Testing Higher Order Aberrations in Intra Ocular Lenses Using a Shack-Hartmann Sensor

Author: Jordy R. Molina Zambrano
Supervisor: Dr. Eva Philippaki
Course code: 6CCP3131
Table of Contents

1   Abstract.......................................................................................................................... 2

2   Introduction....................................................................................................................... 2
  2.1  Parts and Physics of the Eye......................................................................................... 3
  2.2  Surgeries to correct Cataracts..................................................................................... 4
  2.3  The Intra Ocular Lens.................................................................................................. 4
  2.4  Decentration of IOL..................................................................................................... 5
  2.5  Shack-Hartmann Wavefront Sensor............................................................................ 5
  2.6  Zernike Polynomials.................................................................................................... 7
  2.7  Description.................................................................................................................... 8
  2.8  Handling the IOL......................................................................................................... 11

3   Results.................................................................................................................................. 12
  3.1  Spherical IOLs.............................................................................................................. 12
    3.1.1  Rotation of Spherical IOLs...................................................................................... 12
    3.1.2  Translation of Spherical IOLs............................................................................... 15
  3.2  Aspherical IOLs............................................................................................................ 17
    3.2.1  Rotation of Aspherical IOLs.................................................................................. 17
    3.2.2  Translation of Aspherical IOLs............................................................................. 19

4   Discussion............................................................................................................................ 22
  4.1  Comparison of Spherical and Aspherical IOLs............................................................ 22
    4.1.1  Translation.............................................................................................................. 22
    4.1.2  ROTATION............................................................................................................... 23
  4.2  Best Performing IOL.................................................................................................... 24
    4.2.1  Rotation.................................................................................................................. 24
    4.2.2  Translation.............................................................................................................. 24

5   Final.................................................................................................................................... 27

6   References.......................................................................................................................... 28

7   Appendix 1: Protocols....................................................................................................... 30

8   Appendix 2: Dyslexia Form............................................................................................... 32
1 Abstract

By building a Shack-Hartmann wavefront sensor, it was measured higher and lower order aberrations in Intraocular lenses (IOLs). This sensor tested spherical and aspherical IOLs of different dioptries. It was found that Aspherical lenses performed better than spherical lenses. This study emphasized the importance of high order aberrations to treat visual impairments.

2 Introduction

Cataract is a visual impairment that affects more than 16 million people worldwide [1]. Other sources estimate this number to be 20 million [2]. Cataracts are mainly caused by age related changes, but diabetes and smoking increase the chances of developing this condition [3]. Predominantly affecting the elder population, cataracts blur the vision of its patients by accumulating protein deposits in the crystalline lens. This decreases the transmission of light that reaches the retina [4]. In the elderly, visual impairments’ significance arises from the increase in risk of falling leading to susceptibility of complications and slow recovery time. The top percentile of elder patients accessing healthcare have injuries related to falls. This and similar condition affects the society as a whole due to the loss of work time and morbidity due to visual loss [5].

To treat Cataracts, Intra Ocular Lenses are used to replace the natural lens in the eye; this is performed in capsular surgeries such as hydrodissection and capsulorhexis and phacoemulsification; the latter being the most common [5]. The IOL mimics the optical parameters of the natural lens of the eye. This technique corrects aberrations in the vision and it is normally successful. When the pupils are enlarged, high-order aberrations significantly degrade the vision [6]. However, since the first operation in 1949 at St. Thomas Hospital by Harold Ridley, it has been reported dislocations of the IOLs [5, 7]. As cataracts and other eye conditions create distortions in the wavefront of light entering to the eye, A Shack-Hartmann wavefront sensor is a reliable method used to study these phenomena [8].

In this report, we describe the steps taken to build a Shack-Hartmann sensor. It describes the merge of medical, experimental, computational and theoretical aspects to build a whole cohesive system. The medical aspects of this experiments consist of a description of the quality assurance and treatment of IOLs. As well as an evaluation of the clinical implications of higher order aberrations, treatments and findings. The computational section of this report includes a description of the algorithm used to calculate the Zernike Polynomials and the automation for each consecutive test. The theoretical and experimental aspects provide a quantitative description of the setup and a rationale of its configuration.
2.1 Parts and Physics of the Eye

The main optical elements of the human eye are the cornea, iris, retina and the lens; these are shown in figure 1. These components are non-rotationally symmetric components which leads to an optical system with coma tendency [10]. The cornea is transparent, and it is approximately spherical with a radius of curvature of 8mm [11]. Inside, the eye is subdivided in the anterior chamber, posterior chamber and vitreous chamber (see figure 1). The anterior chamber contains aqueous fluid and the vitreous chamber contains a transparent gelatinous mass [9].

Inside the eye, the internal pressure should be greater in than the atmospheric pressure to keep the shape of the cornea [11]. All the optical elements in the eye are not perfect smooth surfaces; they do have bumps and ripples, and this contributes to the aberrations. Further aberrations of the eye are created by decentrations or tilts of the inner lens and the distribution of the index of refraction. If a person sleeps tends to sleep on one side, minerals will deposit towards that are creating an uneven index of refraction throughout the optical elements. These factors create higher order aberrations which cannot be treated with glasses or contact lenses. The

---

1 It is the only tissue that doesn’t have a blood supply; it gets all the oxygen directly by diffusion from the air.
2 Most of the models of the eye tend to oversimplify these imperfections.
cornea has the greatest optical power and converges the photons to the lens as in figure 2. This lens can adjust its optical power in a process called accommodation. Accommodation is done by the ciliary muscles (see figure 1) which is a sphincter: as it contracts the diameter gets smaller and that loosens the tension on the zonular fibres [11]. This makes the lens rounder and thus it increases its optical power. Conversely, when tension it applied to the zonular fibres the optical power of the lens decreases. The crystalline lens is naturally decentred temporally by 0.07 ± 10 mm and downward 0.16 ± 0.11 mm [12] In between the lens and the cornea, an aperture stops called the iris controls the thickness of the light beam [11]. At the retina the photosensors are at its best [10]. The retina can perceive as much as a single photon. The aberrations are measured in with regards to the line-of-sight which is the normal path of the chief ray from the fixation point to the retinal fovea [10]. Angles were measure counter clockwise from the +x-axis and the coordinate system applies for both eyes [10]. Emmetropic is a person with well-proportioned eyes. Conversely, Myopic is a near-sighted eye and hyperopic is far-sighted person.

2.2 Surgeries to correct Cataracts

The main surgery performed to cure cataracts is phacoemulsification. This aims to remove and replace the crystalline lens with an IOL (see figure 3-middle). It is fundamental to have a precise axis alignment of IOL with the meridian of corneal astigmatism [13] Due to the need of flexibility, IOL are currently made of acrylic and silicone [4]. Initially the patient receive eye drops to numb the eye. The patient needs to be awake during the procedure to avoid any eye movement, specially from the REM cycle. A lateral incision is performed on the lateral side of the cornea. Then, an ultrasonic ‘chopper’ with a titanium tip cuts through the lens and the protein deposit. It facilitates cracking the nucleus into smaller pieces. To remove every residual, the chamber is emulsified and suctioned to remove small pieces. Following the emulsification, the Intraocular lens in pump through a small tube and it unfolds into a stable position (see figure 3-right).

2.3 The Intra Ocular Lens

Figure 4. 1-piece Monofocal 4-haptic design and s-shape design intra ocular lenses.

---

3 In ophthalmic optics, this angle is called the meridian [10]
4 Having a specific gravity almost equal to the aqueous humour (1.09), polymethyl methacrylate PMMA was initially used as the material of the IOL [9]
Intraocular lenses (IOL) are used to replace the crystalline lens inside the eye. They are classified by their focal properties: Monofocal, Toric, Multifocal, Accommodating. In this experiment, we deal with Monofocal IOLs. IOLs are also classified by their geometric shape: Spherical and aspherical. IOLs have haptics to aid with stabilization\(^5\). Without haptics, IOLs would not have equatorial support from the capsul bag [9]. However, tension of the haptics resists the torque around the equatorial axis during eye movement which produces rotations of the IOL [13]. The 1-piece design showed relative good centration and stability in comparison with the 3-piece model [13]. The IOLs used for this experiment were Generation-V and generation IV. The Generation-V model is placed in the posterior chamber (see figure 1) whereas the generation-IV is placed in the anterior chamber [5].

### 2.4 Decentration of IOL

Posterior capsule opacification, capsular bag instability and anterior capsule fibrosis are pathological factors that influence the decentration and rotation of the IOLs [7]. Dislocations are produced by inadequate capsular bag or ciliary sulcus support [14]. Quantifying dislocations are estimated by referring to the Limbus and Phaco incision from a phacoemulsification [7]. The maximum rotation from a study was found to be 11.5° being greater in woman, older patients, and those with worse visual acuity [13]. Using the pupil or Limbus, the mean eye rotation researched by Wolffsohn and Buckhurst was found to be 2.23° ± 1.84° [13]. Gravity, related to ocular movement generates rotation of the IOL [7]. For analysis accuracy, rotations can lead to ‘significant errors if not taken into account’ [12].

0.4 mm was estimated to be the critical amount of decentration by three studies [15,16,17]. Whereas, other studies suggested that it was 0.8 mm [18].

### 2.5 Shack-Hartmann Wavefront Sensor

![Image of Shack-Hartmann Wavefront Sensor](image)

**Figure 5.** Schematic of the cross-section of a wavefront sensor. CCD camera and lenslet array.

The Shack-Hartmann wavefront sensor pictures the variation of the gradient of the normal from the wavefront (see figure 5) using a lenslet array and a laser beam [19]\(^6\). This was invented to

---

\(^5\) It took around 40 years to develop haptics in the IOL [2]

\(^6\) Invented by the German astrophysicist Johannes Hartmann and later improved by Roland Shack
as a tool to measure wavefront\textsuperscript{7}. The lenslet array is an array of small lenses that have a common focal length; it produces an image of points such as in figure 6.

![Image from the CCD camera showing the light beams of the wavefront received at the sensor.](d12.jpg)

Figure 6. Image from the CCD camera showing the light beams of the wavefront received at the sensor. File ‘d12.jpg’.

An aberrated wavefront would project an array with spatially displaced points. This displacement key to analysing the shape of a wavefront [3, 14].

![Image shift produced by aberrations at the image plane.](figure7.png)

Figure 7. Image shift produced by aberrations at the image plane [20].

The displacement of points in comparison with the image of a mask (image without lens or induced aberration) is used to reconstruct the wavefront.

\begin{align*}
\Delta x &= -\frac{FS_x}{R} \quad \text{(Eq. 1)} \\
\Delta y &= -\frac{FS_y}{R} \quad \text{(Eq. 2)}
\end{align*}

Equations 1 and 2 quantify the displacement seen in the image plane on figure 7. \( f \) is the focal length of the lens array and \( R \) is the radius of the wavefront [20]. \( S_x \) and \( S_y \) are the average slopes in the x and y axes.

\begin{align*}
S_x &= \frac{1}{A_x} \int \frac{\partial W(u,v)}{\partial u} dudv \quad \text{(Eq. 3)} \\
S_y &= \frac{1}{A_x} \int \frac{\partial W(u,v)}{\partial v} dudv \quad \text{(Eq. 4)}
\end{align*}

\textsuperscript{7} Initially invented to measure the aberrations caused by clouds for satellite imaging.
Equations 3 and 4 are used to calculate the average gradient of the wavefront [20]. However, Zernike polynomials give a more descriptive analysis.

\[
\frac{\partial W(u,v)}{\partial u} = \sum_{i=1}^{I} c_i \frac{\partial z_i(u,v)}{\partial u} \quad \text{(Eq. 5)}
\]

\[
\frac{\partial W(u,v)}{\partial v} = \sum_{i=1}^{I} c_i \frac{\partial z_i(u,v)}{\partial v} \quad \text{(Eq. 6)}
\]

To expand the wavefront in the Zernike polynomials form. Equations 5 and 6 are used [20]. \(Z_i\) represents each individual Zernike polynomial. \(c_i\) is the magnitude variable of Zernike terms.

### 2.6 Zernike Polynomials

![Zernike Polynomials up to the 4th order](image)

Figure 8. Zernike Polynomials up to the 4th order [21].

A simplified version\(^8\) of the Zernike polynomials is used to mathematically represent the aberrations\(^9\) [22]. On figure 8, \(Z_n^m\) defines each polynomials where \(n\) is the radial degree and \(m\) is the azimuthal term. For the present investigation, we dealt with high-order polynomials (3rd and 4th order). Conversely, lower-order polynomials have 0th to 2nd order of radial degree. Using these polynomials, it is possible to represent the aberrations in a more quantitative way (see figure 8). Zernike polynomials represent a wavefront using values for the magnitude and axis [22]. Table 1 presents a list of polynomials and their classical names. Higher order aberrations are complex refractive error that cannot be corrected with traditional eyeglasses and contact lenses. Some of this aberrations can only be seen at night. Therefore, studying aberrations is the aim of our investigation.

---

\(^8\) For a rigorous descriptions of the simplification of the polynomials see Charles E. Campbell’s *A New Method for Describing the Aberrations of the Eye Using Zernike Polynomials.*

\(^9\) These polynomials are normalized to the unit circle.
Table 1. List of Zernike Polynomials, computing version used, classical name of the polynomials and the OSA indexing.

<table>
<thead>
<tr>
<th>Zernike Polynomial $Z_n^m$</th>
<th>Computing form $Z_j$</th>
<th>Classical name</th>
<th>OSA/ANSI index (j)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_0^0$</td>
<td>Z0</td>
<td>Piston</td>
<td>0</td>
</tr>
<tr>
<td>$Z_1^1$</td>
<td>Z1</td>
<td>vertical tilt</td>
<td>1</td>
</tr>
<tr>
<td>$Z_2^1$</td>
<td>Z2</td>
<td>horizontal tilt</td>
<td>2</td>
</tr>
<tr>
<td>$Z_3^2$</td>
<td>Z3</td>
<td>Oblique astigmatism</td>
<td>3</td>
</tr>
<tr>
<td>$Z_4^0$</td>
<td>Z4</td>
<td>Defocus</td>
<td>4</td>
</tr>
<tr>
<td>$Z_2^2$</td>
<td>Z5</td>
<td>Vertical astigmatism</td>
<td>5</td>
</tr>
<tr>
<td>$Z_3^3$</td>
<td>Z6</td>
<td>Vertical trefoil</td>
<td>6</td>
</tr>
<tr>
<td>$Z_5^1$</td>
<td>Z7</td>
<td>Vertical coma</td>
<td>7</td>
</tr>
<tr>
<td>$Z_3^3$</td>
<td>Z8</td>
<td>Horizontal coma</td>
<td>8</td>
</tr>
<tr>
<td>$Z_9^3$</td>
<td>Z9</td>
<td>Oblique trefoil</td>
<td>9</td>
</tr>
<tr>
<td>$Z_4^4$</td>
<td>Z10</td>
<td>Oblique quadrafoil</td>
<td>10</td>
</tr>
<tr>
<td>$Z_4^2$</td>
<td>Z11</td>
<td>Oblique secondary astigmatism</td>
<td>11</td>
</tr>
<tr>
<td>$Z_4^4$</td>
<td>Z12</td>
<td>Primary spherical</td>
<td>12</td>
</tr>
<tr>
<td>$Z_4^2$</td>
<td>Z13</td>
<td>Vertical secondary astigmatism</td>
<td>13</td>
</tr>
<tr>
<td>$Z_4^4$</td>
<td>Z14</td>
<td>Vertical quadrafoil</td>
<td>14</td>
</tr>
</tbody>
</table>

2.7 Description

The present experiment was subdivided into three categories: medical, computational and experimental.

Figure 9. Schematic of the experimental setup.
The experimental team designed a set up that would measure wavefront aberrations using a Shack-Hartmann sensor; the principles applied were based on T. M. Jeong et al’s paper [8]. It used a Melles Griot class 3B green laser as the source of light; a 543.5 nm-wavelength beam was produced at the maximum output of 5 mW. After the laser a spatial filter was introduced to the system. It was composed of a 10/0.25 objective lens and a pinhole located at the focal point of the lens (see figure 9). This creates a synthetic point source. Next to the spatial filter, the beam was collimated using a collimator. A secondary pinhole was used to get the Gaussian profile of the beam to get a planar wavefront\textsuperscript{10}. To fit our system into the workspace, a mirror used to deviate the beam. After this stage, a third pinhole was used to control the beam size. The IOL was located next to third pinhole; It was placed in a mount with protective foam that was capable of XYZ translations and rotations in the azimuth of the lens.

![Schematic mechanism of the telescopic system](image)

Next, two lenses aimed to magnify the image to enhance the analysis; these lenses created a telescopic system to increase the size of the beam to 6.5 mm without losing information during the process; it fills a significant portion of the CCD camera [14]. The first lens (105 mm) was a negative meniscus lens and the second is a convex lens (60 mm). It was chosen the diameter of 6.5 mm mimic light entering the pupil of the human eye [20]. At the following stage, the beam’s intensity was decreased\textsuperscript{11}. Following this stage, it was set up wedge prisms to steer the beam\textsuperscript{12}. The wedge prisms were used to re-centre the beams after each translation and rotation. Next, the beam was split into two perpendicular paths using a beam splitter (see figure 9); this retains the IOL image. One beam pointed towards the sensor and the other beam aimed at the CMOS camera which was used as the pupil camera to align the optical axis [8]. In both routes of the beams, it was placed two extra filters. The Shack-Hartmann sensor was composed of a fused silica lenslet array of 10x10 mm (or 33x33 lens) and a commercial THORLABS® Charged-Coupled Device (CCD) camera placed at the focal length of the lenslet array; it had a sensor of 4.8x3.6 mm [19]. The THORLABS® CMOS camera was used for reference images at manipulating the IOL; it had a 7.18x5.32 mm sensor and an aperture of 1/1.8”. Using the SH sensor, the pictures were taken and stored in accordance to appendix A and the computer form of Table 1.

\textsuperscript{10} This removes the Gaussian fluctuations of the beam.
\textsuperscript{11} It was used a filter to avoid edge effects
\textsuperscript{12} The steering induced in the H-S sensor were the mirror image of the Complementary Metal-Oxide-Semiconductor (CMOS) camera
The computational team designed MATLAB® scripts that aimed to calculate the Zernike Polynomials and plot 3D and 2D models of the aberrations (see figure 11). Using two inputs from the database, namely ‘ref’ and ‘img’, the software analyses each file. ‘ref’ represents the mask, or the reference image captured, by the SH sensor. ‘img’ refers to the image dislocated to induce aberrations. Three functions were created to analyse the data, namely ‘WaveRecon(img, ref)’, ‘centroid(img)’ and ‘imagepro(img)’. First, WaveRecon analyses two inputs from the reference and aberrated wavefront and subsequently it stores in a 2D array. Next, by fitting a 3mm circle (pupil diameter) over a cluster of points, centroid found the centre of the cluster. However, the cluster of dots has a sub-cluster which affects the analysis. Therefore, imagepro was used to find the centre of the sub-cluster (see figure 12) of points to create a single point.

Figure 11. Flow chart of the scripts used to reconstruct wavefronts.

Figure 12. Sub-clusters surrounding the points. Maximized S-H image.
After this loop, Waverecon computes the difference in the $x$ and $y$ distances of the points from the points on the reference image and the points in map of the aberrated image. This is done in three sub-loops. The first loop overlaps with the closest focal point and normalization of the images in three steps. Step one, the centroids were overlap between maps and subsequently they are normalized in the image registration process. Step two, Indices of the nearest were calculated from both images spaces. Step three, the indices are converted into distances and stored in a 2D array. These steps can be seen in figure 11 as numbers 1,2,3. From the 2D, it was calculated the Zernike polynomials up to the 4th order outputting at 1000x14 array. This produced Cartesian coordinates of the displaced focal points. Next, the arithmetic mean of this values were calculated to create a 1x14 matrix of the coefficients. Subsequently, it was taken a linear combination from the previous values to reconstruct 2D and 3D models of the wavefront [19].

2.8 Handling the IOL

The medical group aimed to control the quality standards of testing in IOLs. By using powder-free latex gloves during the whole process, the IOL was handled by the medical team using the following steps. First, the cuvette was cleaned thoroughly using distilled water as this will remove salt deposits from the saline solution13. In addition, the wet cell used was a Starna Scientific Ltd. quartz cuvette. To reach inaccessible areas inside the cuvette, a surgical-grade spear cotton was used. The IOL was stored in an incubator at 37°C14. Next, the packaging of the IOL was removed and the solution inside the packaging was poured into a Petrie Dish. The solution used is saline, or sodium chloride, which is medically used to clean wounds, help remove contact lenses, and help with dry eyes [23]. The IOL is firmly placed inside the packaging. Using surgical forceps, it was carefully removed the IOL from the packaging. It is worth mentioning that excessive force at this step may shear structure of the lens. The IOL should be grabbed from the haptics to avoid damaging the lens. It is important to identify the frontal side of the lens by looking at the surface with lump. After the experiment, the IOLs were stored in bottles (with saline solution) which was labelled with identification numbers in accordance to our designed protocols (Appendix 1).

![Figure 13. Schematic of the IOL holder and the cuvette.](image.png)

During the tests of IOLs, a Petrie dish was filled with saline solution and the IOL was placed temporarily inside it. Next, the cuvette was filled up three quarters with a saline solution to prevent surface deformation and desiccation during measurements [6]15. In the next step the

---

13 The solution, Sensitive Eyes ® Plus Saline Solution, contained boric acid, sodium borate, potassium chloride, sodium chloride, preserved with polyaminopropyl biguanide (0.00003%) and edetate disodium (0.025%) [25]
14 to mimic the generally accepted average normal body temperature [24]
15 It is worth to check that the cuvette is completely clean as this would cause further aberrations.
IOL is placed at centre of the IOL holder making sure that all the haptics are inside the inner gaps of the holder (see figure 13). By carefully checking the frontal side of the IOL, a black pin (see figure 13) to identify the front side of the lens. Once the IOL is in the holder, the IOL holder is carefully placed on the right side of the cuvette to identify the front (see figure 13). It is strongly recommended to make sure that there are no air bubbles inside the solution. Aspherical IOLs from the sample test had UV coating which gave them a light yellow colour. IOLs were tested for rotations in a range from 7 steps: from $-3^\circ$ to $3^\circ$. For translations it was tested for 11 steps: From $-0.05$ mm to $0.05$ mm.

3 Results

Six IOLs were tested during this experiment. 3 Spherical IOLs and 3 Aspherical\textsuperscript{16}. To measure polynomials of orders greater than four, the computing curve limited out the present study. Thus, it was only studied Zernike Polynomials up to the 4\textsuperscript{th} order. The errors of the root mean square values of the polynomials were calculated with Statistical Analysis of Small Data Sets (SASDS) \[25\].

3.1 Spherical IOLs

3.1.1 Rotation of Spherical IOLs

Bellow, table 2 shows the high-order RMS values of Spherical IOLs tested during rotations of the IOL. These IOLs had a 4-haptics around its edge and no UV coating (see figure 4).

\begin{table}[h]
\centering
\begin{tabular}{|c|ccc|}
\hline
Tilt ($^\circ$) & 20.5 D & 20 D & 19.5 D \\
& RMS (\textmu m) & RMS (\textmu m) & RMS (\textmu m) \\
\hline
3.00 $\pm$ 0.01 & 0.94 $\pm$ 0.04 & 0.03 $\pm$ 0.04 & 1.38 $\pm$ 0.04 \\
2.00 $\pm$ 0.01 & 0.83 $\pm$ 0.04 & 2.71 $\pm$ 0.04 & 1.33 $\pm$ 0.04 \\
1.00 $\pm$ 0.01 & 0.58 $\pm$ 0.04 & 0.04 $\pm$ 0.04 & 1.40 $\pm$ 0.04 \\
0.00 $\pm$ 0.01 & 0.45 $\pm$ 0.04 & 0.04 $\pm$ 0.04 & 1.47 $\pm$ 0.04 \\
-1.00 $\pm$ 0.01 & 0.45 $\pm$ 0.04 & 0.04 $\pm$ 0.04 & 1.48 $\pm$ 0.04 \\
-2.00 $\pm$ 0.01 & 0.52 $\pm$ 0.04 & 0.04 $\pm$ 0.04 & 1.60 $\pm$ 0.04 \\
-3.00 $\pm$ 0.01 & 0.47 $\pm$ 0.04 & 0.04 $\pm$ 0.04 & 1.61 $\pm$ 0.04 \\
\hline
\end{tabular}
\caption{High-order RMS values of rotations in spherical IOLs.}
\end{table}

The values on table 2 were plotted bellow in figure 13. In this and subsequent figures, error bars were not plotted due to their small magnitude.

\textsuperscript{16} All the findings in the present paper are quoted using the conventions agreed by 1999 topical meeting on vision science and its applications (VSIA-99) \[10\]
Figure 13. Rotation of three spherical lenses and their RMS values for higher order polynomials.

It can be seen in Figure 13, there is a prominent RMS value at $2^\circ$ of rotation for the 20 dioptre IOL. Therefore, figure 14 was plotted to inspect in more details this reading.

Figure 14. Zernike Polynomials and high-order RMS values of 20 Dioptre IOL at $2^\circ$ of rotation.

From figure 14, the highest coefficient at the $Z^2$ test is oblique trefoil ($Z9$ or $Z_9^3$) and the vertical secondary Astigmatism ($Z13$ or $Z_4^1$).
Further analysis lead to figure 15; it was plotted to quantify how similar the aberrations at the 2° in comparison with the other readings. Consequently, being significantly offset, the file of the test was traced.

It can be seen that source of the 2°-test was attributed to failure to align the beam. It appears that these type of errors is quite common. According to an IOL clinical study of 400 eyes, it raised the concern that large errors can be attributed to the alignment of mounting of the camera [13]. However, if we disregard this file, the 20-D IOL performs the best at this category, having the least RMS values on multiple degrees of rotation. In addition, according to figure 13, there doesn’t seem to be a correlation of the Dioptre and the RMS values for this category.
It was compared the 3D wavefronts at similar degrees of rotation (2° and -2°) for the 20 Dioptre IOL (see figure 17). The figure on the left was the wavefront represented from the corrupted file (by the displaced SH image; see figure 16). On the right, it is shown the wavefront represented at a similar degree of tilt. From aberration theory, both wavefronts should be a mirror image because the lens is symmetric.

3.1.2 Translation of Spherical IOLs

It was also studied the influences on translation on spherical IOL. Below, table 3 contains the RMS values of translated spherical IOLs.

<table>
<thead>
<tr>
<th>Displacement (mm)</th>
<th>20.5 D</th>
<th>20 D</th>
<th>19.5 D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RMS (µm)</td>
<td>RMS (µm)</td>
<td>RMS (µm)</td>
</tr>
<tr>
<td>0.5</td>
<td>0.99 ± 0.04</td>
<td>0.05 ± 0.04</td>
<td>1.62 ± 0.04</td>
</tr>
<tr>
<td>0.4</td>
<td>0.83 ± 0.04</td>
<td>0.05 ± 0.04</td>
<td>1.58 ± 0.04</td>
</tr>
<tr>
<td>0.3</td>
<td>0.87 ± 0.04</td>
<td>0.04 ± 0.04</td>
<td>1.63 ± 0.04</td>
</tr>
<tr>
<td>0.2</td>
<td>0.58 ± 0.04</td>
<td>0.04 ± 0.04</td>
<td>1.55 ± 0.04</td>
</tr>
<tr>
<td>0.1</td>
<td>0.57 ± 0.04</td>
<td>0.04 ± 0.04</td>
<td>1.44 ± 0.04</td>
</tr>
<tr>
<td>0</td>
<td>0.49 ± 0.04</td>
<td>0.04 ± 0.04</td>
<td>1.61 ± 0.04</td>
</tr>
<tr>
<td>-0.1</td>
<td>0.52 ± 0.04</td>
<td>0.04 ± 0.04</td>
<td>1.50 ± 0.04</td>
</tr>
<tr>
<td>-0.2</td>
<td>0.56 ± 0.04</td>
<td>0.04 ± 0.04</td>
<td>1.51 ± 0.04</td>
</tr>
<tr>
<td>-0.3</td>
<td>0.45 ± 0.04</td>
<td>0.05 ± 0.04</td>
<td>1.50 ± 0.04</td>
</tr>
<tr>
<td>-0.4</td>
<td>0.54 ± 0.04</td>
<td>0.05 ± 0.04</td>
<td>1.42 ± 0.04</td>
</tr>
<tr>
<td>-0.5</td>
<td>0.81 ± 0.04</td>
<td>0.08 ± 0.04</td>
<td>1.42 ± 0.04</td>
</tr>
</tbody>
</table>

Table 3. Displacement and RMS of three spherical IOLs.
Figure 18. High-order RMS values of spherical IOLs caused by translation

Figure 18 was plotted from the values in table 3. From this group, this figure shows that the 19.5 D Lens produced the highest aberrations. The 20-D lens had the lowest aberrations for translations and rotations from the spherical category. Again, there doesn’t seem to be correlation between the dioptre and the aberrations.

Figure 19. Aberrations from displaced IOLs
From the values in table 3, the plot in figure 19 demonstrates that the 20-D performed significantly better in this test group.

### 3.2 Aspherical IOLs

#### 3.2.1 Rotation of Aspherical IOLs

Similar rotations were performed for Aspherical IOLs and the results can be seen in table 4. It is worth mentioning that in IOLs, each off-axis degrees result in a loss of optical power by a factor 3.3% [7]. These IOLs presented the S-shape haptics (see figure 4). In addition, they were coated with UV protection. The results of these findings can be seen in table 4.

<table>
<thead>
<tr>
<th>Tilt (°)</th>
<th>21 D</th>
<th>16 D</th>
<th>17 D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RMS (µm)</td>
<td>RMS (µm)</td>
<td>RMS (µm)</td>
</tr>
<tr>
<td>3.00 ± 0.01</td>
<td>0.06 ± 0.04</td>
<td>2.05 ± 0.04</td>
<td>0.22 ± 0.04</td>
</tr>
<tr>
<td>2.00 ± 0.01</td>
<td>0.06 ± 0.04</td>
<td>1.80 ± 0.04</td>
<td>0.17 ± 0.04</td>
</tr>
<tr>
<td>1.00 ± 0.01</td>
<td>0.06 ± 0.04</td>
<td>1.85 ± 0.04</td>
<td>0.08 ± 0.04</td>
</tr>
<tr>
<td>0.00 ± 0.01</td>
<td>0.05 ± 0.04</td>
<td>1.84 ± 0.04</td>
<td>0.08 ± 0.04</td>
</tr>
<tr>
<td>-1.00 ± 0.01</td>
<td>0.05 ± 0.04</td>
<td>1.80 ± 0.04</td>
<td>0.07 ± 0.04</td>
</tr>
<tr>
<td>-2.00 ± 0.01</td>
<td>0.10 ± 0.04</td>
<td>1.68 ± 0.04</td>
<td>0.11 ± 0.04</td>
</tr>
<tr>
<td>-3.00 ± 0.01</td>
<td>0.43 ± 0.04</td>
<td>2.09 ± 0.04</td>
<td>0.18 ± 0.04</td>
</tr>
</tbody>
</table>

Table 4. High-order RMS values of rotations in Aspherical IOLs

From the values of table 4, figure 20 was plotted. Table 2 contains the uncertainties of these readings, however it was not possible to plot them due to their small magnitude.

![Comparison of Rotation in Spherical Lenses](image)

Figure 20. Rotation of three aspherical lenses and their RMS values for higher order polynomials.
Figure 20 depicts the influence of rotation on the RMS values of aspherical lenses of three different dioptres. From figure 20, the IOL with the most aberrations was the 16-Dioptre lens and that the 17- and 21-Dioptre lenses had virtually no aberration. Again, this supports our finding that there is no correlation of Dioptres and aberrations.

![Figure 20](image)

Figure 21. Magnitudes of the RMS induced by rotations.

It can be from figure 21 that the 16-D IOL produced the most aberrations by a significant margin. In order to examine this discrepancy in more detail, figures 22, 23 and 24 were plotted.

![Figure 21](image)

Figure 22. Aberrations presented in 16-D lens at -3 degrees; most aberrations from this test.
19

Figure 23. Aberrations presented in 17-D lens at -3 degrees; least aberrations from this test.

The 16-D lens presented 299.3% more vertical trefoil (Z6) than 17-D lens. As well as a 215.1% difference of the vertical quatrefoil (Z14). Between this two IOLs, the percentage difference of higher & lower RMS was 38.7%. However, if we take into account only the 3rd and 4th terms the percentage difference will be 169.4%. These discrepancy of aberrations highlights the significance of studying higher order aberrations.

Figure 24. 3D plot of the 16-D (on the left) and 17-D (on the right) lenses at a rotation of -3 degrees.

It was necessary to plot figure 14 to see that both wavefront posit similar low-order aberrations but they differ as a quatrefoil (Z14) at the edge.

3.2.2 Translation of Aspherical IOLs
Table 5. Displacement of three aspherical IOLs.

<table>
<thead>
<tr>
<th>Displacement (mm)</th>
<th>21 D</th>
<th>16 D</th>
<th>17 D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RMS (µm)</td>
<td>RMS (µm)</td>
<td>RMS (µm)</td>
</tr>
<tr>
<td>0.50 ± 0.01</td>
<td>0.19 ± 0.04</td>
<td>2.26 ± 0.04</td>
<td>0.11 ± 0.04</td>
</tr>
<tr>
<td>0.40 ± 0.01</td>
<td>0.09 ± 0.04</td>
<td>1.87 ± 0.04</td>
<td>0.08 ± 0.04</td>
</tr>
<tr>
<td>0.30 ± 0.01</td>
<td>0.07 ± 0.04</td>
<td>1.87 ± 0.04</td>
<td>0.08 ± 0.04</td>
</tr>
<tr>
<td>0.20 ± 0.01</td>
<td>0.10 ± 0.04</td>
<td>1.97 ± 0.04</td>
<td>0.08 ± 0.04</td>
</tr>
<tr>
<td>0.10 ± 0.01</td>
<td>0.14 ± 0.04</td>
<td>1.72 ± 0.04</td>
<td>0.07 ± 0.04</td>
</tr>
<tr>
<td>0.0 ± 0.01</td>
<td>0.09 ± 0.04</td>
<td>1.61 ± 0.04</td>
<td>0.08 ± 0.04</td>
</tr>
<tr>
<td>-0.10 ± 0.01</td>
<td>0.05 ± 0.04</td>
<td>1.50 ± 0.04</td>
<td>0.10 ± 0.04</td>
</tr>
<tr>
<td>-0.20 ± 0.01</td>
<td>0.11 ± 0.04</td>
<td>1.46 ± 0.04</td>
<td>0.11 ± 0.04</td>
</tr>
<tr>
<td>-0.30 ± 0.01</td>
<td>0.06 ± 0.04</td>
<td>1.53 ± 0.04</td>
<td>0.09 ± 0.04</td>
</tr>
<tr>
<td>-0.40 ± 0.01</td>
<td>0.09 ± 0.04</td>
<td>1.36 ± 0.04</td>
<td>0.11 ± 0.04</td>
</tr>
<tr>
<td>-0.50 ± 0.01</td>
<td>0.23 ± 0.04</td>
<td>1.41 ± 0.04</td>
<td>0.10 ± 0.04</td>
</tr>
</tbody>
</table>

Table 5 presents the RMS values of the displacements and their uncertainties. Similarly, these values were plotted in figure 25.

![Comparison of Translation in Aspherical Lenses](image)

Figure 25. Translation of aspherical IOLs coated with UV-protection

Figure 25 shows a 16-D IOL having more aberrations in comparison the 21- and 17-Dioptre model lenses.
Figure 26. Comparison of the magnitude of the aberrations between three aspherical IOLs.

At 0.5 mm of displacement, 180% difference of high-order RMS values between the 16 and 17 Dioptre lenses. 46.8% difference of higher & lower order RMS values. The Zernike polynomials (see table 1 for classical names) with the most discrepancy between these two lenses were: Z8 (221.8%), Z9 (210.1%), Z7 (206.2%).

Figure 27. Wavefront of 16 Dioptre lens (left) VS 17 Dioptre lens at 0.5 mm of displacement.

From figure 27, the horizontal coma (Z8), oblique trefoil (Z9) and vertical coma (Z7) are more pronounced on the 16-D lens. It has been examined that the 17-Dioptre lens produced less aberrations during test rotational and translations tests.
4 Discussion

4.1 Comparison of Spherical and Aspherical IOLs

It was compared a spherical lens of 20.5 Dioptre and an aspherical lens of 21 Dioptres.

4.1.1 Translation

Figure 28. Comparison of translations of a spherical and aspherical lens.

It is worth mentioning that the aspherical lenses were asymmetric. Figure 28 shows that the 20.5-D lens produced higher aberrations during all the translations.

Figure 29. Magnitude of difference between two models of IOLs.
At 0.5 mm of displacement, the discrepancy of the RMS values was the largest. Figure 29 portrays this difference which is 119%.

### 4.1.2 ROTATION

Similarly, these lenses were tested for rotations.

![Comparison in rotation test of a spherical and aspherical lens.](image)

At the -3 degrees both RMS values differ by 9%. However, at 3 degrees of rotation the RMS values by 176%; this is depicted in figure 31 seen bellow. This relationship can be attributed to the asymmetrical structure of the aspherical lens.

![Test performed at 3-degrees to show the magnitude of the discrepancy.](image)
4.2 Best Performing IOL

A conclusive analysis lead to the comparison of the IOLs of least aberrations of both sample groups: Spheric and Aspheric.

4.2.1 Rotation

![Graph showing rotations of best performing lenses.](image)

Figure 31. Rotations of best performing lenses.

If we don’t consider the 2-degree error from SH corrupted file (see figure 14), both lenses had a good performance. However, the aspherical lens had less aberrations.

4.2.2 Translation
Figure 32. Shows the comparison performed on the best performing Spheric and aspheric lens for the translation test.

From figure 32, the IOL that performed the best was 17-Dioptre IOL because it was the lens with the least aberrations during rotation and translation tests. Figure 33 shows the Zernike coefficients at this test.

Figure 33. Zernike and high-RMS values of the aspheric lens of 17 D at 0.0 degrees of tilt.

Figure 33 shows the Zernike coefficients of the IOL with least aberrations during the present investigation. It should be noted that the most influential factor affecting the aberrations is the primary spherical (Z12).
From the analysed data described in this paper, aspherical IOLs had an average of $0.67 \pm 0.04 \mu m$ of high order aberrations which was lower than $0.79 \pm 0.04 \mu m$ from spherical lenses. Similarly, the higher and lower aberrations produced from the aspherical lenses were $1.55 \pm 0.04 \mu m$ and for the spherical lenses were $1.70 \pm 0.04 \mu m$.

Figure 35. Percentage of higher and lower aberrations of spherical and aspherical IOLs.
Figure 36 shows percentage of total high and low order aberrations present on the lenses which highlights the significant for correction of this visual problems. For translation and rotations, there were lenses that produced no average aberrations for certain polynomials. The 20.5 D Spherical lens had 0.00 ± 0.04 μm for the Z6, Z9, Z10 and Z14. In addition, the aspherical 21 D IOL had an average of 0.00 ± 0.04 μm for the terms Z9.

![Pie chart](image)

**Figure 36.** Number of test where the Primary Spherical term presented the most aberration.

## 5 Final

Out of 108 tests, 98 readings showed that the value of Z12 term had the biggest magnitude of RMS value. 12 of the readings presented different coefficients as the most aberrant term. Due to the significance of higher order aberrations from the present study, these findings emphasize the need for studies on aberrations of orders greater than 4th. In conclusion, it was successfully designed and created a Shack-Hartmann sensor capable of reading up to 4th order aberrations. From the IOLs tested, the aspherical lenses performed better than the spherical lenses. The IOL that performed the best 17 Dioptré lens. Our findings emphasize the importance of higher order aberrations for eye to treat visual impairment problems.
6 References


7 Appendix 1: Protocols

Protocols for Testing IOL Samples
Date: 16/03/2018
Time: 13:40

Classification and Labelling
The geometrical structure of the samples was identified by the codes given from the supplier. For Spheric IOLs the code was MICS26P. Similarly, for Aspheric IOLs the code was H64AY26P. Below, it is a list of the samples received:

<table>
<thead>
<tr>
<th>Batch</th>
<th>ID Code</th>
<th>Optical Power (Dioptre)</th>
<th>Overall Length (mm)</th>
<th>Diameter of Optical Part (mm)</th>
<th>Reference No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>97</td>
<td>17GXWC</td>
<td>19.5</td>
<td>10.50</td>
<td>6.00</td>
<td>1</td>
</tr>
<tr>
<td>59</td>
<td>17KPUB</td>
<td>20.0</td>
<td>10.50</td>
<td>6.00</td>
<td>2</td>
</tr>
<tr>
<td>115</td>
<td>17KTUB</td>
<td>20.0</td>
<td>10.50</td>
<td>6.00</td>
<td>3</td>
</tr>
<tr>
<td>36</td>
<td>17KBVB</td>
<td>20.5</td>
<td>10.50</td>
<td>6.00</td>
<td>4</td>
</tr>
<tr>
<td>83</td>
<td>17KBVB</td>
<td>20.5</td>
<td>10.50</td>
<td>6.00</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 1. List of Spheric IOLs
Table 1 provides the extensive information to identify each intra ocular lens.

<table>
<thead>
<tr>
<th>Batch</th>
<th>ID Code</th>
<th>Optical Power (Dioptre)</th>
<th>Overall Length (mm)</th>
<th>Diameter of Optical Part (mm)</th>
<th>Reference No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>17LFUB</td>
<td>16.0</td>
<td>12.50</td>
<td>6.50</td>
<td>6</td>
</tr>
<tr>
<td>14</td>
<td>17FVJB</td>
<td>17.0</td>
<td>12.50</td>
<td>6.50</td>
<td>7</td>
</tr>
<tr>
<td>83</td>
<td>17LGN</td>
<td>21.0</td>
<td>12.50</td>
<td>6.50</td>
<td>8</td>
</tr>
<tr>
<td>45</td>
<td>16BKDC</td>
<td>21.5</td>
<td>12.50</td>
<td>6.50</td>
<td>9</td>
</tr>
<tr>
<td>12</td>
<td>17LSN</td>
<td>22.5</td>
<td>12.50</td>
<td>6.50</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 2. List of Aspheric IOLs
Table 2 shows identification codes, batch number and properties of each IOL.

<table>
<thead>
<tr>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Format: CellNo.jpg</td>
</tr>
<tr>
<td>Reference Number in dropbox excel</td>
</tr>
<tr>
<td>URL: C:\Users\camera\Documents\Data (2018)</td>
</tr>
<tr>
<td>Sources of Error: The IOL might be tilted</td>
</tr>
<tr>
<td>Different Camera Saving: The images taken with the CMOS camera have a C at the end</td>
</tr>
<tr>
<td>Dislocation error: 0.01 mm</td>
</tr>
<tr>
<td>Tilt error: 0.5 degrees</td>
</tr>
<tr>
<td>Tape: The end of the tape marks the start of the collimator</td>
</tr>
</tbody>
</table>
Table 3. Notes on classification of IOLS

The protocol for classifying and storing the information from each test of the IOLs can be seen in table 3.

Trials
The following trials were performed under the Advanced Laser Safety regulations from Health & Services from King’s College London. Below, table 4 shows the tested samples.

Table 4. List of performed tests
8 Appendix 2: Dyslexia Form

Note to the Marker

Please consider the following candidate's written work in respect of specific learning difficulties

Y34047
(Candidate Number)

Status of Application:
The Personalised Examination Provisions Committee (PEPC) has approved the use of a coursework cover note in respect of specific learning difficulties

For The Marking of Work for Language Modules

• In the case of language modules, please consider carefully what specifically is being assessed. If it is purely the accuracy of the use of the language (e.g. the spelling, grammar and punctuation) that is being marked, then exceptions should NOT be made for specific learning difficulties. However, if the paper is being assessed either fully or partly on other criteria, then please follow the guidance described below as appropriate.

Guidelines for Markers Assessing Coursework of Students with Specific Learning Difficulties

o Although students with specific learning difficulties should be marked with regards to the elements of content in their work, the logical argument of an essay or report may not be constructed in a very sequential manner. In addition, grammatical and sentence structure errors can be missed by the student.

o Students with specific learning difficulties commonly make errors in the form of the omission of small function words, the addition or repetition of such words, the transposition of words and the substitution of other function words (the /a / an / for / from). Such errors should be disregarded.
With the exception of essential technical vocabulary, poor spelling, grammar and punctuation should be disregarded.

The use of spell- and grammar-checkers has a limited use for students with specific learning difficulties. Word substitution, phonetic equivalent and American spelling errors can occur.

A summary of approaches for markers is given below (from "Guidelines for Examiners" document available from the Examinations and Awards Office)

- Read passage quickly for content
- Include positive/constructive comments
- Use clear English
- Use non-red coloured pens for comments
- In correcting English, explain what is wrong and give examples

**Academic year: 2017/8**

Alteration or misuse of this document in any way will result in referral to the Disciplinary Committee