Ali H. Al-Hamdani
Laser and Optoelectronics Engineering Department, University of Technology, Baghdad, Iraq.
140002@uotechnology.edu.iq

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Design and Performance Analysis of Contact Lens Materials for Chromatic and Polychromatic Aberrations Correction

Abstract-*A material scientists worldwide has investigated optical plastics as alternative materials for glasses that have been widely used over the years. Plastics have numerous advantages over glasses in optical applications, especially in ophthalmic applications. Recently, researchers have developed new polymer materials to satisfy the ophthalmic industry requirements. Mechanical, chemical and physical tests were conducted to determine the polymers for contact lenses. In this study, the optical properties of polymers were evaluated and analyzed by using Zemax program depending on Liou & Brennan model. The effect of achromatic and polychromatic light on the performance of the polymers contact lenses was investigated. The modulation transfer function (MTF) and root mean square spot size (RMS) were the two criteria for analyzing the results and determining the effect of chromatic aberration on different polymers contact lens performances.*

Keywords*-Contact lens material, Chromatic aberration, Biooptics, Human eye error correction.*

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1. Introduction

Contact lenses, which are worn on the eyes, are used to treat human eye defects such as, a hyperopia, myopia, presbyopia and astigmatism. Contact lenses are worn straight on the eye surface. The intraocular lenses are surgically implanted after cataract abstraction and for purely refractive purposes [1]. The myopia (Nearsightedness) needs divergent lenses, while hyperopia (Farsightedness) needs to convergent lenses [2-4]. Contact lenses typically serve the same corrective purpose as conventional glasses, but contact lenses are lightweight and virtually invisible. Many commercial lenses are tinted with faint blue for visibility when immersed in cleaning and storage solutions. Several cosmetic lenses are deliberately coloured to alter the appearance of the eye. People wear contact lenses for many reasons, especially given their appearance and practicality [5]. Contact lenses are less affected by wet weather, do not moisten, provide a wider field of vision and are more suitable for a number of sporting activities than spectacles [6]. In addition, glasses may not accurately correct Ophthalmological conditions, such as keratoconus and aniseikonia. There are many varieties of contact lenses are available. Rigid or 'hard' contacts were the first lenses developed in the 1960s. They are made of a type of plastic called polymethyl methacrylate (PMMA) which is durable and blocks the air oxygen straight reaching the cornea. The lens directly moves when the eyes are blinking, thereby allowing the dissolved tears as well as consist to the oxygen touch the cornea. Inflexible lenses (Rigid) are uncomfortable as contact lenses and there are no longer being used. Conversely, many users are selecting them because of given their robustness as well as cheap.

New type of lenses are merged (Gas-permeable lenses). This type of lens has low cost and there are very rigid, which is made from combined two materials such plastic and other type of material, for instance silicone or fluoropolymers. In addition, the oxygen is passed easily through the lens, therefore, this type called a (gas permeable). Delicate contact lenses normally made from plastics that integrate water. The water helps the lenses to be delicate and changeable, as well as allowing oxygen to reach the cornea. Generally, contact lenses should be detached from the eyes at sleeping time considering the risks of contamination and intolerance. The selection of an optical material is based on their physical, chemical and mechanical properties. The mechanical properties of selected polymer materials were determined in [7] by using Ashby's selection diagrams [8]. In the real world, the features are required of an optical applications consist of firmness, high stability of different temperature and, thermal increasing, affinity to absorb as well as retain water, easy to

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

manufacture, transparency, lightness, low cost, bio-compatible and low elastic modulus. For polymer contact lens, the optical properties are crucial to select the proper type of materials [9-10]. There are four general optical properties, namely, refractive index, Abbe number, light transmission and reflection, are considered. Optical properties of some optical polymer materials are presented in Table 1. The refractive index and the Abbe number are the key parameters for optical polymers used in geometrical optics. The refractive index for a typical optical polymer was as low as 1.49-1.5 [11-12]. The contact lens made of these low refractive index polymers has the disadvantage of being too thick at both the center and edge. In addition, a low refractive index means high optical dispersion of a polymer, so, a low refractive value, limits its application in optical lenses. Conversely, a large refractive index (n) value indicates a low optical dispersion, that is, a small chromatic aberration is presented.The refractive index of a polymer estimated in terms of molecular refraction (R) [13].

$$n = \sqrt{\frac{V+2(R)}{V-(R)}}$$
(1)

where n is the refractive index, and V is the molar volume.

The Abbe number refers to characterize of the dispersion power of the materials;

$$v_d = \frac{n_d-1}{n_f-n_c} \quad (2)$$

where n_d, n_f and n_c is the refractive index for (λ=587.56 nm, 486.13 nm and 656.27 nm respectively). The Abbe number is inversely proportional according to chromatic dispersion of the material normally expressed by refractive index (n), molecular refraction (R) and molecular dispersion (ΔR), as shown in Equation (3) [13].

$$v_d = \frac{6n_d}{(n_d+2)(n_d+1)} \frac{|R|}{|\Delta R|}$$
(3)

In Equation (3), a larger refractive index diminishes the Abbe number and vice versa. The Abbe number has a varies broadband which is starting from 60 for the least chromatic to 30 for the most chromatic materials [14]. The organic polymers at n = 1.70 or upper, typically have an Abbe number that is less than 20.0. Consequently, an ideal value balance between the Abbe number and refractive index is required to eliminate the chromatic aberration in the materials [15-16]. Polymers exhibit a significant diversity of optical transparency that ranges from a transparent optical quality to completely opaque. Transparency is commonly described by a four-level ranking that uses easy-to-understand terms, namely, 'opaque', 'translucent', 'transparent' and 'water- clear '. Figure 1 illustrates the transparency ranking of common materials. It is shown that, for glass, PET and PMMA are in are (water-clear) region. Epoxies can be transparent but without water clarity. Nylons are translucent. The reflectance of the lens surfaces is calculated from the refractive index of a material. When light is incident normally on a lens surface in the air, the percentage of light reflected at each surface is given by:

$$R = \frac{(n_1-n_2)^2}{(n_1+n_2)^2} * 100\% \quad (4)$$

where n_1, n_2 is the refractive index of the first and the second medium respectively. If the first medium is air the equation (4) become,

$$R = \frac{(n_2-1)^2}{(n_2+1)^2} * 100\%$$
(5)

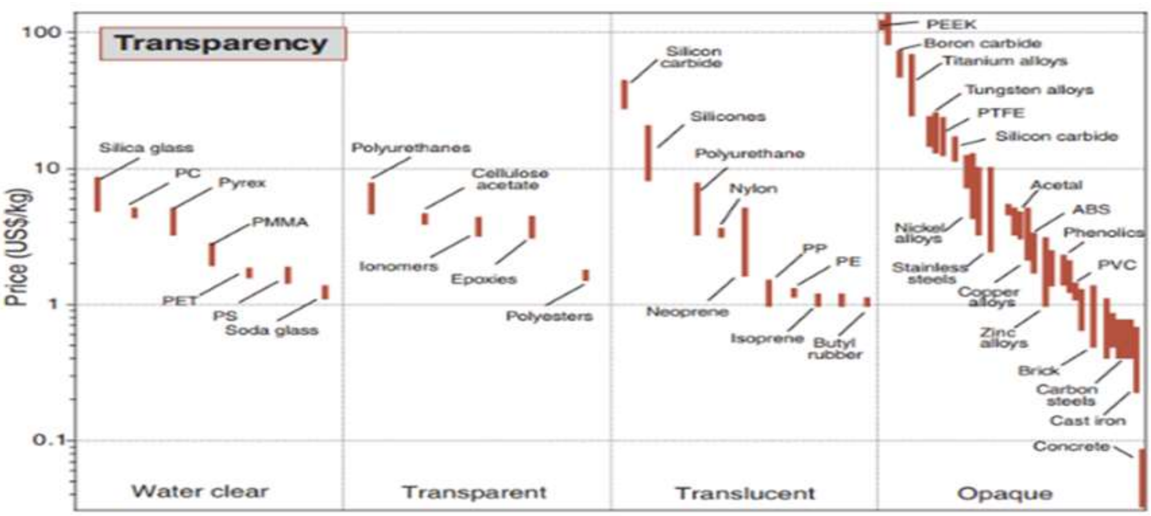
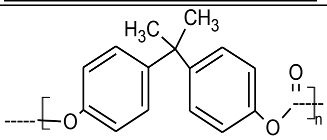
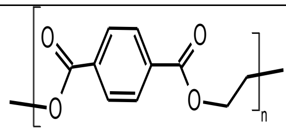
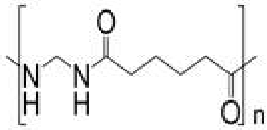
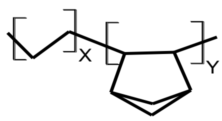
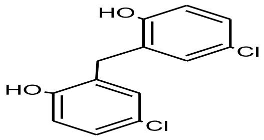
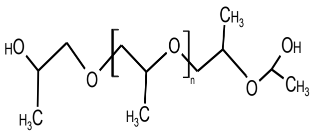
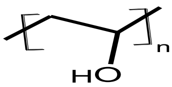


Figure 1: Transparency is ranked on a four-point scale, that is, from a water-clear to opaque [8].

Table 1: The optical properties of selected polymer materials [10]

	Polymer	Chemical structure	Refractive index	Abbe number	T %	R%
1	PMMA Poly(methylmethacrylate)	[redacted]	1.49	53	92	7.80
2	PC Polycarbonate		1.59	29	89	12.30
3	PET Polyethylene terephthalate		1.66	39	89	6.15
4	PA Polyamide		1.54	32		4.20
5	COC Cyclic Olefin copolymer		1.54	56	91	4.20
6	TRIVEX 4-chloro-2-[(5-chloro-2-hydroxy-phenyl) methyl]phenol,		1.54	45	91	4.40
7	TRIBRID Polypropyleneglycol		1.6	41	91	5.32
8	PVA Polyvinyl alcohol		1.36	60	89	6

2. Optical Testing

The quality analysis of the image performed by the retina of the eye with a contact lens manufactured from the selective materials was done by using Zemax program (Radiant Zemax LLC,WA). In the present study, the root mean square (RMS) spot blurs size, point spread function (PSF) and modulation transfer function (MTF) are the important criteria that are used for analysing the eye performance. The effect of the selected polymer on the monochromatic and polychromatic aberrations is investigated in details and comparisons with the Liou & Brennan model [17]. Zemax program is used to evaluate and analyse the effect of the different contact lens materials on the eye performances [18], and the suitable material for manufacturing contact lenses is selected.

3. Results and Discussion

The MTF values are recorded at a 2.5 mm pupil diameter. The MTF is measured under each tail frequency (ranging from 0.0 cycle/mm to 30 cycle/mm). MTF_{550nm} was monochromatic MTF that is measured at 550nm, whereas $MTF_{470–650nm}$ was a polychromatic MTF that is measured at 470,510,550,610 and 650 nm with weights of 0.091, 0.503, 0.503 and 0.107. The results were limited to the sagittal MTF in order to avoid confusion. Figure 2, shows that monochromatic MTF_{555nm} values are significantly higher than polychromatic $MTF_{470–650nm}$ for the Liou & Brennan model and extended to all the contact lens material. This result is due to chromatic aberration, which degrades the image vision. The presence of the chromatic aberration increases the RMS spot size. Figure 3, illustrates that the RMS wavefront error for all materials increased when a polychromatic light in wavelength from 470 nm to 650nm was used. This depicts the ΔRMS, which represents the difference between the RMS spot size for monochromatic and polychromatic lights for each material. In this figure, PA polymer is the highest polymer affected by polychromatic aberration (ΔRMS=0.203 λ), whereas PET is the lowest polymer (ΔRMS=0.068 λ). The Liou & Brennan model (without contact lens) is (ΔRMS=0.031 mm).Figure 4, indicates the peak to the valley for the wave front function on the retina for a different polymer contact lens for monochromatic and polychromatic light. It is shown that PA polymer has the highest P-V (0.534 λ) while PET have the lowest (P-V=0.068 λ). The results in figures 2-3 refer that PET polymer was less affected than other polymers when using polychromatic light. PMMA, TRIVEX and TRIBRID were affected nearly in the same magnitudes with chromatic aberration. The MTF is one of the best criteria to evaluate and analysis the effect of the materials refractive indices and Abbe number on chromatic aberration. MTF was determined by evaluating the polychromatic MTF on the wavelength (470,510,550,610 and 650nm with weights 0.091, 0.503, 0.503 and 0.107) and comparing with achromatic MTF (λ=555nm). The results show that the monochromatic MTF is higher than the polychromatic MTF for all the materials. This finding indicates that chromatic aberration significantly affects the performance of the eye. Figure 5, demonstrates the comparison between the MTF (λ=555nm) for Liou & Brennan (without contact lens) and models with different contact lens materials. For the monochromatic MTF, the materials in the Liou & Brennan model indicate that the MTF for all material and PA polymer is low (poor performance). Figure 6, exhibits the polychromatic MTF at wavelengths (470,510,550,610 and 650 nm with weights of 0.091, 0.503, 0.503 and 0.107) for the Liou & Brennan model (without contact lens) and models with different contact lens materials. This figure displays that the polychromatic MTF for the Liou & Brennan model is the highest, whereas the polychromatic MTF for the PA polymer is the lowest.In this work, the initial value is the monochromatic MTF_{550nm} and the polychromatic $MTF_{470–650nm}$ is the final value of the same material. The (A-value) for each spatial frequency (0–30 cycle/mm) to investigate the change in MTF when polychromatic light is used instead of monochromatic light 550 nm)

$$A - \text{value} = \frac{(MTF_{550\ nm}) - (MTF_{470-650\ nm})}{MTF_{550\ nm}} * 100 \qquad (6)$$

Figure (7) presents the A-value for the different polymer frequencies (0–30 cycle/mm). Figure (7) and Table 2 indicate that the A-value (for all materials) increased as spatial frequency increased, thereby recognizing the higher effect of the chromatic aberration on the MTF values. Conversely, the A-value for the eye model using PMMA, PA, and TRIBID materials are meagrely higher than the A- value of the Liou & Brennan model at using a spatial frequency are ≥14, 20 and 2 cycle/mm respectively. This result indicates that the effect of the chromatic aberrations on the MTF for these materials is higher than the Liou & Brennan model or other polymers. The A-value of residual materials is substantially less than those of the Liou & Brennan eye model, which indicates that of the effect of chromatic aberration on the MTF by using these materials as contact lenses, is less than the Liou & Brennan model. From the entire above results, one concludes that PET polymer is the preferred contact lens material because of higher MTF and less affected by chromatic aberration besides the other optical properties (clearer transmittance, lighter and clearer).

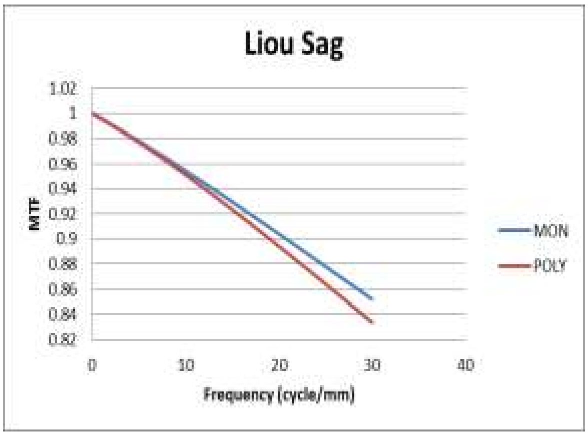


Figure 2: The sagittal MTF for monochromatic and polychromatic light.(case study).

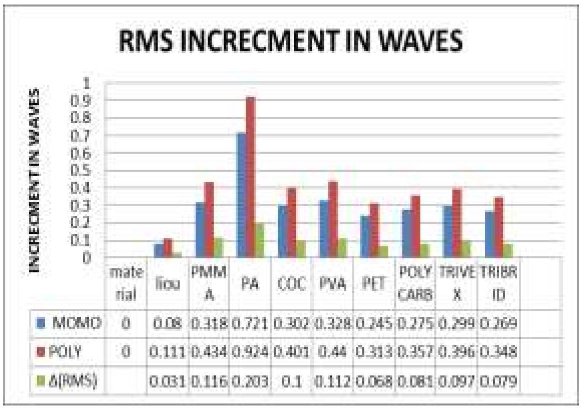


Figure 3: RMS wavefront error for Monochromatic light 555nm (Blue), polychromatic light (470-650 nm) (red) and the increment in RMS due to chromatic aberration (green) for different polymer

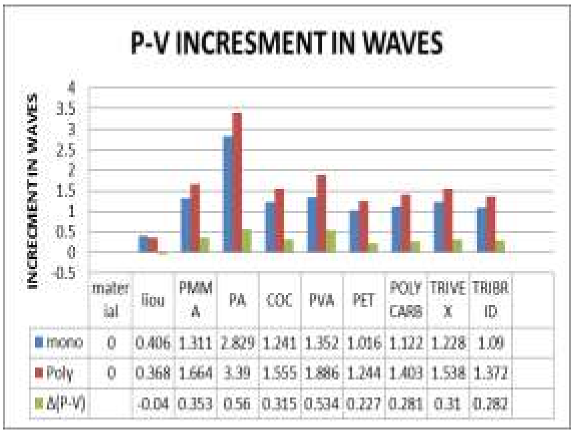


Figure 4: Peak to Valley in waves for Monochromatic light 555nm (Blue), polychromatic light (470-650 nm) (red) and the increment in P-V due to chromatic aberration (green) for different polymer

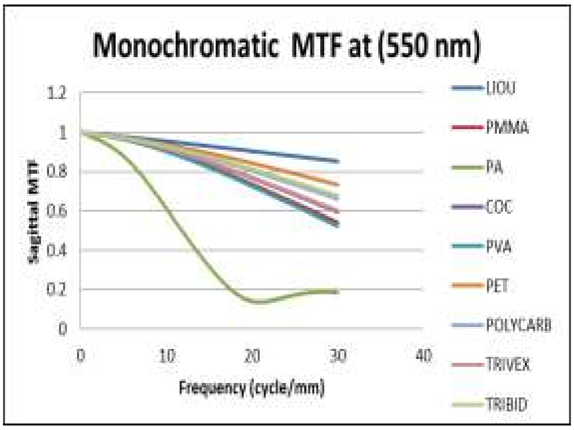


Figure 5: Monochromatic (550 nm) MTF for different materials

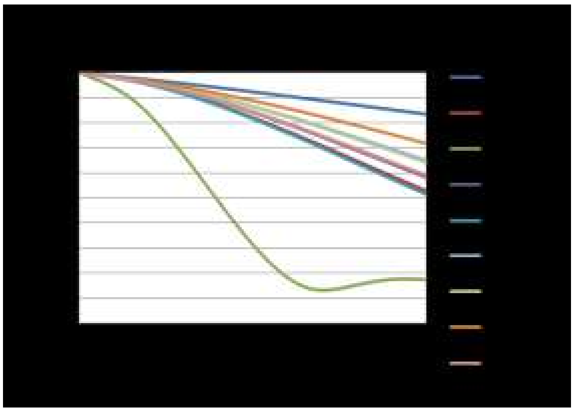


Figure 6: Polychromatic MTF (470–650 nm) for different materials.

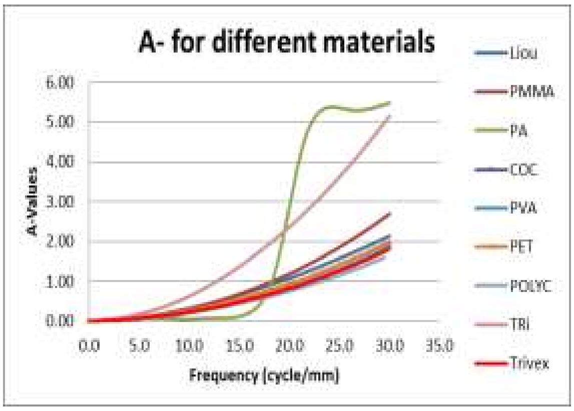


Figure 7: The A-value between polychromatic (470–650 nm) and monochromatic (550nm), Sagittal MTF for the different materials.

Table 2: Present change (A-value), for Liou & Brennan model MTF with different polymer materials (at 2.5 mm pupil diameter).

Frequency (cycles/mm)	LIOU	PMMA	PA	COC	PVA	PET	PC	Trivex	TRIBID
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2.000	0.028	0.027	0.026	0.023	0.024	0.024	0.021	0.023	0.052
4.000	0.070	0.066	0.061	0.055	0.056	0.057	0.050	0.054	0.131
6.000	0.137	0.123	0.081	0.099	0.099	0.109	0.092	0.097	0.250
8.000	0.224	0.203	0.071	0.158	0.157	0.179	0.147	0.155	0.416

10.000	0.329	0.309	0.055	0.233	0.231	0.265	0.215	0.228	0.630
12.000	0.450	0.444	0.078	0.327	0.326	0.369	0.300	0.320	0.895
14.000	0.587	0.601	0.087	0.437	0.435	0.490	0.398	0.426	1.204
16.000	0.740	0.777	0.216	0.559	0.557	0.625	0.508	0.545	1.551
18.000	0.906	0.973	0.825	0.694	0.691	0.774	0.630	0.677	1.937
20.000	1.085	1.195	2.869	0.844	0.842	0.939	0.764	0.824	2.366
22.000	1.275	1.441	4.879	1.013	1.012	1.120	0.914	0.987	2.839
24.000	1.476	1.713	5.370	1.197	1.199	1.316	1.077	1.167	3.354
26.000	1.688	2.011	5.302	1.399	1.407	1.527	1.254	1.363	3.909
28.000	1.907	2.337	5.328	1.619	1.638	1.752	1.445	1.577	4.506
30.000	2.136	2.695	5.478	1.861	1.898	1.993	1.165	1.811	5.145

4. Conclusions

The diffraction limited eye lens pupil diameter is 2.5 mm used in this study. The differences between the polychromatic and monochromatic MTF depend on the refractive index and Abbe number of the polymer materials. These refractive index and the abbe number are mainly parameters control the chromatic aberrations in the eye image. The monochromatic and polychromatic MTF was evaluated and compared to analysis the effects of chromatic aberration on retinal image quality. From the results, a high Abbe number and a high refractive index for the contact lens polymer are the important parameters for reducing the chromatic aberration in the eye image. All materials with a higher Abbe number demonstrated a low refractive index. Therefore, the Abbe number and refractive index of the selected contact lens polymer should be optimized carefully. Zemax program and Liou & Brennan model are a good tool in selecting and analysing contact lens polymers. PET has the best properties to be used as lens materials.

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Author biography

Assist. Prof. Dr. Ali H. Al-Hamdani, University of Technology, Baghdad, Iraq, Laser and optoelectronics engineering Dept. Born in Iraq on 3th November 1957, Completed Bachelor of Sciences (Physics) in the year of 1981 and completed Master and PH.D of Physics (Optics) in the year of 1986 and 1997. His research area is optics, optoelectronics and nonlinear optics