A comparative study of optical quality for different polymeric contact lenses

Lina M. Shaker¹, Ali H. Al-Hamdani¹* and Ahmed A. Al-Amiery²

1 Laser and Optoelectronics Engineering Department, University of Technology, Baghdad, IRAQ.
2 Energy & Renewable Energy Technology center, University of Technology, Baghdad, IRAQ.
Correspond: Email: - 140002@uotechnology.edu.iq

Abstract. The comparison between pure organic polymer namely Poly(methyl methacrylate) “PMMA” and impregnated with Titanium dioxide nanoparticles (TiO₂ NPs) as contact lenses on image quality of human eye have been investigated. Pure PMMA and TiO₂-PMMA materials were considered and applied using ZEMAX software as contact lenses (CLs) basis on Liou & Brennan eye model. Ocular performance was evaluated and analysis by three criteria, namely tangential modulation transfer function (TMTF), wavefront aberration characteristics and root mean square (RMS) of spot diagram. All the criteria showed that contact lens made of TiO₂-PMMA when its refractive index (RI) = 1.61 and Abbe number (νd) = 31.8 provided the closest imaging properties to the healthy eye. From the results of our investigation, PMMA doping with TiO₂ resulted in balanced RI with νd polymer and it provided the best retinal image when it used in CLs in comparison with image properties of the resulting image using the lens of pure PMMA polymer.

1. Introduction
Contact lenses (CLs) are considered as an essential optical device in therapeutic uses and ophthalmic care. They are classified into hard, soft and hybrid CLs according to the material used in fabrication. The earlier CL was unhealthy and uncomfortable to the eye because it was made of glass shells [1]. Then, suitable optical polymers were discovered to make the polymeric contact lenses; they are poly methyl-methacrylate (PMMA) hard CLs and rigid gas permeable CLs [2], hydroxy-ethyl methacrylate (HEMA) soft CLs and the hybrid one which characterized by hard central zone surrounded by a soft polymeric area [3]. So the candidate material [5,6] must be biologically appropriate to maintain the corneal tissues and also the CLs must be compatible to physiological conditions of the eyeball. Polymers of high refractive index (RI) and low dispersion; high Abbe number νd such as PMMA transparent thermoplastic of RI (1.49), νd of (59) [7,8], characterized by light weight, high resistant to scratching and safe to the eye but it is impermeable to the water or oxygen. On the other hand adding nano-particles (NPs) to the optical polymers can enhance the optical properties of PMMA [9,10]. The RI of titania-PMMA (TiO₂-PMMA) increased to 1.61 but νd decreased to 31.8 [11,12]. Lately developments and improvements in optical plastics included a progress in the selected CLs material fabrication, light transmission, oxygen and water access into the cornea. In this work, pure PMMA and hybrid one “TiO₂-PMMA” of optical properties are shown in table (1). They were chosen as CLs materials.
Table 1. Optical properties and chemical structures of the selected optical polymers. T: visible light transmittance (%) [11,12].

| Polymer abbreviation | T% | RI | ν_d | Structure | Chemical formula |
|----------------------|----|----|-----|-----------|-----------------|
| PMMA                 | 92 | 1.45 | 53 | (C$_5$O$_2$H$_8$)$_n$ |
| TiO$_2$-PMMA         | 90 | 1.61 | 31.8 | TiO$_2$-(C$_5$O$_2$H$_8$)$_n$ |

1.1 Modulation Transfer Function (MTF)
Modulation transfer function (MTF) is the modulus Fourier transformation of point spread function (PSF):

$$MTF = |FT(PSF)|$$

(1)

or it refers to the ability of an optical system (for example eye optics) to form the image at different spatial frequencies. Spatial frequency defined as an array of bar targets at specific spacing and it is given by units of line-pairs per millimeter (or cycle per millimeter).

$$MTF = \frac{I_{Max} - I_{Min}}{I_{Max} + I_{Min}}$$

(2)

Where $I_{Max}$ and $I_{Min}$ in the numerator are the maximum and minimum irradiance of the image, while $I_{Max}$ and $I_{Min}$ in the dominator represent the maximum and minimum intensities of radiant emittance for the object. [12]

1.2 Root Mean Square
Root Mean Square (RMS) is the radius of spot diagram. It is a way of visualizing the amount and type of aberration in the image. Perfect optical system has a small RMS [13]. So it is an image quality criteria and it defined as below [14]:

$$RMS = \sqrt{\frac{\sum_i (x_i+x_c)^2 + (y_i+y_c)^2}{n}}$$

(3)

Where n is a number of points, the reference point ($x_c, y_c$) is taken as the spot center (0,0) and ($x_i,y_i$) is the location of the rays intersection.

2. Analytical Work
In order to evaluate and compare the retinal image quality of a free CLs model and the model with CLs, Liou & Brennan eye model (healthy eye) was simulated using ZEMAX optical design program (see table (2)). After a brief survey on optical polymers that can be used in medical applications, two high transparency, high RI and ν_d optical plastics were tested as contact lenses: PMMA and TiO$_2$-PMMA.

Table 2. Construction data of Liou & Brennan eye model in ZEMAX software.
Input parameters: F.O.V. = 5 degrees, \( \lambda = 470, 510, 555, 610 \) and 650 nm

| Surface    | Radius [mm] | Thickness [mm] | RI  | \( \nu_d \) | E.P.D. [mm] |
|------------|-------------|----------------|-----|-------------|-------------|
| Cornea     | 7.77        | 0.55           | 1.38| 50.23       | 10          |
| Aqueous    | 6.4         | 3.16           | 1.34| 50.23       | 10          |
| Pupil      | Infinity    | 0              | 1.34| 50.23       | 4           |
| Lens-Front | 12.4        | 1.59           | -   | -           | 10          |
| Lens-Back  | Infinity    | 2.43           | -   | -           | 10          |
| Vitreous   | -8.1        | 16.23883       | 1.34| 50.23       | 10          |
| Retina     | -12         | -              | -   | -           | 10          |

The parameters of these two polymers were collected in table (3). A comparison between the effect of polychromatic light of different wavelengths 470, 510, 555, 610 and 650 nm and with weights of 0.091, 0.503, 1, 0.503 and 0.107%, respectively was studied. Construction of Liou & Brennan eye model was done by inserting 7 surfaces between the object and retina and entering their details into ZEMAX software as shown in table (2); they are the input beam, cornea, aqueous humor, pupil aperture, the lens front portion, the rear portion of the lens and finally the vitreous body of the eye. The field of view (F.O.V.) and entrance pupil diameter (E.P.D.) were fixed at 5 degrees and 4 mm, respectively. Contact lenses made of PMMA and TiO\(_2\)-PMMA polymers were applied the Liou & Brennan model (parameters are given in table 3). Modulation transfer function (MTF) and the spot diagrams (RMS; RMS belongs to root mean square of the spot in the image plane) have been used to evaluate the image quality before and after submission of PMMA and TiO\(_2\)-PMMA contact lenses.

### Table 3. Construction data of PMMA and TiO\(_2\)-PMMA CLs.

| Material | CL Front Radius [mm] | CL Back Radius [mm] | CL Front Thickness [mm] | CL Back Thickness [mm] | RI  | \( \nu_d \) |
|----------|----------------------|---------------------|-------------------------|------------------------|-----|-------------|
| PMMA     | 7.747957             | 7.8                 | 0.1                     | 7.8                    | 1.45| 59          |
| TiO\(_2\)-PMMA | 7.747957 | 7.8                 | 0.1                     | 7.8                    | 1.78| 31.8        |

3. Results and discussion

The results included the effect of the presence of hybrid contact lens (TiO\(_2\) nanoparticle doped PMMA polymer) and comparing them with pure PMMA organic lenses. Liou & Brennan eye model was used, which is free of contact lenses, as a reference to the comparison. The polychromatic light source was used in this study. These results were analyzed using basic criteria for optical systems quality analysis such as the modulation transfer function (MTF), aberration coefficients and spot diagram (RMS).

3.1. **TMTF and Wavefront aberration coefficient**

Figure (1) shows the tangential component (TMTF) variability as a function of spatial frequency range of (0-30 cycle/mm) for polychromatic (470-650 nm) light, respectively. It is clear from this figure that CL made of polymer doping with TiO\(_2\) NP has improved the image formed by the eye and made its TMTF value nearly equal to the image TMTF that formed by the Liou & Brennan model. TMTF of the two mentioned cases are better than that obtained when using the pure polymer PMMA and under the same conditions of 4 mm pupil size and 5 degrees field of view.
Figure 1. TMTF for three different models for polychromatic light.

Figure (2) shows the spherical, coma, astigmatism, field curvature, distortion, defocus and tilt aberration coefficients, these coefficients are denoted by W040, W131, W222, W220P, W311, W020 and W111, respectively. The presence of polychromatic light played a major role in generating the chromatic aberration (function of distortion) in addition to the spherical one (spherochromatic aberration). The effect of generated distortion when Liou & Brennan model, PMMA CL and TiO2-PMMA CL were applied remained approximately at the same value W020 = 1.31, 1.32 and 1.33, respectively. Although the other aberrations are present, they are ineffective because they have lower values than it does in the spherical and distortion aberration. These aberration coefficients are measured in wavelength units, that means the difference between perfect eye, PMMA CL and TiO2-PMMA CL models are not considered as a small difference. For example, the maximum value of spherical aberration is 0.5λ, higher than it will reduce the Strehl ratio to less than 0.8. The Strehl ratio is defined as the ratio between the peak intensity of the PSF of aberrated system to the peak intensity of the un-aberrated system. The perfect eye (diffraction–limited) has a Strehl = 1.

The averaged TMTF with the Standard deviation (SD) as (mean TMTF ± SD) are given in figure (3). Error bars represent the variation in SD according to the applied model. Both of TiO2-PMMA CL and Liou & Brennan model had the same (mean ± SD) values (0.92 ± 0.06) but a lower value of (0.813 ± 0.15) was gotten by the pure polymer CL.
Figure 2. Effect of polychromatic light on the aberration coefficients for each of the two CLs and the perfect eye.

Figure 3. The standard deviation of the Mean TMTF for polychromatic light after inserting the CLs as well as without inserting them.

3.2. Spot Diagram
Spot diagram belongs to the focused light rays on the retina. We used the RMS criteria to show the retinal image performance under variation of CL material. From figure (5), the spot diagram and RMS radius, it is easy to say that the best optical performance at obtained by TiO$_2$-PMMA CL (RMS = 3.7 µm) and (RMS = 4 µm), respectively. It is the nearest size to the RMS radius obtained by Liou &
Brennan eye and RMS = 7.1 µm, respectively. PMMA CL of RMS = 7.2 µm, indicates that the largest amount of aberration was generated when employing the pure PMMA CL and it caused a change in shape and size of this spot diagram. The spherical aberration presence affect the spot size while existence of both of spherical and distortion enlarged the RMS spot size.

![Graph](image)

**Figure 4.** RMS values and spot diagrams of the image for Liou & Brennen model with and without CL.

4. Conclusion

In spite of the high IR and $\nu_d$ of the two selected materials, a clear difference in the influence of each one of them on image quality. From the results, the doped state TiO$_2$-PMMA provided an optimum behavior resulted in the based criteria which make it a good candidate in CLs fabrication. Standard deviation (SD) shows that image quality when using TiO$_2$-PMMA CL have the same mean $(0.893 \pm 0.07)$ and $(0.92 \pm 0.06)$ for polychromatic light. PMMA gave the worst image response, despite of its high IR and high $\nu_d$.

5. References

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