# Efficacy of estimations of Hartmann–Shack sensors in small pupil sizes

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## Abstract:

**PURPOSE:** The purpose of this study was to evaluate the *in vivo* efficacy of the estimations of wavefront analyzers using Hartmann–Shack technology to measure optical aberrations when the pupil size is smaller than the evaluated pupil area.

**METHODS:** Patients implanted with the monofocal ZCB00 intraocular lens (Johnson and Johnson) were examined with the KR-1W Wavefront Analyzer (Topcon) without pharmacological mydriasis and with it afterward. Optical aberrations were analyzed considering a 4-mm pupil and a 6-mm pupil for both examinations.

**RESULTS:** Sixty-six eyes of 33 patients with a mean axial length of 23.35 ± 0.91 mm were assessed. The mean pupil diameter at the baseline examination was 5.05 ± 0.88 mm and under pharmacological mydriasis, it was 6.29 ± 0.84 mm. Outcomes were similar with and without dilation in the 4-mm comparison. However, there was a great disparity in the 6-mm comparison. Most of the values obtained under mydriasis were statistically lower than at baseline ($P < 0.05$).

**CONCLUSION:** The iris interferes with measurements of wavefront aberrations, and therefore, real pupil size should always be checked before evaluating optical aberrations with Hartman–Shack sensors. When pupil size is smaller than the analyzed diameter, ocular, and internal, and sometimes, corneal aberrations are estimated far more positive than real values.

**Keywords:**

Hartmann–Shack, intraocular lens, optical aberrations, pupil size, wavefront analyzer

## Introduction

Visual acuity (VA) has traditionally been the main measurement to evaluate an optical system such as the human eye. However, a good VA might not be associated with good vision in some patients and this is why optical quality is becoming increasingly important. It encompasses some aspects such as contrast sensitivity, color discrimination, halos perception, or optical aberrations.

Optical aberrations are the result of disorders in the light wavefront along its way to its focus on the retina. Total optical aberrations are divided into corneal and internal, depending on their origin. Most of them are included in the Zernike polynomials, which are a mathematical classification according to the radial and azimuthal degrees of the aberrated wavefront. Some others were excluded from this classification such as the distortion or the Petzval field curvature. Thus, those included in that classification can be divided into low- and high-order aberrations (HOAs). The former include defocus, astigmatism, and tilt. They represent the biggest part of total aberrations in human eyes and are usually easily rectifiable with optical means. They are called low-order aberrations because they represent the first and second orders in the Zernike polynomials. On the other hand, the latter represent a low percentage of the total in human eyes; they are not easily rectifiable with optical means and are composed of a larger number of aberrations ranging from the third order onward. Therefore, third-order aberrations include trefoil and

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coma; fourth-order aberrations include tetrafoil, secondary astigmatism, and spherical aberration; fifth-order ones include pentafoil, secondary trefoil, and secondary coma. The higher the order is, the lower impact they have on vision.

Optical aberrations vary with pupil diameter,[1,2] increasing with larger pupil sizes. This fact together with modifying lighting conditions is used in optical benches to assess how visual quality in a human eye might be affected. Despite optical benches not being always optically perfect, they are indeed much more than human eyes. It should be taken into account that there is also a great variation in biometry features and pupil sizes between patients.

Wavefront aberrations are becoming increasingly important, especially in refractive surgery,[3-5] and HOAs such as spherical aberration have an impact on vision which can be partially compensated with the implantation of an appropriate intraocular lens (IOL).[6] Although its quantity is relatively small, HOAs may lead to a negative result in visual quality which cannot be modified with spectacles or contact lenses.

Wavefront analyzers are optical devices whose main purpose is to evaluate optical aberrations in patients. There are different types of analyzers depending on the method they use, such as Hartmann–Shack, ray tracing, or Tscherning. In daily practice, aberrations are usually measured under scotopic conditions but patients are not always examined under pharmacological mydriasis. As far as we know, no previous studies have evaluated the efficacy of Hartmann–Schack sensors in small pupil sizes in real patients and not in optical benches. Our aim in this study is to evaluate the *in vivo* efficacy of the estimations of wavefront analyzers using Hartmann–Shack technology when pupils do not reach a required diameter.

## Methods

This study was approved by the local Ethics Committee and followed the Declaration of Helsinki. Inclusion criteria were patients bilaterally implanted with monofocal ZCB00 IOL (Johnson and Johnson) between 2 and 3 months before and age lower than 75 years old. Patients were excluded in case of corneal astigmatism higher than 1 diopters, spherical refractive error higher than 3 diopters previous to cataract surgery, amblyopia, and any ophthalmological pathology.

The ZCB00 IOL belongs to the TECNIS platform. It is a biconvex hydrophobic acrylic one-piece IOL whose optics have a diameter of 6 mm, it has an ultraviolet filter and an aspheric anterior surface. According to the manufacturer, it has a spherical aberration of − 0.27 µm to compensate its positive corneal equivalent.

### Instruments

Axial length (AL) was measured with IOLMaster 500 (Carl Zeiss, Jena, Germany). Patients were examined with the KR-1W Wavefront Analyzer (Topcon Medical Systems, Tokyo, Japan), which integrates Hartmann–Shack technology. The Hartmann–Shack sensor consists of an array of lenses of the same focal length, which are crossed by the light beams coming from inside the eye. Each lens is focused onto a photon sensor, then the deviation between the focused light beam and its ideal position is analyzed, and this is how optical aberrations of the wavefront are calculated.

Patients were examined under scotopic conditions. Afterward, another mydriasis examination was performed, which was achieved with the topical instillation of tropicamide. The optical aberrations considered for this study were the ones obtained within the central 4- and 6-mm diameters and all of them are expressed as root mean square data in µm. We used the following parameters to define the aberrations: total HOAs, third-order aberrations, fourth-order aberrations, trefoil, coma, tetrafoil, secondary astigmatism, and spherical aberration.

### Statistical analysis

Statistics were calculated with the SPSS software for Windows (SPSS Inc., Chicago, IL, USA). First, it was verified whether the sample adjusted to normality, and as it did not, Wilcoxon test for paired data was performed. Lineal regression analysis was performed afterward. Means and standard deviations were calculated for every variable. Figures were created with Microsoft Excel (Microsoft).

## Results

Sixty-six eyes of 33 patients implanted with the ZCB00 IOL were included in this study. Twelve were males and 21 were females. The mean age was 62.58 ± 6.97 years old, the mean AL was 23.35 ± 0.91 mm, and the mean power of the implanted IOL was 22.00 ± 2.62 D. At the baseline examination, the mean pupil diameter was 5.05 ± 0.88 mm, and under pharmacological mydriasis, it was 6.29 ± 0.84 mm.

Table 1 displays aberratometric outcomes considering a 4-mm pupil and Table 2 considering a 6-mm pupil. Statistically significant differences are highlighted in gray. Few differences were found in the 4-mm comparison but most of the aberrations differed in the 6-mm comparison. The values obtained under mydriasis were always lower or more negative than the ones at baseline. Figures 1 and 2 show these differences between both examinations.

Lineal regression analyses were performed between mean pupil size and the change between baseline and mydriatic examinations within the 6-mm analysis. No statistically significant result was obtained with corneal astigmatism or with corneal coma. As for the change in ocular total HOA, a moderate correlation was found (0.62, $P = 0.00$) with the regression line ocular total HOA change = 3.14 – 0.55 × pupil size shown in Figure 3. As for the change in internal total HOA, a moderate correlation was found (0.60, $P = 0.00$) with the regression line internal total HOA change = 3.18 – 0.57 × pupil size shown in Figure 4.

## Discussion

Pupil diameter is a key factor for quantitative evaluations of optical aberrations.[1,2] The larger a pupil is the more aberrations alter vision. This fact becomes quite relevant at night and that is why vision may decline more than expected in some cases.[7] In

**Table 1: Optical aberration outcomes in 4-mm pupil**

| Variable±SD | Ocular | | | Corneal | | | Internal | | |
|---|---|---|---|---|---|---|---|---|---|
| | Baseline | Tropicamide | *P* | Baseline | Tropicamide | *P* | Baseline | Tropicamide | *P* |
| Astigmatism (D) | −0.81±0.50 | −0.75±0.43 | 0.09 | −0.88±0.57 | −0.82±0.51 | 0.06 | −0.60±0.25 | −0.60±0.24 | 0.95 |
| Total HOA, (μm) | 0.16±0.08 | 0.15±0.05 | 0.22 | 0.19±0.11 | 0.18±0.07 | 0.60 | 0.12±0.05 | 0.12±0.04 | 0.53 |
| 3rd order (μm) | 0.14±0.07 | 0.14±0.05 | 0.47 | 0.16±0.11 | 0.16±0.07 | 0.84 | 0.09±0.05 | 0.09±0.05 | 0.56 |
| 4th order (μm) | 0.06±0.04 | 0.07±0.03 | 0.06 | 0.09±0.05 | 0.09±0.04 | 0.34 | 0.07±0.03 | 0.07±0.02 | 0.29 |
| Trefoil (μm) | 0.12±0.07 | 0.11±0.05 | 0.58 | 0.14±0.10 | 0.13±0.07 | 0.51 | 0.05±0.05 | 0.06±0.04 | 0.23 |
| Coma (μm) | 0.07±0.05 | 0.07±0.04 | 0.79 | 0.07±0.05 | 0.08±0.05 | 0.66 | 0.07±0.04 | 0.06±0.04 | 0.67 |
| Tetrafoil (μm) | 0.05±0.04 | 0.04±0.03 | 0.04 | 0.06±0.05 | 0.05±0.04 | 0.03 | 0.04±0.03 | 0.03±0.02 | 0.51 |
| Secondary astigmatism (μm) | 0.03±0.02 | 0.03±0.02 | 0.92 | 0.03±0.02 | 0.03±0.02 | 0.45 | 0.02±0.01 | 0.02±0.02 | 0.95 |
| Spherical aberration (μm) | 0.01±0.04 | 0.00±0.03 | 0.01 | 0.04±0.03 | 0.05±0.03 | 0.41 | −0.03±0.03 | −0.05±0.02 | <0.001 |

SD: Standard deviation, D: Diopters, HOA: High-order aberration

**Table 2: Optical aberration outcomes in 6-mm pupil**

| Variable±SD | Ocular | | | Corneal | | | Internal | | |
|---|---|---|---|---|---|---|---|---|---|
| | Baseline | Tropicamide | *P* | Baseline | Tropicamide | *P* | Baseline | Tropicamide | *P* |
| Astigmatism (D) | −1.00±0.77 | −0.71±0.44 | <0.001 | −0.63±0.37 | −0.56±0.33 | 0.01 | −0.81±0.70 | −0.51±0.30 | <0.001 |
| Total HOA (μm) | 0.94±0.83 | 0.59±0.29 | <0.001 | 0.60±0.34 | 0.57±0.23 | 0.66 | 0.81±0.91 | 0.51±0.28 | 0.03 |
| 3rd order (μm) | 0.59±0.50 | 0.44±0.21 | 0.01 | 0.40±0.24 | 0.39±0.16 | 0.68 | 0.45±0.57 | 0.30±0.23 | 0.06 |
| 4th order (μm) | 0.59±0.67 | 0.29±0.20 | <0.001 | 0.35±0.19 | 0.35±0.14 | 0.80 | 0.53±0.66 | 0.30±0.15 | 0.11 |
| Trefoil (μm) | 0.44±0.33 | 0.33±0.18 | 0.01 | 0.32±0.21 | 0.29±0.16 | 0.21 | 0.27±0.33 | 0.17±0.16 | 0.11 |
| Coma (μm) | 0.36±0.41 | 0.26±0.17 | 0.13 | 0.22±0.17 | 0.23±0.11 | 0.03 | 0.35±0.48 | 0.22±0.20 | 0.15 |
| Ocular tetrafoil (μm) | 0.31±0.34 | 0.17±0.12 | <0.001 | 0.18±0.17 | 0.17±0.15 | 0.52 | 0.28±0.36 | 0.14±0.13 | <0.001 |
| Secondary astigmatism (μm) | 0.25±0.33 | 0.15±0.12 | 0.04 | 0.11±0.13 | 0.10±0.08 | 0.72 | 0.24±0.36 | 0.12±0.12 | 0.07 |
| Spherical aberration (μm) | 0.33±0.55 | 0.11±0.19 | <0.001 | 0.24±0.13 | 0.26±0.09 | 0.34 | 0.10±0.56 | −0.15±0.16 | <0.001 |

SD: Standard deviation, D: Diopters, HOA: High-order aberration

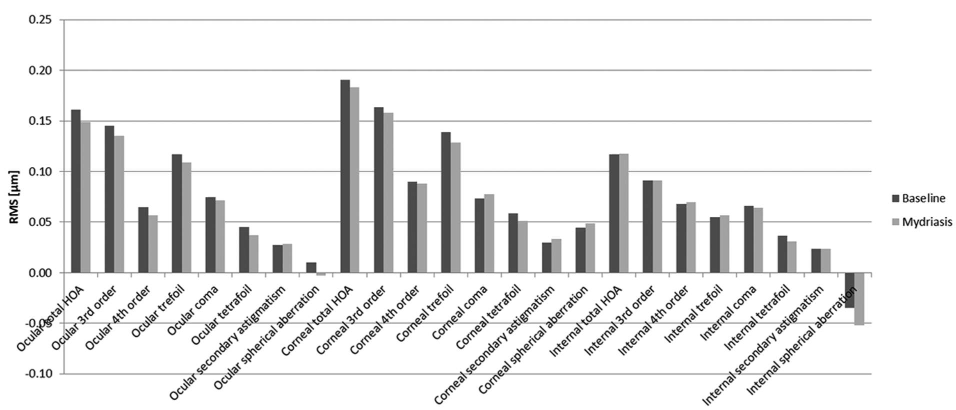


**Figure 1:** Optical aberrations in 4-mm pupil. HOA: High-order aberration, RMS: Root mean square

this study and as expected, optical aberrations increased with a larger analyzed pupil diameter. The outcomes in a 6-mm pupil were higher than in a 4-mm one.

As not all the patients may reach the established pupil diameter in the software analysis, it is important to know what happens in these cases. In addition, pharmacological mydriasis is not always an option because of the drug duration or because of a narrow anterior chamber. Our study is trying to assess the efficacy of the Hartmann–Shack technology in these cases. Including only patients implanted with the same monofocal IOL avoids any bias due to cataracts[8] or to the combination of a diffractive IOL and a device using infrared light.[9]

The KR-1W Wavefront Analyzer is an optical aberrometer whose repeatability and reproducibility have been proven[10-12] and its outcomes have been compared with other devices.[13] It provides reliable measurements but they should not be interchangeable between devices.[10,11,14] Its automated refractor is reliable despite cataracts or corneal refractive surgery.[15]

When considering a 4-mm pupil, aberrations did not differ too much from baseline to pharmacological mydriasis, although corneal tetrafoil and internal spherical aberration have significantly more negative values after dilation. Far more remarkable are the outcomes in 6-mm pupil, in which nearly all aberrations decreased significantly. It might be explained as

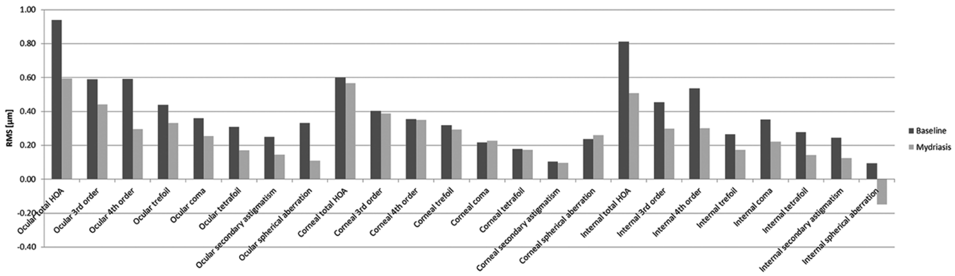


**Figure 2:** Optical aberrations in 6-mm pupil. HOA: High-order aberration, RMS: Root mean square

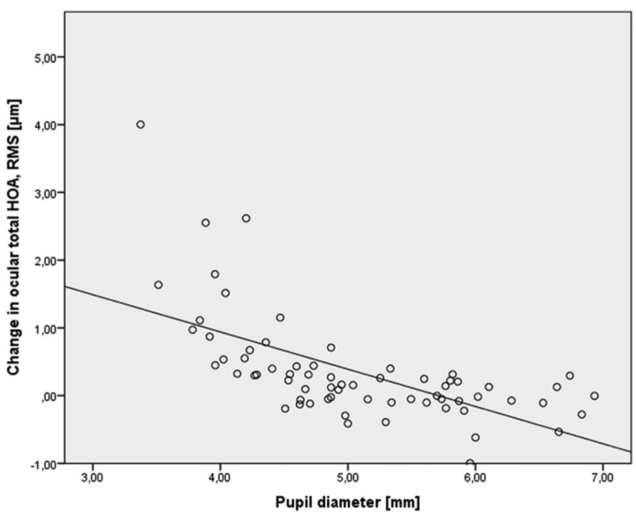


**Figure 3:** Regression line within 6-mm analysis between pupil diameter and the change in ocular total high-order aberration. RMS: Root mean square

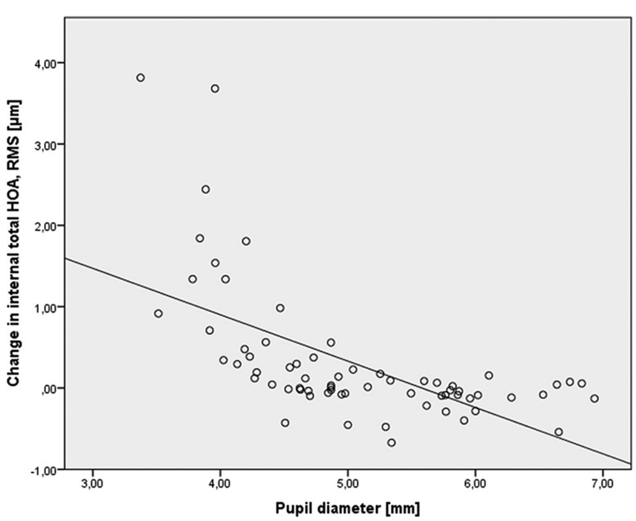


**Figure 4:** Regression line within 6-mm analysis between pupil diameter and the change in internal total high-order aberration. HOA: High-order aberration, RMS: Root mean square

a result of an accuracy loss of the software when it estimates aberrations in a pupil area covered by the iris. Nevertheless, corneal aberrations are also affected, although to a much lesser extent. If we examine these results in detail, we can see that differences have been found in ocular third, fourth, trefoil, and secondary astigmatism but not in their corneal or respective internal values. A possible explanation would be that despite laying beneath the cornea, the iris may affect all aberrometric measurements, and the way the internal software estimates those aberrations tends always to higher values than the real ones. Another explanation would be that all those points covered by the iris are taken as really highly aberrated, without making any estimation. These theories are supported by the positive correlation between pupil diameter and the difference in total ocular and internal HOA between the examinations in 4 and 6 mm pupils, which is shown in Figures 3 and 4.

The difference between 6 mm and the mean pupil diameter at the baseline examination is 0.95 mm, whereas the mean pupil size under tropicamide is larger than 6 mm. As for the evaluation in 4 mm, both examinations have always a diameter higher than those 4 mm. Thus, it is clearly noticed that the iris is responsible for these results. Hardly any differences were found in the 4-mm evaluation because the mean pupil diameter was higher all the time, and a great number of differences were found in the 6-mm evaluation because there was a difference of 0.95 mm between the baseline and the mydriatic examinations.

As far as we know, this is the first publication bringing out this event in any wavefront analyzer. The pupillary shift between photopic and scotopic conditions may be an underlying factor contributing to the differences we observed.[16] This would explain those differences found in the 4-mm analysis but the great disparity in the 6-mm analysis still remains unclear. Hao *et al*. reported higher internal HOA with the KR-1W than with the iTrace, which did not happen when evaluating corneal outcomes.[13] They attributed this event either to a difference in the algorithm locating the chief ray or to the different optical principles used. This chief ray is placed on the retina and all aberrations are calculated through the corneal center. Wu *et al*. investigated the relationship between the measured area of wavefront aberrations with this technology and ablation parameters and myopic laser refractive surgery.[17] They found that the measured pupil area was always smaller than the real pupil area, and therefore, aberrations were underestimated. Our investigation is just the opposite, when pupil size does not reach the analyzed size, it can be noticed that smaller or higher sizes affect Hartman–Shack wavefront aberrations measurements to a significant degree.

## Conclusion

In daily practice, this fact implies that real pupil size should always be checked before evaluating optical aberrations with Hartman–Shack sensors. Larger pupil sizes may imply higher aberrations than measured but in the case of smaller pupil sizes, real ocular, internal, and sometimes, corneal aberrations are more negative than measured.

Further research should be performed to assess whether this fact also occurs with other wavefront analyzers.

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### Conflicts of interest

There are no conflicts of interest.

## References

1. Petermeier K, Frank C, Gekeler F, Spitzer MS, Messias A, Szurman P. Influence of the pupil size on visual quality and spherical aberration after implantation of the Tecnis 1-piece intraocular lens. Br J Ophthalmol 2011;95:42-5.
2. McKelvie J, McArdle B, McGhee C. The influence of tilt, decentration, and pupil size on the higher-order aberration profile of aspheric intraocular lenses. Ophthalmology 2011;118:1724-31.
3. Rocha KM, Soriano ES, Chalita MR, Yamada AC, Bottós K, Bottós J, *et al.* Wavefront analysis and contrast sensitivity of aspheric and spherical intraocular lenses: A randomized prospective study. Am J Ophthalmol 2006;142:750-6.
4. Chen WR, Ye HH, Qian YY, Yang WH, Lin ZH. Comparison of higher-order aberrations and contrast sensitivity between Tecnis Z9001 and CeeOn 911A intraocular lenses: A prospective randomized study. Chin Med J (Engl) 2006;119:1779-84.
5. Iseli HP, Jankov M, Bueeler M, Wimmersberger Y, Seiler T, Mrochen M. Corneal and total wavefront aberrations in phakic and pseudophakic eyes after implantation of monofocal foldable intraocular lenses. J Cataract Refract Surg 2006;32:762-71.
6. McKelvie J, Ku JY, McArdle B, McGhee C. Wavefront aberrometry: Comparing and profiling higher-order aberrations produced by intraocular lenses *in vitro* using a physical model eye system and Hartman-Shack aberrometry. J Cataract Refract Surg 2009;35:547-55.
7. Campbell FW, Green DG. Optical and retinal factors affecting visual resolution. J Physiol 1965;181:576-93.
8. Wu CZ, Jin H, Shen ZN, Li YJ, Cui X. Wavefront aberrations and retinal image quality in different lenticular opacity types and densities. Sci Rep 2017;7:15247.
9. Vega F, Millán MS, Vila-Terricabras N, Alba-Bueno F. Visible versus near-infrared optical performance of diffractive multifocal intraocular lenses. Invest Ophthalmol Vis Sci 2015;56:7345-51.
10. Piñero DP, Juan JT, Alió JL. Intrasubject repeatability of internal aberrometry obtained with a new integrated aberrometer. J Refract Surg 2011;27:509-17.
11. López-Miguel A, Martínez-Almeida L, González-García MJ, Coco-Martín MB, Sobrado-Calvo P, Maldonado MJ. Precision of higher-order aberration measurements with a new Placido-disk topographer and Hartmann-shack wavefront sensor. J Cataract Refract Surg 2013;39:242-9.
12. Xu Z, Hua Y, Qiu W, Li G, Wu Q. Precision and agreement of higher order aberrations measured with ray tracing and Hartmann-shack aberrometers. BMC Ophthalmol 2018;18:18.
13. Hao J, Li L, Tian F, Zhang H. Comparison of two types of visual quality analyzer for the measurement of high order aberrations. Int J Ophthalmol 2016;9:292-7.
14. Hua Y, Xu Z, Qiu W, Wu Q. Precision (repeatability and reproducibility) and agreement of corneal power measurements obtained by Topcon KR-1W and iTrace. PLoS One 2016;11:e0147086.
15. Park JH, Kim MJ, Park JH, Song IS, Kim JY, Tchah H. Accuracy of an automated refractor using a Hartmann-shack sensor after corneal refractive surgery and cataract surgery. J Cataract Refract Surg 2015;41:1889-97.
16. Tabernero J, Atchison DA, Markwell EL. Aberrations and pupil location under corneal topography and Hartmann-shack illumination conditions. Invest Ophthalmol Vis Sci 2009;50:1964-70.
17. Wu Y, He JC, Zhou XT, Chu RY. A limitation of Hartmann-shack system in measuring wavefront aberrations for patients received laser refractive surgery. PLoS One 2015;10:e0117256.