Human Eye Response to the Iris Diameter Variation at polychromatic light Programmatically

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Abstract. Performance of the human eye is affected by generated aberrations along the optical path of the eye. So that, different the human eye models were designed and studied to understand the philosophy of this issue to treat it. The aim of this work is to study the impact of the iris diameter on the response of the human eye programmatically when white light is applied. The models of perfect and abberated eyes were designed by ZEMAX, PC software (version 15), and the iris diameter was changed from 2-10 mm gradually by 2 under the influence of white light. The modulation transfer function (MTF), wavefront aberration and root mean square of the spot sizes (RMS) were used to analysis the eye response to diameter variation and applied light. The results showed that the ideal image quality obtained at 2 mm iris diameter and started to get worse as the diameter was getting large. The lowest values of aberrations can be achieved by smaller iris diameters. Different types of aberration are generated whenever the iris diameter becomes larger, especially when the white light is applied due to generation of chromatic aberration, which in turn causes the dispersion of light to focus on a small spot on the retina.

1. Introduction
Optical devices where the eye is part of the system considered to be complicated. Schematic eye models have been developed to treat this problem. These models simulate real eyes under certain conditions as much as possible to evaluate the retinal image performance. Traditional schematic eye models are generic used to understand the vision and optics of human eye in order to design common visual optics. All models have ideal rotationally symmetrical, centered, and aligned surfaces. Real eyes show degrees of irregularities with no well-defined optical or symmetry axes. Each individual eye has a wide Field of View (F.O.V.) about 65, 75, 60 and 95 degree in superior, inferior, nasal and temporal semimeridians, respectively (see Figure 1) [1]. The two monocular fields overlap to form the binocular field, which in turn has a lateral extent 120 degree. Optical quality of retinal image, while somewhat degraded in peripheral field, in general, adequate to meet the neural network needs. Since the neural retina spatial resolution falls away from the visual axis. Typically, the visual axis orientation differs from the optical axis orientation by a few degrees, as the fovea (optimal neural resolution), is slightly displaced from the intersection point of the retina with optical axis [2]
1.1. Models of Human Eye

Study of optical properties, manifestation and visual acuity of human eye come from the 19\textsuperscript{th} century. Hermann Von Helmholtz (1821-1894) is known for many major contributions to science and medicine, especially in physiological optics. Allvar Gullstrand proposed a simplification of Helmholtz’s eye model [3] this model is meant to adequately describe the optics of the human eye only for paraxial rays. Emsley is a simpler model with only one refracting surface to describe the behavior of the eye [4]. Also, Le Grand [5] proposed a simplification of Gullstrand’s original eye model. Referred to as the Gullstrand-Le Grand theoretical eye, this eye model is perhaps the most widely used eye model that uses all spherical optical surfaces.

From the Gullstrand-Le Grand eye, Lotmar constructed an eye model [6] that used the sphericity in the anterior surface of the cornea and the posterior surface of the lens to account for the spherical aberrations as measured in clinical studies. Then Kooijman [7] used aspheric optics for all four refracting surfaces based on the light distribution on the retina. Similarly, Navarro [8] used aspheric optics, for all four refracting surfaces and added dispersion to account for the chromatic aberrations. In 1995 Greivenkamp and colleagues suggested an eye model of four non-spherical refracting surfaces which considered retinal contrast sensitivity and refraction-limited properties [9]. Liou and Brennan (1997) have proposed an eye model which is the closest to anatomical, biometric and optical data as compared to the physiological eye [10].

The best one is Liou & Brennan’s eye model (LBEM) is optically and physically more similar to the biological eye because it uses aspherical surfaces, together with two gradient media to describe spherical aberration and astigmatism very precisely. The aim of this work is testing the human eye vision based on Liou & Brennan model by using ZEMAX Software and then evaluate the image quality by Modulation Transfer Function (MTF), the Root mean Squaer (RMS) of spot diagram and wavefront aberration coefficients.

1.2. Optical Aberrations

Imperfections in human eye optical components may cause deviation of light from its path. Such deviations are called optical aberrations, causes blurred image and reduces the eye performance. Optical aberrations comes into two kind; monochromatic aberrations (Spherical, coma, astigmatism, image curvature and distortion) and chromatic aberrations. Aberration caused by tear film is more severe in the pathological dry eye compared to normal eyes [11]. Monochromatic aberrations tend to change with accommodation as in spherical aberration [12]. Ocular aberration generated also due to changes in crystalline lens [13], and corneal aberrations [14]. Correction of chromatic aberration [15], in addition to the monochromatic aberration can provide substantial visual benefit [16]. The Seidel polynomial use the polar coordinate system and described mathematically as follows:

\[ W = \sum_{i,j,k} W_{ijk} \frac{H}{H'} \rho \cos \phi \]  

(1)

\( W_{ijk} \) is the wavefront aberration coefficient whose value can be positive or negative (in units of wavelength). The subscripts \( i, j \) and \( k \) refer to the powers on the other factors that indicate the aberration kind. The factor \( H \) is the fractional image height. Its value ranges between 0 and 1. The
fractional pupil radius $\rho$ also ranges between 0 and 1. Another pupil coordinate denoted by $\phi$ in the cosine term (has values between -1 and 1). Ocular aberrations generated inside the eye can be reduced by aspherical optical surface and gradient refractive index lenses, where the index of refraction reducing from the center toward outer layer of the lens. Further, off-axis aberrations can be eliminated by centering the optical and detector surfaces with a common curvature center at the stop aperture [17].

2. Method and Analytical Work
LBEM was chosen for the purpose of evaluating the impact because it obtained experimentally from the human eye [10]. Input parameters of this model are entered into ZEMAX software ZEMAX 13 Release 2 SP4 (serial number 34900) as illustrated in Table (1). The anterior and posterior corneal surfaces were selected as aspherical surfaces. The pupil diameter (E.P.D.) was decentered nasally by 0.5 mm [18], and set at 4 mm [19].

Table 1. Input parameters of human eye modeling based on Liou and Brennan eye model. All measured in (mm); C is the radius of curvature of each surface.

| Surface              | Surface Type       | C       | Thickness | RI, $\nu$ | E.P.D. | Conic |
|----------------------|--------------------|---------|-----------|-----------|--------|-------|
| Anterior cornea      | Standard Aspherical surface | 7.77    | 0.55      | 1.37, 50.23 | 10     | -0.18 |
| Aqueous              | Standard Aspherical surface | 6.40    | 3.16      | 1.33, 50.23 | 10     | -0.60 |
| Pupil                | Standard           | Infinity| 0         | 1.34, 50.23 | 4      | 0.00  |
| Lens-Front surface   | Gradient3          | 12.40   | 1.59      | -         | 10     | 0.00  |
| Lens-Back surface    | Gradient3          | 2.43    | -         | -         | 10     | 0.00  |
| Vitreous humor       | Standard           | -8.1    | 16.23     | 1.33, 50.23 | 10     | 0.96  |
| Retina               | Standard           | -12     | -         | -         | 10     | 0.00  |

The crystalline lens was performed by two homogeneous gradient index shells whose refractive index (n) is described by:

$$n = n_0 + n_{r_2}r^2 + n_{r_4}r^4 + n_{r_6}r^6 + n_{z_2}z^2 + n_{z_3}z^3$$  \hspace{1cm} (2)

$$r^2 = x^2 + y^2$$  \hspace{1cm} (3)

Both of the vitreous body of the eye and the retinal imaging surface were selected as standard surfaces. The standard surface position is centered on the optical axis and its vertex located at the Z-axis. The z-value (sag) of the standard surface is given by [20]:

$$z = \frac{c r^2}{1 + \sqrt{1 - (1 + k c^2 r^2)}}$$  \hspace{1cm} (4)

Where c is the curvature (reciprocal of the radius), r is the radial coordinate in the lens unit and K refers to conic constant.

This work has been studied effect of eye exposure to a monochromatic light source at 555 nm and another polychromatic light source on retinal image quality. All ray tracing simulations were analyzed by MTF, RMS and aberration coefficients.

3. Results and Discussion

3.1. MTF
MTF is the ratio of image contrast to object contrast. MTF considers the degradation of contrast (modulation) as a function of spatial frequency. Spatial frequency measures the capabilities of the examined visual system. The contrast of a sinusoidal pattern is defined as:

$$MTF = \frac{I_{\text{Max}} - I_{\text{Min}}}{I_{\text{Max}} + I_{\text{Min}}}$$  \hspace{1cm} (5)

where $I_{\text{max}}$ is the irradiance of the peak of the sinusoid and $I_{\text{min}}$ is the irradiance of the trough of the sinusoid.
The retinal image sharpness (spatial frequency) measured by cycles/mm and contrast (MTF) is characterized by MTF criteria. For an optimal retinal image quality, the lens should perform over 50% (0.5) contrast at 20 cycles/mm. Maximum spatial frequency was set in this investigation at 12 cycles/mm as the optimum contrast area. 5-degree off-axis polychromatic MTF simulations have obtained for all tested models exemplified in Figure (2). The white light significantly degraded the visual quality of all cases. This degradation attributes to the presence of monochromatic aberrations in the eye [21]; spherical, coma, astigmatism and distortion. While the chromatic aberration resulted from the separation of white light into its wavelength components and focusing them in different focal points [15].

\[ R_{\text{RMS}} = \frac{\sum_{i=1}^{n} (x_i - x_0)^2 + (y_i - y_0)^2}{n} \]  

Where \( n \) represents the total number of rays considered.

For more explanation, RMS variations were studied to show the retinal image performance under variation of pupil size and for the affixed field of view of polychromatic light. Spot diagram is a way of visualizing the aberration effect have on image quality and hence lens resolution. RMS belongs to root mean square of the spot in the image plane. It is calculated as the RMS of all distances between each peripheral intersection \((x_i, y_i)\) with the image plane and a reference point \((x_0, y_0)\), generated by intersection of the chief ray. RMS is computed from Equation (6) and obtained by ZEMAX [20]:

**Figure 2.** Image Contrast at different iris sizes.

3.2. RMS

For more explanation, RMS variations were studied to show the retinal image performance under variation of pupil size and for the affixed field of view of polychromatic light. Spot diagram is a way of visualizing the aberration effect have on image quality and hence lens resolution. RMS belongs to root mean square of the spot in the image plane. It is calculated as the RMS of all distances between each peripheral intersection \((x_i, y_i)\) with the image plane and a reference point \((x_0, y_0)\), generated by intersection of the chief ray. RMS is computed from Equation (6) and obtained by ZEMAX [20]:

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Where \( n \) represents the total number of rays considered.

The RMS plot in \((\mu m)\) as a function of the pupil size (2, 4, 6, 8 and 10 mm) at field of view values (5 degrees). The results at different scale bars showed that the RMS values getting increase as the pupil size increase at specific F.O.V. as shown in Figures (3) and (4). Chromatic aberration in addition to spherical, coma and astigmatism were generated due to the polychromatic light effect. Different spot shapes were yielded when comparing between the effects of iris diameters at white light. The eye response at 2 mm iris diameter, produced small spot size and high accumulated energy and this response is getting degrades as the iris diameter increases from 4-10 mm because the divergence of polychromatic light beam enlarges the spot size.
Figure 3. Different shapes of spot diagram on the retina at the iris diameters: a. 2 mm, b. 4 mm, c. 6 mm, d. 8 mm and e. 10 mm.

Figure 4. RMS variation with pupil diameter change.
3.3. Wavefront Aberration Coefficients

The most effective aberration kind on MTF degradation and then affect the image quality obtained from the human intraocular lens can be known from the aberration coefficient curves as shown in Figure (5). MTF was decreased when the diameter is increased, this is because of spherical aberration and chromatic aberration (W040 and W020, respectively) generated inside the eye, these two aberrations are the most effective aberrations that affect the response of each model. W020 increased when the pupil Semi-Diameter enlarged > 4 mm, which in turn prevented the light rays from being focused on the same spot on the retina. The other kinds of aberrations in these cases are ineffective because the rays are on axis and the F.O.V. is fixed. This defect can be corrected by contact lenses made of high refractive index and low dispersion [22-24]. Such lenses focused the incoming light rays into a small spot and hence obtaining high image contrast.

![Figure 5](image_url)

**Figure 5.** Polychromatic wavefront aberration coefficient at 5 degrees. Where W040: spherical aberration, W131: coma, W222: astigmatism, W220: field curvature, W311: distortion, W020: lateral chromatic aberration and W111: chromatic transverse aberration.

4. Conclusion

This work showed that the retinal response of the constructed eye models at 2, 4, 6, 8 and 10 mm iris diameter. The best values response was obtained when the iris size (diameter) is small (2 and 4 mm) and F.O.V. at (5 degree) for polychromatic light. MTF was decreased when the diameter increased, this is because the amount of different aberrations generated inside the eye, and this affects the image quality.

Also, one can conclude that the spherical aberration and chromatic aberration are responding about the degradation in the eye vision when E.P.D. increases. From all the results which consist of MTF, wavefront aberration coefficients, spot diagram and RMS indication, one can say that the minimum E.P.D. < 4 represent the case of near diffraction limited eye (perfect eye system) at F.O.V. ≤ 5 degree.

The most effective aberration is the chromatic aberration (dispersion) which refers to the fact that the secondary focal length of a lens will be different for each of the monochromatic constituents of white light.

5. References

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