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# Effect of Optical Eccentricity of Human Eye on Vision Quality

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## Abstract

The purpose of this paper is to give detailed explanations to the eccentricity related errors of human eye. An optical metrology is studied to determine the errors present in the eccentric eye with respect to emmtropic eye. To study optical metrology, the forms of errors that might be present need to be analyzed in the eye design. The possible eccentric errors were considered and produced on the adopted eye optical design. The most interesting optical functions were estimated and evaluated, the results showed a significant effect impacts the optical functions due to the eccentricity. The degradation of vision quality was interpreted according to the behavioral comparison between the estimated functions of the eccentric eye with respect to emmtropic eye. This study offers the chance for the researchers in the eye related topics to dissolve the vagueness concerning with the complexity of human eye design, and introduce a qualitative and quantitative analyses to consider the subject of human eye design and activities.

Keywords: human eye, eccentricity, optical errors, aberrations.

## Introduction

The understanding of the optical system of the eye is evolving quite rapidly due to the combined effort of new experimental methodologies and advanced modeling. Optical design plays a central role since this branch of science and technology deals with finding the best combinations of optical elements (lenses, etc.) to obtain a desired function with optimal performance. Optical testing is also necessary for the verification and validation of designs. The study of the optical system of the eye has similarities, but also remarkable differences with optical design and testing [1]. The optical design of the eye is already given by nature (optimization through evolution), so its study can be seen as an inverse engineering problem employed to unravel such design. Inverse problems are difficult in general and must be solved by successive approaches. Each approach consists of: (1) some starting hypothesis based on previous knowledge; (2) a set of experimental data; and (3) a model relating those data and the hypothesis. The testing stage (4) compares model predictions to experimentally assessed optical performance. Population studies have therefore been performed to investigate the image quality in normal eyes both foveally (on-axis) and peripherally (off-axis, in oblique viewing angles, peripheral retinal location *PRL*) as shown in Fig.(1) [2].

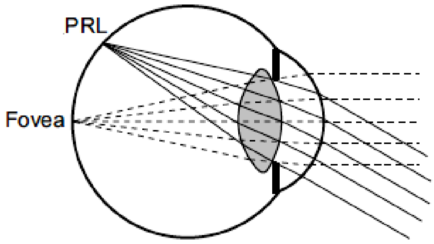


***Fig.(1) Foveal and peripheral vision[2].***

The formation of an image on the retina is often far from perfect. One reason is that the human eye has significant optical defects (i.e., aberrations) that distort the passing optical wavefront. This distortion blurs the retinal image, thereby degrading the visual experience. Also, diffraction is caused by the finite size of the eye’s pupil, is the other reason for blurriness. Together, aberrations and diffraction limit not only what the eye sees looking out, but also determine the appearance of fine details in the image. Fig.(2) shows the distortion due to non uniformity of wavefront that causes a defocusing and leads to embed the fine details in the image.

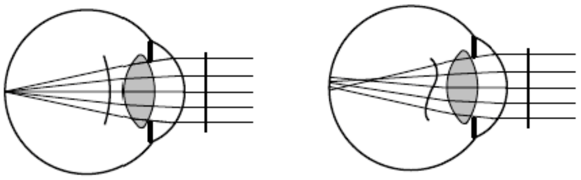


*Fig.(2) Uniformity of wavefront affects the image quality[3].*

In addition, the most common imperfection may strongly impact the vision quality is the refraction error, i.e. the best image is not focused on the retina. Foveal vision uses the best part of both the optics and the retina, and thus provides the highest resolution. In the periphery, vision is of lower quality, it becomes important to people who have lost their foveal vision due to eccentricity with respect to the optical axis, i.e., have a central visual field loss (CFL) shown in Fig.(3), such vision depends only on the remaining peripheral vision [3].

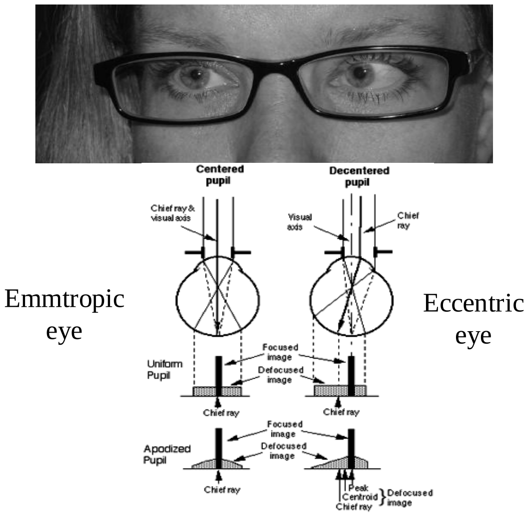


*Fig.(3) Ray traces in eccentric eye are different from emmtropic one[3].*

The CFL is one type of eccentric errors that can be caused by a variety of pathologies [4]. Practically, CFL is an increasing problem in the aging population and magnifying devices are currently the only help for affected persons to use their remaining visual function [5].

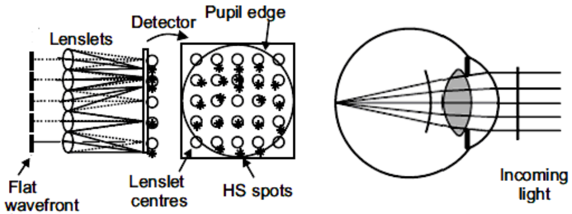
In general, vision in eccentric viewing angles is limited both by the resolution capacity of the peripheral retina and by the large aberrations in the peripheral optics of the eye [6]. Measuring the peripheral optics and refractive errors with traditional methods in subjects connected with CFL is often difficult due to the large aberrations, reduced retinal function and poor fixation [6]. The aim of this study is to emulate the optical situation of the eccentric eye due to refractive errors, and describe all visual functions may be found important in CFL subject.

## Problem Description and Contribution

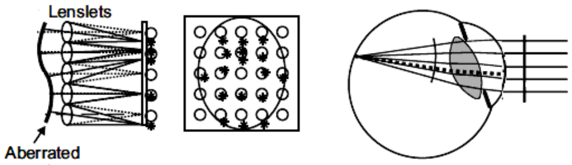
Eccentricity (or CFL) in the eye is a problem of predictable effects on the vision system. The effect of CFL in the eye extent to impact the vision health besides vision quality. Most papers focus on the description of anatomical and optical properties of the human eye, and explain which are or are not included in the system, and how they are simulated. While some attention must be paid to all of the portions of the optical pipeline, we go into implementation detail only for the two major new contributions of this work: (i) the way of wavefront distributed in the eye that loss the central field of vision, and then (ii) determining the factors in the optical system that influence vision quality in such case. However, imaging model was based on the assumption that the returned light always tends to a Gaussian form. We show that this is not always the case.

## Eccentric Eye Description

In an optically perfect emmtropic eye, all rays from a distant target converge to a single point on the retina. Conversely, in such an eye, the wavefront exiting the eye created by a point on the retina would be a plane wave as Fig.(4a) shows. Most objective aberrometers examine the exiting wavefront and describe optical quality in terms of the shape of this wavefront relative to a plane wave (eg, wavefront error). An aberrated eye produces an undulating exiting wavefront Fig.(4b) and the magnitude of the aberrations is usually quantified by the root mean squared deviation from plane wave (RMS). Although this standard metric describes the wavefront typically provided by clinical aberrometers, RMS wavefront error is unfortunately a poor predictor of the subjective impact of aberrations on vision, so that an additional optical measures are employed to describe the behavior of the wavefront through the pipeline [7], such measures are mentioned in the next section. The preceding discussion of the eye's optical quality stops at the retina, but this is just the first step of the visual process. The retinal image is then converted to neural signals by the mosaic of photoreceptors and these signals pass through many stages of neural processing before visual perception occurs [8].



(a) Emmtropic Eye



(b) Eccentric Eye

*Fig.(4) Eccentric error impacts the wavefront[7].*

## Proposed Image Quantification

Since our ultimate goal is to quantify visual quality (not just optical quality) it makes sense to devise metrics that reflect visual performance.

Generally, two approaches are used to quantify the optical and visual qualities of the eye; the first describes the optical properties of the eye components, and the second describes the effect of those properties on the retinal image, which determines the visual quality. Optical properties are typically quantified by an aberration map or wavefront error map in the pupil plane. Alternative metrics based on measuring refraction errors, such as the standard deviation of wavefront slopes or wavefront curvatures shown in Fig.(5). The usual method for computing root mean square (RMS) of wavefront error treats equally all parts of the aberration map [3].

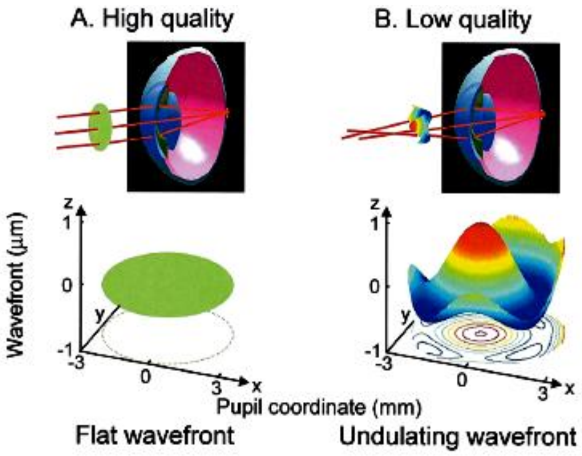


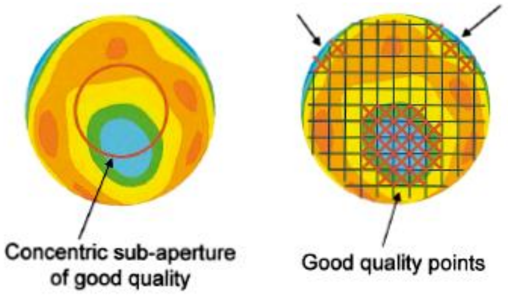
*Fig.(5) Image quality versus wavefront[3].*

The second approach describes optical quality in the image plane for fundamental objects such as a point source or a sinusoidal grating. An alternative approach to quantification of vision quality is to evaluate resolution based measures for which the aberration map is reasonably good quality. Point spread function (PSF) and optical transfer function (OTF) are used to evaluate the imaging quality in the eye. Sharp PSF indicates that most of the light entering the eye forms a high visual quality. The OTF of a visual system is most sensitive to the variety of the ray's intensity constituting the retinal image; this metric of visual quality should give greater image contrast to the rays of greater intensity range [9].

In both approaches, the resulting description is complex and multi-dimensional, due to the combined effect of different types of errors. The goal of quality metrics is to reduce these complex data to a single number. A clinically useful metric is one that is highly correlated with visual performance or the subjective judgment of the quality of vision. The employed quality metrics are explained in the following:

## Pupil Fraction Metrics

One such metric is pupil fraction, which is a better predictor of visual acuity than is RMS wavefront error [3]. Fig.(6) illustrates two ways to compute the pupil fraction. The “critical pupil” method Fig.(6a) quantifies wavefront quality inside a sub-aperture that is concentric with the pupil; it starts with a small sub-aperture, where image quality is diffraction-limited, and then expands this aperture until some criterion level of wavefront quality is reached. The endpoint is the “critical diameter” for the specified criterion and the ratio of the area of this critical pupil to the area of the full pupil is the pupil fraction. This metric is biased in favor of the central region of the pupil, which is a reasonable approach because the central pupil makes a larger contribution to vision due to the Stiles-Crawford effect. The second method, “full pupil” Fig.(6b), gives equal weight to the entire pupil. The wavefront error map is subdivided with a grid and one can count the number of grid points that satisfy some criterion of optical quality. The ratio of number of good quality grid points to total number of grid points is the pupil fraction. Both of these methods for computing pupil fraction rely on some criterion for relatively good optical quality [10].



(a) Critical pupil method

(b) Full pupil method

*Fig.(6) Pupil fraction computation[10].*

**OTF Related Metrics**

Sinusoidal gratings may seem to be more complicated than simple points of light, but they have one very convenient feature that greatly simplifies the study of optical systems. Unlike point objects, which can produce an infinite variety of images depending on the nature of the eye's aberrations, sinusoidal grating objects always produce sinusoidal grating images no matter how aberrated the eye. Consequently, there are only two ways that an optical system can affect the image of a grating. First, it can reduce the contrast and, second, it can translate the image sideways, which is called a phase-shift. Both of these effects are illustrated in Fig.(7). In general, the amount of contrast attenuation and the amount of phase shift depend on the grating's spatial frequency and orientation as well as the eye's optical quality. The ability of an optical system to faithfully transfer contrast and phase from the object to the image is called the modulation transfer function (MTF) and phase transfer function (PTF), respectively. The eye's optical transfer function (OTF) comprises the MTF and PTF. Optical theory tells us that any object can be conceived as the sum of gratings of various spatial frequencies and orientations. From this context we think of the optics of the eye as a filter that lowers the contrasts (low MTF) and changes the relative position (phase shifts in PTF) of each spatial frequency in the object spectrum as it forms a degraded retinal image. A high-quality OTF is therefore indicated by high MTF values and low PTF values. Simple optical quality metrics based on the OTF are (1) the high frequency cutoff frequency, and (2) the volume under the MTF or OTF [11].

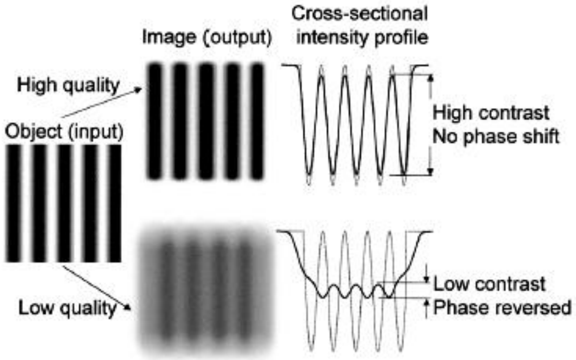
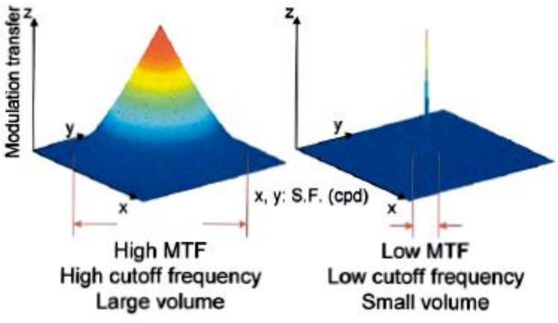


*Fig.(7) OTF based quality description [11].*

**PSF Related Metrics**

Optical imperfections will always spread out the image of a point object resulting in the point-spread function (PSF; described in Fig.(8)). A high-quality PSF is characterized by high contrast and compact form as shown in Fig.(8a) whereas a low-quality PSF is less compact and lower contrast because the light is blurred by imperfect optics as shown in Fig.(8b). Quantifying the PSF is important because all visual objects can be considered as an array of points. The retinal image of an extended object is, therefore, just the linear summation of all the PSFs of individual points in the image; hence the PSF can be used to quantify the optical quality of the eye for any image [3]. A popular metric of optical quality, the Strehl ratio, is a contrast metric defined as the maximum intensity ($I$) in the PSF divided by the maximum intensity for an optically perfect PSF (limited only by diffraction).



(a) High quality (b) Low quality

*Fig.(8) MTF versus optical quality [3].*

Another contrast metric is the light in the bucket or called encircle energy ($EE$), which defined as the percentage of energy that falls inside the core of a diffraction-limited PSF as Fig.(9) shows. A convenient metric of spatial compactness is the “equivalent width,” which is defined as the diameter of a uniform blur circle that has the same peak intensity and the same total amount of light as the PSF. “Half-width-at-half-height” is another popular compactness metric, as is the area of a circle centered on the peak of the PSF, which catches 50% of light [3].

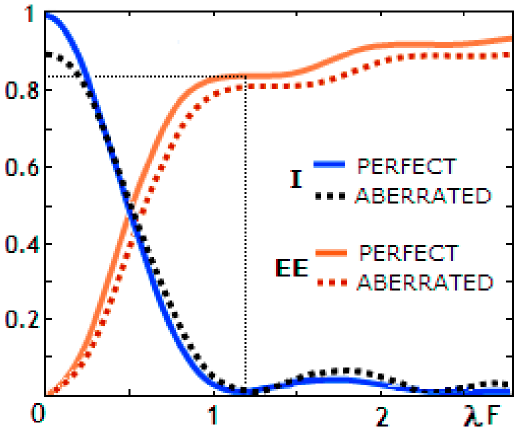


*Fig.(9) PSF and encircle energy [3].*

Incorporating the properties of the visual system into image plane metrics improves their ability to predict visual performance. One example of an image plane metric that includes neural contrast sensitivity is the visual Strehl-ratio, which weights the PSF by a visual receptive field before computing the Strehl ratio. Visual acuity is highly correlated with visual Strehl-ratio [12].

## Materials and Method

The used material is a commercially eye modeling system; Advanced Human Eye Model (AHEM) that developed by MIT optician team, and built in Zemax software [13]. This software is specialized in optical design. All methods for computing the optical design, display, parameters, and measurements are performed and measurements are performed and established by Zemax. The AHEM is composed of three main components, cornea, iris, and lens as shown in Fig.(10). Table (1) lists the numerical optical properties of such design; where $R_1$ and $R_2$ are the radius of curvature of the first and second surface of the optical elements, $n$ is the index of refraction, $d$ is the distance between optical elements, $D$ is the diameter, and $t$ is the thickness of the optical elements [2].

***Table (1)***
***Optical features of AHEM, measured by millimeter (mm).***

| *Opt.El* | *R1* | *R2* | *n* | *d* | *D* | *T* |
|---|---|---|---|---|---|---|
| **Cornea** | **6.489** | **7.657** | **1.37** | **3.42** | **8.2** | **0.56** |
| **Lens** | **7.682** | **-5.00** | **1.33** | **16.65** | **7.1** | **2.51** |
| **Retina** | **-11.7** | **-11.7** | **-** | **-** | **-** | |

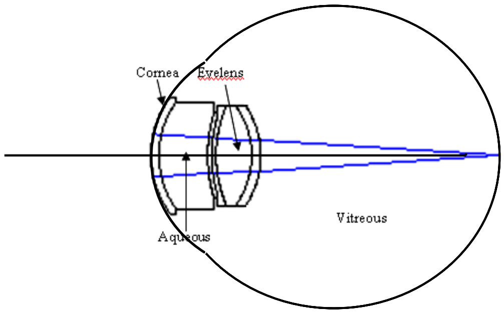


*Fig.(10) AHEM design by Zemax [2].*

The structures of these three components are complex, and their description could fill volumes. Discussion in this article is limited to their optical properties, which impacts image quality. The cornea is the transparent first surface of the eye. It is an extension of the sclera, which is the tough, white outer shell of the eye. The pupil serves two main optical functions. It limits the amount of light that reaches the retina, and it alters the numerical aperture of the eye's image system. The lens is positioned immediately behind the iris. The lens in the eye adds another 20–30 *diopters* to the optical system. It is held in place near its equator via zonules attached to the ciliary body. The tension on the zonules is relaxed by contraction of the ciliary muscle. This action increases lens curvatures making the eye focus, or ''accommodate'', on near objects. Tension on the zonules increases by relaxing the ciliary muscle, thereby flattening the lens and allowing the eye to focus on distant objects. The lens tends to harden as it ages, which diminishes its ability to change shape.

To create an eccentric eye contains a CFL using Zemax, the emmtropic eye design was modified to be eccentric, the optical path in eccentric eye is oblique by an angle ($\theta$). The modification contains the concept of rotating all the eye parts about its center by $\theta$ angle. The optical features in the eccentric eye were remaining same as emmtropic eye, Fig.(11) shows the eccentric eye created by Zemax.

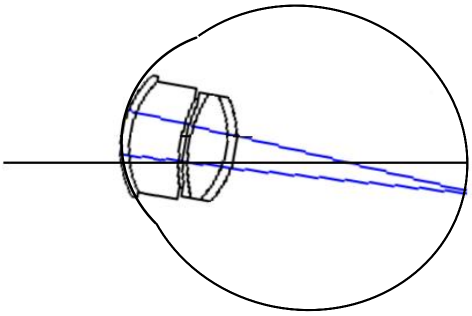


*Fig.(11) The eccentric AHEM design by Zemax [2].*

## Results and Discussion

The optical functions of interest were extracted using the established tools of Zemax. Fig.(12) shows the magnitude of refraction errors expressed as the root mean square (RMS) in microns at each component of emmtropic and eccentric eyes for eccentricity angles ($\theta$=0,5,10,15,20 *degrees*). Zero angle express the situation of emmtropic eye, and angles between 5-20 *degrees* represent eccentric eyes, whereas angles greater than 20 *degrees* are excluded since there is no vision may be provided by such eye.

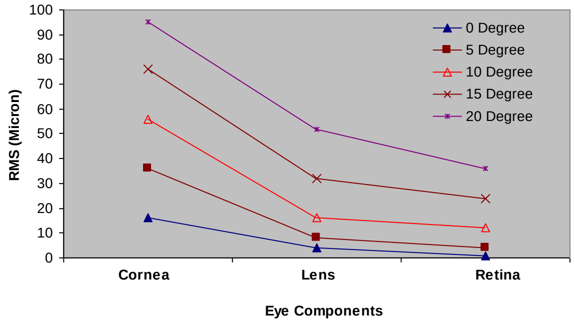


*Fig.(12) RMS at each optical component in both emmetropic and eccentric eyes.*

The average amount of RMS values in the considered cases was found to be quite differet. However, the RMS of the cornea and lens were larger with increasing the angle of refraction, and in all cases larger than the emmtropic eye. We calculated a parameter (compensation factor) to describe the fraction of the corneal refraction error that was compensated by the lens for a particular eye. This parameter was given by ($RMS_{cornea}$-$RMS_{eye}$)/$RMS_{cornea}$ [9]. Positives values indicate compensation; small values around zero, a lack of compensation; and eventually negative values would note an addition of aberrations by the lens. Fig.(13) presents this compensation factor averaged for the five cases of eccentricity angle (i.e. $\theta$=0,5, 10, 15, and 20) that gives different range of refractive errors, from emmtropic to high eccentricity. The increase of $\theta$ showed an increase in the amount of refraction errors in the eccentric eye exceeded the amount of compensation.

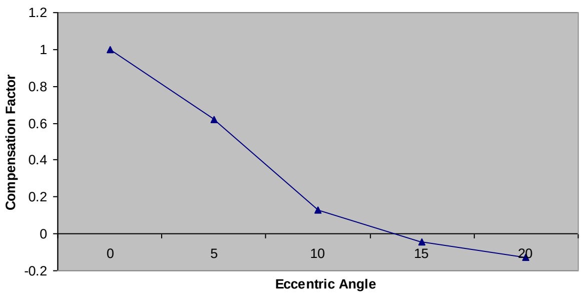


*Fig.(13) The compensation factor versus eccentricity angles.*

We further explored the behavior of specific aberration terms in each eye. The average value of spherical aberration shown in Fig.(14) is small value in emmtropic eye: it is positive for the cornea, negative for the lens and slightly positive for retina (complete eye). In emmtropic eye, regardless of refractive error, spherical aberration was well compensated, whereas it was a greater in eccentric eye.

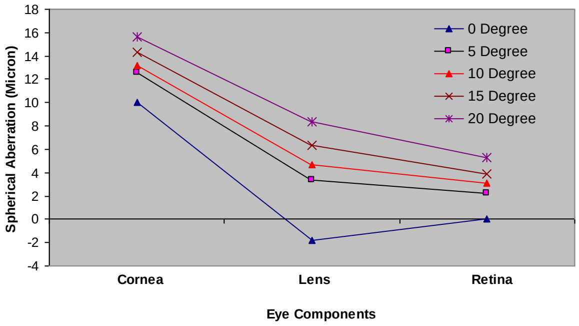


*Fig.(14) Spherical aberration of emmtropic and eccentric eyes.*

Fig.(15) shows the behavior of lateral coma. However, in emmetropic eye the coma is zero at all components of the eye, while it is linearly decreasing at both the lens and retina in eccentric eye. This indicates more significant compensation of coma in emmtropic eye and less in eccentric one. In particular, lateral coma presents the most remarkable compensation.

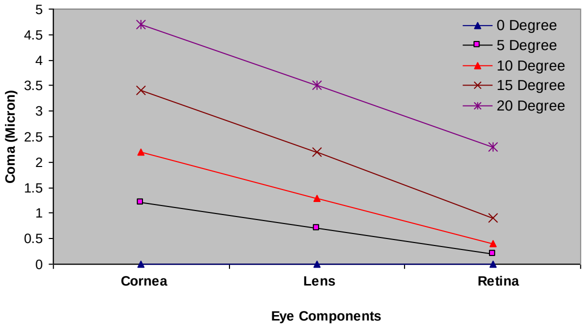


*Fig.(15) Coma aberration of emmetropic and eccentric eyes.*

Fig.(16) shows, for the two studied eyes, the amount of astigmatism for the cornea, lens, and retina with the variation of optical axis decentration. The eccentric eye with small values of pupil decentration present smaller values of coma see Fig.(15) and astigmatism see Fig.(16) in the cornea, lens, and retina. However, eyes with larger optical axis decentration have a higher coma and astigmatism in the cornea. The aberration exceeded the level of compensation in eccentric eye, but it remains under the compensation level in the emmtropic eye. This is the reason that the coma and astigmatism in the emmtropic eye remains within a normal range.

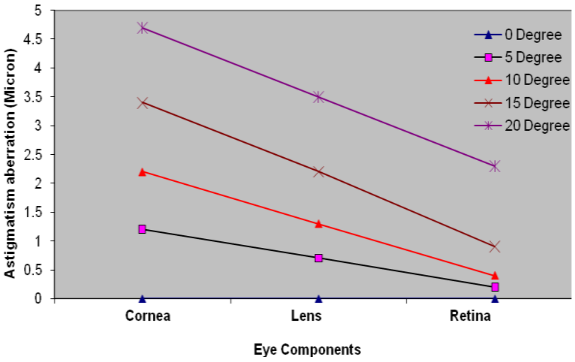


*Fig.(16) Astigmatism aberration of emmetropic and eccentric eyes.*

Fig.(17) and (18) shows that the dominating optical aberrations in the peripheral eye for different eccentricity angles are the field curvature and distortion. The field of curvature results due to the effective CFL refractive error, whereas the distortion results due to the combined effect of defocusing for all types of aberrations. Such that, the most prominent difference compared with central refraction is an induced distortion in the periphery rays.

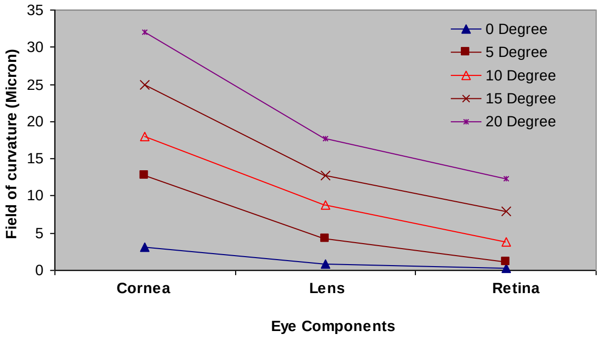


*Fig.(17) Field of curvature aberration of emmetropic and eccentric eyes.*

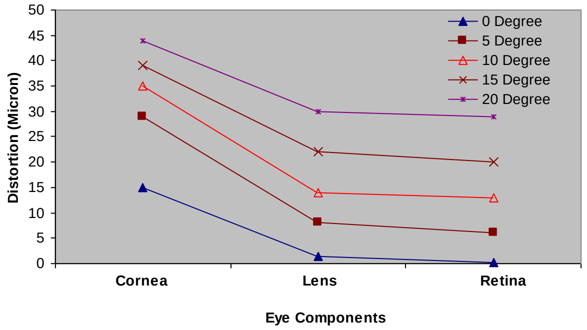
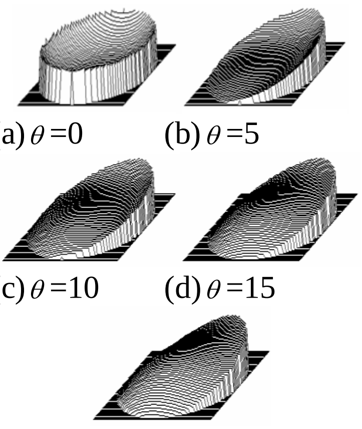


*Fig.(18) Distortion aberration of emmetropic and eccentric eyes.*

Also, the eccentric eye with pupil decentration showed skewed wavefront distribution as shown in Fig.(19).


(a) $\theta$=0 (b) $\theta$=5

(c) $\theta$=10 (d) $\theta$=15

(e) $\theta$=20

*Fig.(19) Wavefront distribution of emmetropic and eccentric eyes.*

The wvefront skewness is increasing with a larger angle of pupil decentration. On the contrary, smaller height (less light intensity) of the wavefront is commonly found in greater $\theta$ that corresponding to the eccentric eye. These eyes have higher values of coma in both ocular components and a smaller overall compensation. In most subjects, both corneal and internal pupil fraction is similar in area but shifted in center. Large values of pupil fraction, caused by oblique incidence, occur in the eye with larger viewing angle. The same condition, oblique incidence, generates a circular corneal section, Fig.(20) shows schematically this situation in the eye.

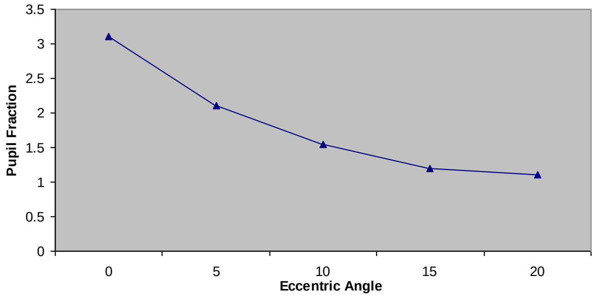


*Fig.(20) Pupil fraction versus eccentricity angles.*

On the other hand, Fig.(21) represents the PSF and spot diagram for both the emmtropic and eccentric eyes for different eccentricity angle using Zemax software. These results should be compared with the standard (perfect) measurements of PSF and spot diagram of zero eccentricity angle. It is shown that the shapes of PSF and spot diagram varied greatly. The difference between them can be understood as the contribution to the refraction error to the intrinsic eccentricity, this interpret why the eccentric eye is degraded as a result of optical axis decenterization. It is interesting to note that the height of the PSF decreases and the number of secondary peaks increased with increasing eccentricity angle. The interference of non-uniform secondary peaks make the distribution of the spot diagram to be bubbled.

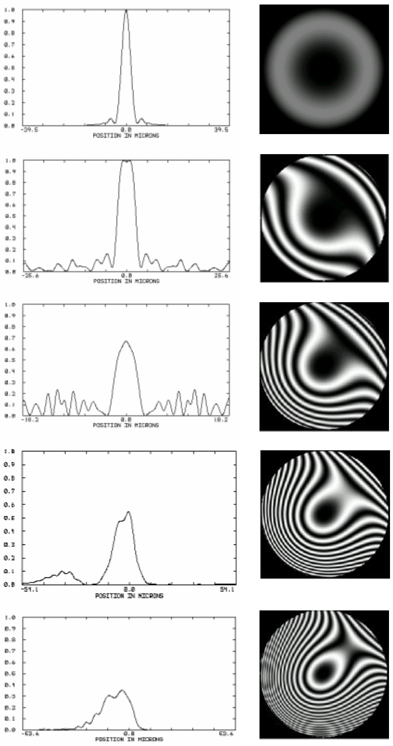


*Fig.(21) PSF of emmtropic and eccentric eyes.*

Figs. (22) and (23) shows the Strehl ratio and encircled energy of an emmtropic and eccentric eyes. The relative decentering of the pupil is affecting the amount of energy found in the retinal image. So that there are some loss induced in the retinal image and approximately cancel the fine structure of the image. It is important to note that this is a simplified studied case.

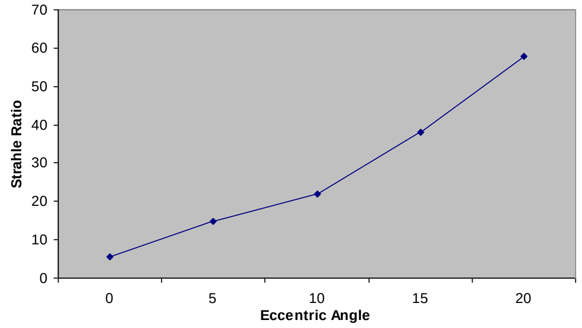


*Fig.(22) Strehl ratio versus eccentricity angles.*

The actual situation is more complicated: Both the emmtropic and eccentric eyes have some amounts of aberration besides the refraction errors. In addition, the lens itself is tilted and decentered inducing other higher order aberration beyond those described herein.

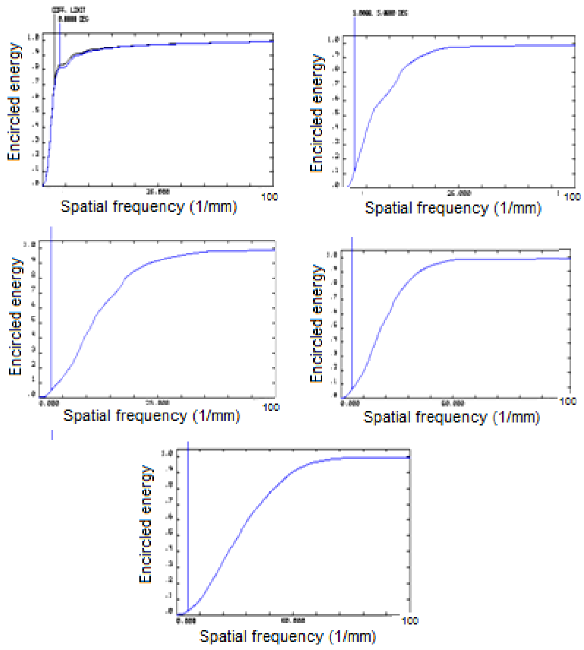


*Fig.(23) Encircled energy of emmtropic and eccentric eyes.*

Fig.(24) shows the MTF results in the two considered eyes. Moreover, MTF was perfect for emmtropic eye, whereas it was in general different for eccentric eye especially at the high frequencies.

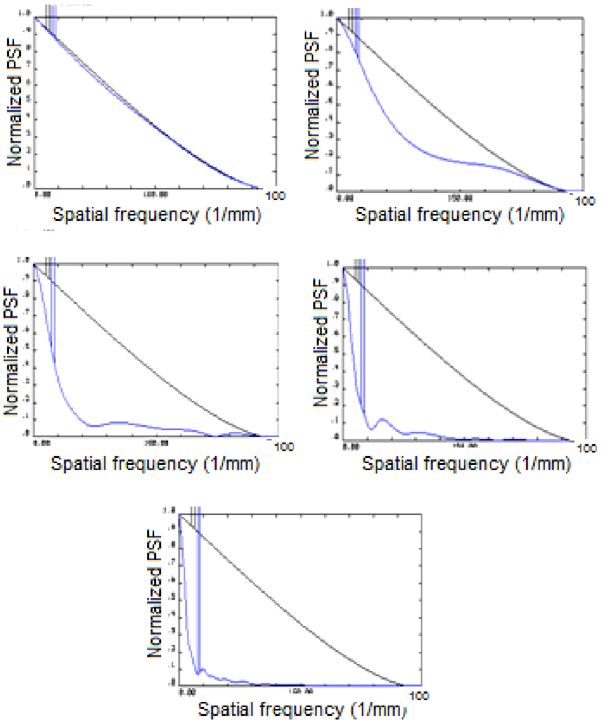


*Fig.(24) MTF of emmtropic and eccentric eyes.*

## Conclusions

We explored the nature of the refractive error due to eccentric viewing within the human eye by analyzing the eye's optical functions with different decentration angles. If defocus is excluded, eyes with very different geometrical features have similar optical performance. This is a remarkable example of an auto-compensating mechanism for the optics of the eye. These results may indicate a passive, geometry-driven mechanism for aberration compensation in the normal young eye leading to a simple but at the same time extremely robust layout of the optical components in the eye.

Results evaluation of multiple quality metrics based on wavefront description indicates that the RMS wavefront error was mostly less than 0.25 wavelengths of light. It has also been shown that there are optical limitations to the detection of sinusoidal gratings in peripheral vision. This experiment had indicated that the MTF varies strongly with defocus, whereas resolution acuity for high-contrast targets is robust against refractive blur in the periphery. The eccentric eyes display this type of behavior concerning all types of aberrations in the eye. This may be understood as a result of evolution working toward corneal and lens functions that reduce the optical errors in the eye. The aberrations in the cornea are relatively increasing, but the lens changes becoming more positive and thereby removing the compensatory effect. The vision quality of the eye is depending on the eccentricity angle; the increase of eccentricity may distort the image and leads to destroy the vision in the eye.

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## الخلاصة

ان الغرض من هذا البحث هو إعطاء تفسيرات مفصلة للأخطاء المتعلقة بمركزية العين البشرية. تم دراسة المقاييس البصرية لتحديد الأخطاء الموجودة في العين اللامركزية نسبةً الى العين السليمة (emmtropic). ولأجل ذلك، تم تحليل أنواع الأخطاء المحتمل وجودها في تصميم العين المعتمد وتحديدها . ثُم تم تقُديم وتقييم ال دوال الأكثر اهمية لوصف اداء العين، اظهرت النتائج ان هناك تأثير سلبي مُميز يصيب الدوال البصرية بسبب لامركزية العين. وان هناك تدهور في نوعية الرؤية فُسِرَ طبقاً لمقارنة التصرف بين الدوال المقدرة في العين اللامركزية نسبةً الى العين السليمة. هذه الدراسة توفر فرصة للباحثين في الموضوعات ذات الصلة بالعين لحل الغموض المتعلق بتعقيد تصميم العين البشرية، ويقدم تحليلات كمية ونوعية للنظر في موضوع تصميم العين البشرية وأنشطتها.