

Effect of field of view and iris pupil diameter on the quality of retinal image with allyl carbonate (CR-39) polymer contact lenses

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Abstract. Contact lenses are manufactured from high-grade plastic polymers and prescribed by specialists to treat myopia, hyperopia, astigmatism and presbyopia. Some people opt to wear contact lenses directly on the cornea for aesthetic reasons. The formed image is mainly focused on the retina. Manufacturers are constantly searching for and developing optimal materials for contact lenses to satisfy patients and practitioners in terms of the standard optical characteristics (i.e. Refractive index, abbe number, light reflectance and light transmittance). In this study, allyl carbonate, which is commonly known as CR-39, was tested as the polymer material for contact lenses. The CR-39 polymer material data (refractive index, 1.49; density, 1.32; Abbe number, (58–59) were used in establishing the Liou & Brennan model. The effect of iris, pupil size and the field of view (F.O.V.) on the retinal image was evaluated and analyzed using Zemax-EE software (2005), The modulation transfer function (MTF), point spread function (PSF), blur spot size (RMS), encircled energy (EE) and the type and amount of aberrations, are used as a criteria to analysis the retinal image degradation. The results show that the CR-39 polymer material has good optical properties, which render it a recommended material for ophthalmic contact lenses.

Keywords: Human eye, Liou & Brennan model, Zemax, contact lens material, CR-39 and field of view.

1. Introduction

People have several reasons for opting to wear contact lenses to correct some vision defects, including myopia, hyperopia, astigmatism and presbyopia. Some people choose to wear contact lenses rather than spectacles because of their light weight and imperceptibility [1-3]. Unlike spectacles, contact lenses are directly placed on the cornea. Recently, they have been used for purely refractive purposes. Myopia requires divergent lenses, whereas hyperopia (farsightedness) requires convergent lens. Previous studies [3, 4] showed that millions of Americans and Japanese are wearing contact lenses. Contact lenses are comfortable to wear low cost and affordable; in addition, they provide excellent vision [5]. Some essential optical characteristics are considered in selecting materials that are suitable for contact lenses. Amongst these characteristics are refractive index, Abbe number, light transmittance and light reflectance.

The refractive index, which measures the propagation of a ray of light through a substance, is defined as,

$$n = \frac{\sin(i)}{\sin(r)}, \quad (1)$$



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Where n is the refractive index, (i) is the angle of incidence and (r) is the angle of refraction. The Abbe number (v_d) represents the dispersion of a transparent material and is expressed as

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

Where v_d is the Abbe number; and n_d , n_f and n_c are the refractive indexes at wavelengths of 550, 470 and 650 nm respectively.

Light transmittance (T) measures the amount of light that passes through a transparent material. It is expressed as

$$T = \frac{I}{I_o}, \quad (3)$$

Where I and I_o are the transmitted and incident light intensities, respectively.

Light reflectance (R) is a phenomenon of light direction variation of incident light in which the rays are falling at a certain angle on the reflective surface [6]. It is computed as

$$R = \left[\frac{(n-1)}{(n+1)} \right]^2 * 100\% \quad (4)$$

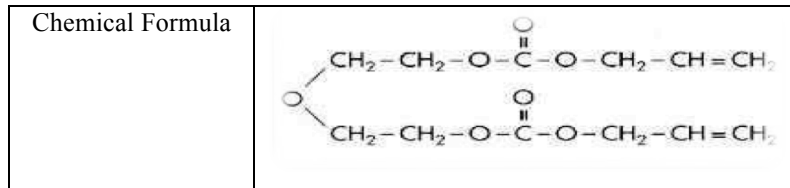
Other important physical properties considered in optical applications are density, severity, durability and rigidity [7-9].

The first contact lens materials were glass shells filled with jelly. In 1930, The first polymer contact lenses were produced in 1950. The first polymer contact lenses became widely used and available in the early 1960s. They were made from a polymer called poly(methylmethacrylate) (PMMA). These polymer lenses are hard, rigid and uncomfortable to wear. The first soft contact lenses were introduced in 1971. These contact lenses were made from a polymer called polyacrylamide, which is different from PMMA because it contains nitrogen atoms in its structure. Water constitutes 38%–79% of soft contact lenses. However, the high water content renders the lenses to be fragile and results in reduced clarity. In 1979, the first rigid gas-permeable lenses (RGPs) became available. These polymer lenses, which are made of a mixture of PMMA, silicone and fluoropolymer, are comfortable to the wearer compared with the previous contact lenses because the material used allows oxygen to pass directly through the lens to the eye. However, the major disadvantages of RGPs include high cost and inflexibility of the lens.

At the beginning of the Second World War, The CR-39 lens was born. CR stands for ‘Columbia Resins’. Subsequently, the researchers created the plastic polymer allyl carbonate monomer which seemingly has features, as shown in Table (1), making it a recommended material for ophthalmic lenses [10].

Table 1. Properties of CR-39 polymer material.

Material	Allyl Carbonate
Refractive index	1.49
Abbe Number	58–59
Density	1.32
Transmittance (%)	89–91
Reflectance (%)	4



2. Materials and Methods

In the 1940s, scientists in Columbia Corporation found allyl carbonate, which is in liquid form, but hardens by polymerization under the effect of heat and a catalyst. This polymer has the following optical characteristics: refractive index, 1.49; density, 1.32 and Abbe number, 58–59. This polymer can be coated and tinted. It presents high transparency and high impact resistance. All these features render CR-39 an optimal material for contact lenses [6].

The quantitative comparison in this study was performed using the Zemax software program and a Liou & Brennan human eye model. Unlike other models that were not considered, the Liou & Brennan model contains the features of a biological eye, such as surface curvature, reliability and gradient index. The retinal image was evaluated and analyzed using different criteria, namely, the tangential modulation transfer function (MTFT), sagittal modulation transfer function (MTFS), blur spot size (RMS), point spread function (PSF), encircled energy (EE) and the type of aberrations that affect and degrade the retinal image [11, 12].

2.1 Modulation Transfer Function (MTF)

The MTF indicates the sharpness and contrast of an imaging system and measures the quality of the retinal image [13, 14]:

$$OTF(v) = MTF(v)e^{-iPTF(v)}. \quad (5)$$

MTF(v) is responsible for the reduction in image modulation (or contrast) and is expressed as

$$MTF(v) = \sqrt{v^2(v) + w^2(v)}, \quad (6)$$

Where

$$w(v) = \frac{\int_{-\infty}^{\infty} h(x) \sin(2\pi vx) dx}{\int_{-\infty}^{\infty} h(x) dx} \quad \text{and} \quad v(v) = \frac{\int_{-\infty}^{\infty} h(x) \cos(2\pi vx) dx}{\int_{-\infty}^{\infty} h(x) dx} \quad (7)$$

$$PTF(v) = \tan^{-1} \left[\frac{w(v)}{v(v)} \right]. \quad (8)$$

Equation (8) defines the phase transfer function (PTF(v)), which is responsible for the lateral shifting.

2.2 Point Spread Function (PSF)

The second important criterion is the PSF. It is the fast Fourier transform (FFT) of the pupil function $f(x)$ [14]:

$$PSF = \int_{-\infty}^{\infty} f(x) e^{-i2\pi vx} dx. \quad (9)$$

The pupil function is $f(x) = \tau(x)e^{ikW}$, where $\tau(x)$ represents the pupil transparency and is equal to 1 if the pupil is uniform, $W(x,y)$ is the wave aberration polynomial in the system, k is the wavenumber ($k=2\pi/\lambda$) and λ is the light wavelength.

2.3 Root Mean Square (RMS)

The spot radius is another measure of retinal image quality, and it relies on the spot diagram. It is computed as the RMS of all the distances between each marginal ray intersection (x_i, y_i) with the image plane and a reference point (x_0, y_0) generated by the chief ray intersection [12]. The RMS spot radius is given by,

$$R_{rms} = \frac{\sum_{i=1}^n \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2}}{n} \quad (10)$$

Where n is the total number of rays considered, x_i, y_i and x_0, y_0 are the reference points and the ray intersection points respectively. Figure 1, shown a simple spot size diagram if the reference point (x_0, y_0) is taken as $(0,0)$.

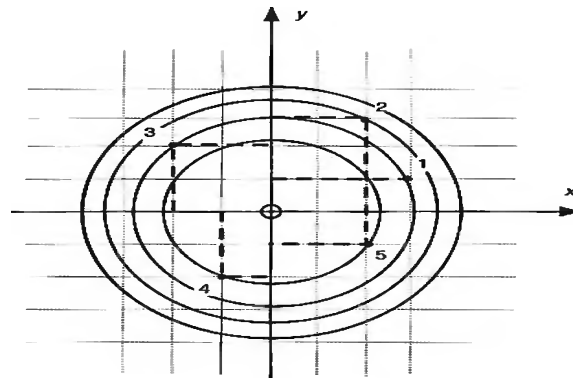


Figure 1. Spot diagram for RMS calculation [15].

2.4 Encircled Energy

The encircled energy is the percentage of total energy enclosed as a function of the distance from either the chief ray or the centroid of the image of a point object [15]:

$$EE(z) = 2\pi \int_{-a}^a PSF(r) r dr \quad (11)$$

Where a is the pupil diameter.

3. Results and Discussion

The quality of the retinal image is affected by the field of view (FOV). In this study, this effect was studied within the FOV range of 5° – 60° for different pupil diameters of 1.25, 2, 3 and 4 mm. MTFT, MTFS, RMS, PSF and EE were used as analysis criteria.

Figures 2–4 present the performance of the human eye for different pupil diameters. Figures 2-A, 2-B, 2-C, 2-D and 2-E present the MTFT, MTFS, wave aberration, PSF and EE for a pupil diameter of 1.25 mm, respectively.

The MTF curves reached the maximum MTF normalized value of 1 at 0 spatial frequency, then the MTF value was reduced as the frequency increased. Figure 2-A shows that the MTFT decreased as the FOV increased, that is, an inward aberration will affect the image. Figure 2-B shows that the MTFS decreased as the FOV increased, further verifying that an inward aberration will affect the image. These results can be explained by Figure 2-C, which shows that, when the FOV increased, the distortion aberration increased, thereby affecting the quality of the formed image. However, the MTFS degrade more than the MTFT, as shown in Figures 1-A and 1-B. Given that the PSF was asymmetrical (Figure 1-D); a difference existed in the lens performance in the sagittal and tangential planes between the MTFT and the MTFS. Figure 2-E shows that, with an increase in FOV, the

encircled energy on the retina decreased. With an increase in the entrance pupil diameter, the MTFT decreased further, as shown in Figure 2-A. Thus, an increase in the band size of the rays that pass through the pupil can increase spherical aberration.

Figure 3-B presents the MTFs. This figure indicates that the MTFs were different from the MTFT because the PSF was asymmetrical. Furthermore, MTFs decreased by increasing the FOV. Figure 3-C shows that aberration affected the formed image with an increase in the FOV. Figure 2-D presents the difference between the MTFT and the MTFs due to the asymmetrical PSF. MTF, which is the FFT of the PSF, was also asymmetrical. The MTFs decreased as the human pupil diameter decreased.

Figures 4 and 5 show other results that indicate the influences of F.O.V. and pupil diameter. The retinal image was more degraded as a more spherical aberration entered the pupil when the pupil diameter increased and a more distortion aberration introduced as the FOV increased.

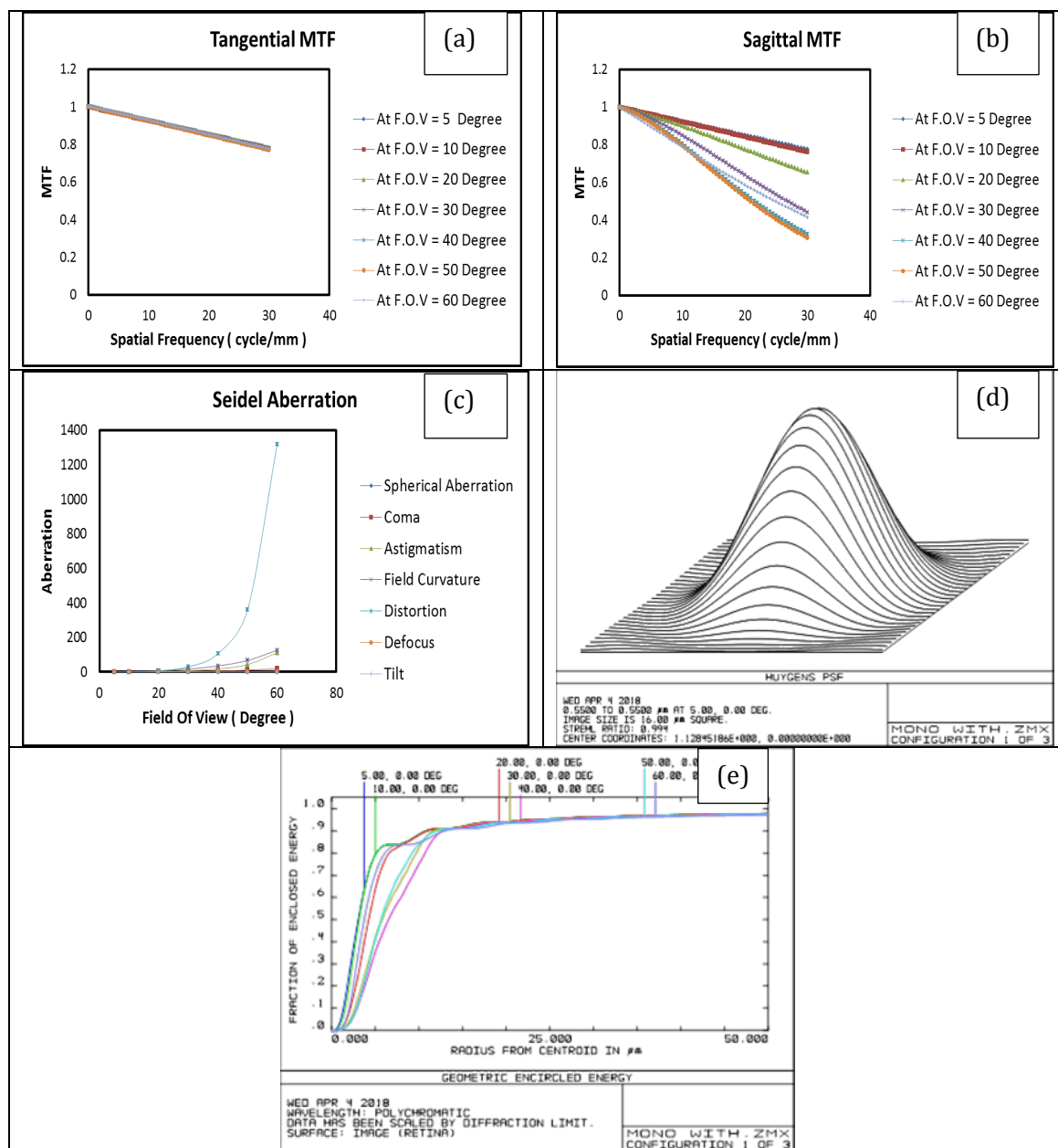


Figure 2. a) Tangential Modulation transfer function (MTFT), b) Sagittal Modulation Transfer Function (MTFS), c) Wave aberration with field of view, d) The Point Spread Function (PSF), e) Encircled Energy

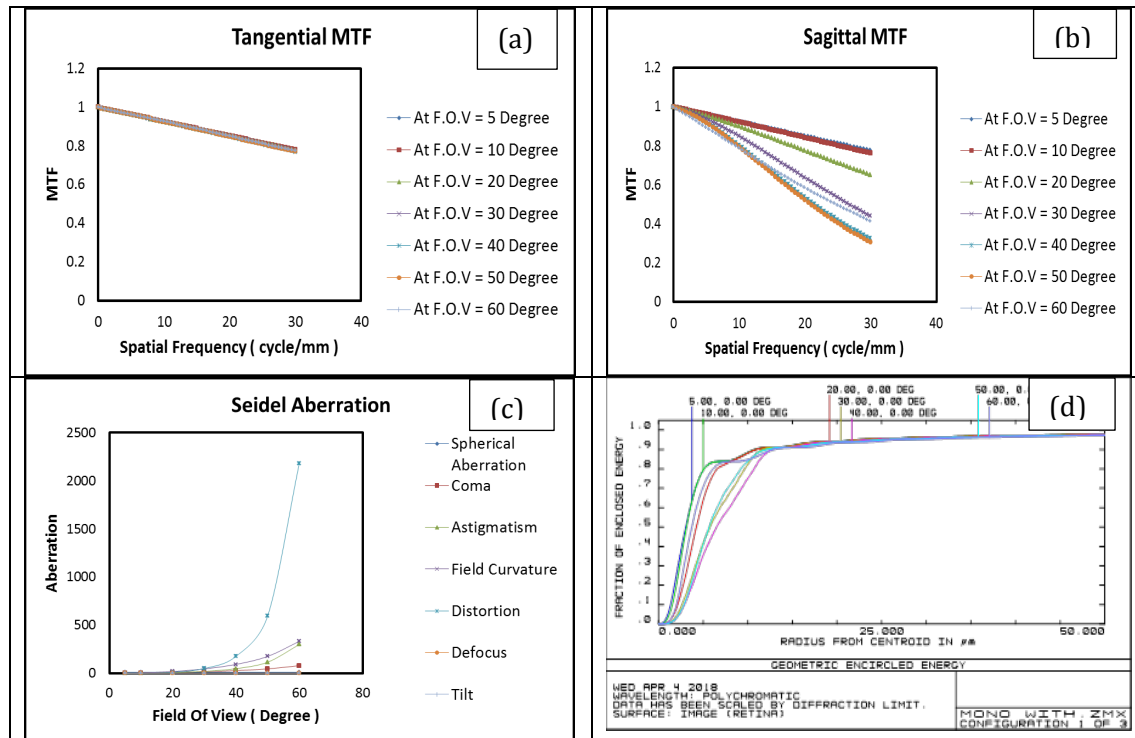


Figure 3. a) Tangential Modulation transfer function (MTFT), b) Sagittal Modulation Transfer Function (MTFS), c) Wave Aberration with field of view, d) Encircled Energy

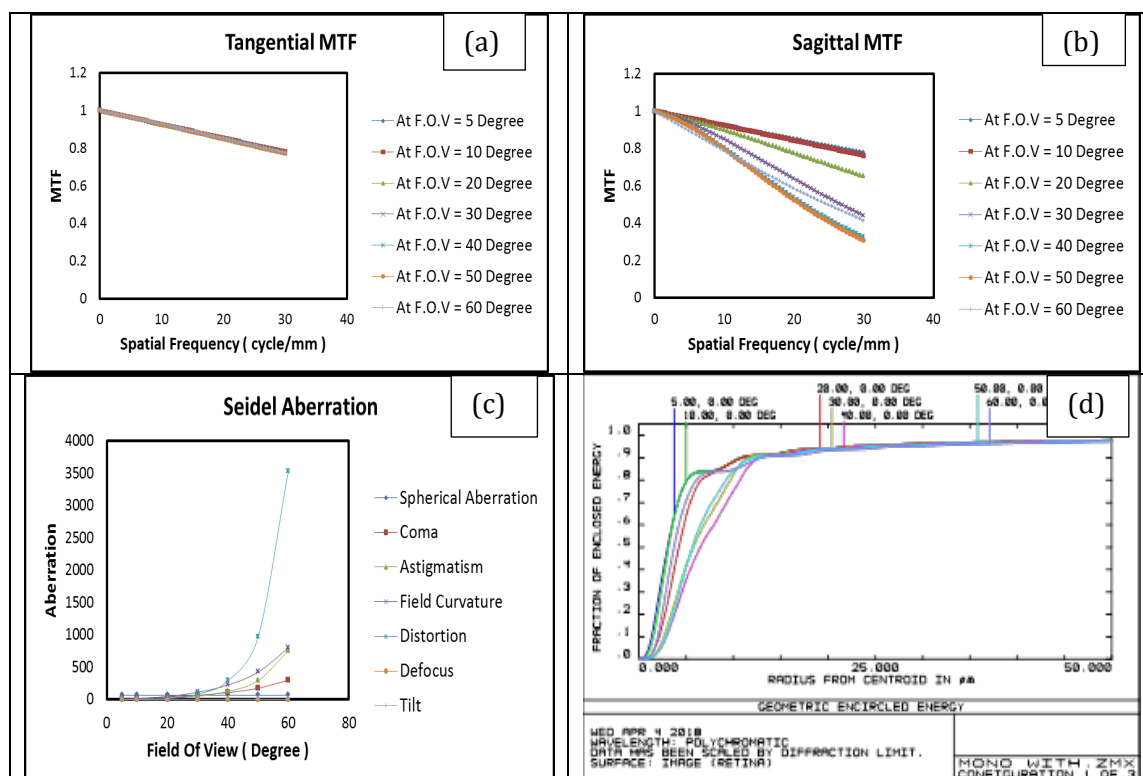


Figure 4. a) Tangential Modulation transfer function (MTFT), b) Sagittal Modulation Transfer Function (MTFS), c) Wave Aberration with field of view, d) Encircled Energy

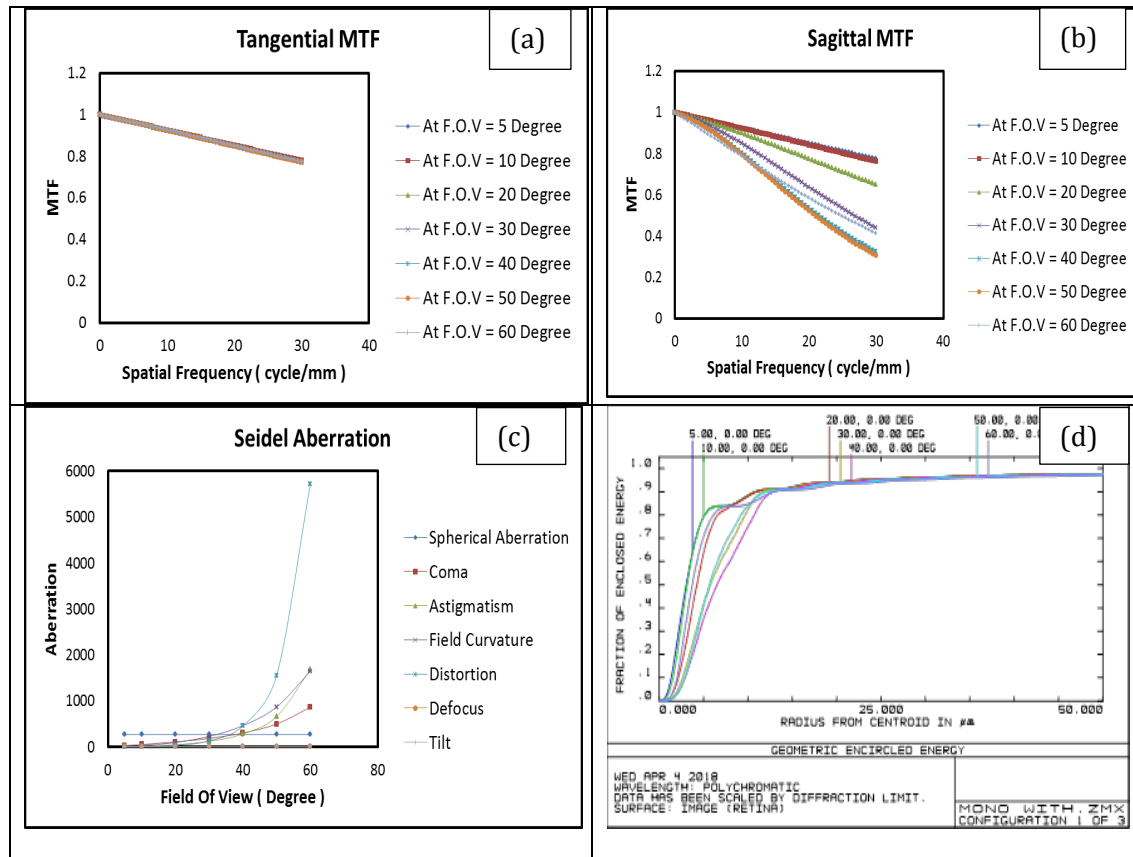


Figure 5. a) Tangential Modulation transfer function (MTFT), b) Sagittal Modulation Transfer Function (MTFS), c) Wave Aberration with field of view, d) Encircled Energy

4. Conclusion

The effects of the pupil diameter and the FOV on the quality of the retinal image were studied in detail. By using the Liou & Brennan model and Zemax-EE software to design a contact lens where the CR-39 polymer was tested as the polymer material used for manufacturing contact lenses. The results showed the influences of FOV and pupil diameter the retinal image was more degraded as a more spherical aberration entered the pupil when the pupil diameter increased and a more distortion aberration introduced as the FOV increased, But with this polymer that's used for eye lenses would give less distortion aberration, Therefore, we get a better image quality than Liou & Brennan does. The outcomes showed that the CR-39 polymer material has good optical properties, which render it a recommended material for ophthalmic contact lenses. CR-39 lenses are half the weight of glass lenses; thus, the former are more comfortable to wear. That provides a very good optical and eyesight correction. To overcome soft surfaces of these lenses, scratch-resistant coatings should be applied.

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