index	Abbe number	<b>Even Aspheric Coefficients</b>		
Element	Radius (mm)	Thickness (mm)				Conic constant	4 <sup>th</sup> order	6 <sup>th</sup> order
Anterior Surface	15.50	0.45	б	1.470	71.00	-7.60	-2.103E-4	-3.067E-4
Intermediate Surface 1	15.50	0. 39	6	1.550	37.00	-125.62	0.0000	0.0000
Intermediate Surface 2	7.00	0.45	6	1.470	71.00	-10.56	0.0000	0.0000
Posterior Surface	-7.29	2.43	6	1.336	50.23	-6.14	-9.419E-3	-2.569E-4

The overall optical performance of eye implanted MIOLs were based on the evaluation of the point spread function (PSF) and modulation transfer function (MTF). Figure 2 depict Liou & Brennan eye model of a healthy eye polychromatic PSF and the different types classic refractive MIOLs [singlet; doublet & triplet] implanted for a pseudophakic eye. It also showed that the optical performance of all polychromatic PSF shapes of the pseudophakic eye with refractive MIOLs seems to be look like healthy eye. Figure3 present the respective polychromatic MTF curves.

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**Figure 2.** Cross-section of the polychromatic PSF of the Liou and Brennan model, and refractive MIOLs [singlet; doublet & triplet] implanted for a pseudophakic eye.



**Figure 3.** Polychromatic MTF of the Liou and Brennan model( healthy eye), and refractive MIOLs [singlet; doublet & triplet] implanted for a pseudophakic eye.

The Liou & Brennan eye model (healthy eye) polychromatic spot diagram and different types MIOL curves were presenting in Figure 4. Root-mean square error (RMS) radius (standard for aberration spots) in Polychromatic spot diagram for Liou &Brennan eye model (healthy eye) it is equal to about 2.670, and for the eye model with refractive (singlet, doublet and triplet) MIOLs it are equal to about 2.618, 2.389 and 1.367, respectively. The aberration spots on the retina for all MIOLs proposed design less than of a healthy eye.

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**Figure 4.** Polychromatic spot diagram for: (a) Liou-Brennan eye model (healthy eye) and models eye with refractive MIOLs implanted into three types: (b) singlet, (c) doublet, (d) triplet.

Material and design shape variation of the considered MIOLs were taken into account in this study, the effective focal length (standard for calculation power) for healthy eye and refractive MIOLs(singlet, doublet and triplet) were 16.588, 13.557, 16. 539 and 16.655 *mm*, respectively. Figure 5 illustrate the (LCA) (left side), the sphero-chromatic aberration(right side) for Liou &Brennan model eye (healthy eye) and three eye models of classic refractive MIOLs for a pseudophakic eye.

Maximum focal shift range (LCA) and sphero-chromatic aberration of a healthy eye and optimum result over the spectral wavelength range (455-655 nm) with increment 60nm were as follows:

- healthy eye approximately equal to 128µm & 0.176mm.
- refractive MIOLs implanted pseudophakic eye :
  - singlet about 109  $\mu m \& 0.255$ mm.
  - doublet about 72  $\mu m \& 0.070$ mm.
  - triplet about  $31\mu m \& 0.048$ mm.

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The results showed that the proposed refractive (doublet- and triplet-) MIOLs have a good correction of chromatic dispersion and spherical aberration.







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**Figure 5**. LCA (left) and sphero-chromatic aberration (right) for: (a) Liou &Brennan eye model (healthy eye) and models eye with refractive MIOLs implanted into three types are: (b) singlet, (c) doublet, (d) triplet.

## 4. Conclusions

Image characteristic functions, *i.e.* MTF, PSF, (longitudinal-, Sphero-) chromatic aberration and spot diagrams were used in this study to describe the image quality of retinal image for healthy eye and artificial refractive MIOLs. Simulation with ZEMAX show that the optimum design of refractive triplet MIOLs was the best model, then after, refractive doublet MIOLs model. Refractive singlet MIOLs optimum design (including 8-zones) still safer from sphero-chromatic aberration than healthy eye. To overcome this problem, more surface (within the thickness limit) and materials of pseudophakic eye were introduce in Liou &Brennan eye model. Sphero-chromatic aberration of the pseudophakic eye with refractive (triplet- & doublet-) MIOLs implanted are less than healthy eye.

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