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Wavefront Aberrations

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1. Introduction

The eye is an optical system having several optical elements that focus light rays representing images onto the retina. Imperfections in the components and materials in the eye may cause light rays to deviate from the desired path. These deviations, referred to as optical or wavefront aberrations, result in blurred images and decreased visual performance (1).

Wavefront aberrations are optical imperfections of the eye that prevent light from focusing perfectly on the retina, resulting in defects in the visual image. There are two kinds of aberrations:

1. Lower order aberrations (0, 1st and 2nd order)
2. Higher order aberrations (3rd, 4th, ... order)

Lower order aberrations are another way to describe refractive errors: myopia, hyperopia and astigmatism, correctible with glasses, contact lenses or refractive surgery. Lower order aberrations is a term used in wavefront technology to describe second-order Zernike polynomials. Second-order Zernike terms represent the conventional aberrations defocus (myopia, hyperopia and astigmatism). Lower order aberrations make up about 85 per cent of all aberrations in the eye.

Higher order aberrations are optical imperfections which cannot be corrected by any reliable means of present technology. All eyes have at least some degree of higher order aberrations. These aberrations are now more recognized because technology has been developed to diagnose them properly. Wavefront aberrometer is actually used to diagnose and measure higher order aberrations. Higher order aberrations is a term used to describe Zernike aberrations above second-order. Third-order Zernike terms are coma and trefoil. Fourth-order Zernike terms include spherical aberration, and so on. Higher order aberrations make up about 15 percent of the overall number of aberrations in an eye.

2. Myopia

Myopia (nearsightedness, shortsightedness) is a refractive error where parallel light rays coming from a distance after refraction through the cornea and lens focus before the retina in the vitreous body and mature behind the focus in the state of divergence generate on retina wasteful circles (Fig. 1 and 3). Because of this, the image that one sees is out of focus when looking at a distant object but comes into focus when looking at a close object. Therefore, shortsighted people cannot see clearly at a distance (2).

Myopia can be classified by cause, degree, clinical features and age of onset. By cause myopia can be: *axial myopia*, attributed to an increase in eyes axial length (more than 24 mm), and *refractive myopia*, attributed to the condition of refractive elements of the eye, like curvature myopia (increased curvature of cornea) or index myopia (variation in the index of refraction of one or more ocular media, like in nuclear cataract). By degree myopia can be: *low myopia* (-3.0 diopters or less), *medium myopia* (between -3.0 and -6.0 diopters), and *high myopia* (-6.0 diopters or more). By clinical features myopia can be: *simple myopia*, characterized by the eye being too long for its optical power or optically too powerful for its axial length, and *degenerative (malignant, pathological, progressive) myopia* characterized by expressed fundus changes (conus myopicus, staphyloma posticum, degeneratio chorioretinae peripherica, maculopathia) and associated with a high refractive error and subnormal visual acuity after correction. This form of myopia worsen progressively over time and can become complicated with retinal tear and retinal detachment. By age of onset myopia can be: *congenital myopia*, present at birth and persisting through infancy, *youth-onset myopia (school myopia)* with onset between around 5 years of age and physical maturity, *early adult-onset myopia* with onset after physical maturity and up to about 40 years of age, and *late adult-onset myopia* with onset after around 55 years of age due to changes in the nucleus of the crystalline lens (2,3,4,5,6).

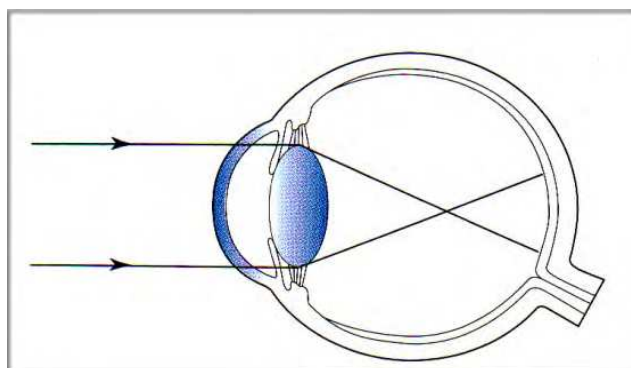


Fig. 1. Myopia with accommodation relaxed. Parallel light rays from infinity focus to a point anterior to the retina, forming a blurred image on the retina (6).

3. Hyperopia

Hyperopia (farsightedness, longsightedness) is a refractive error where parallel light rays coming from a distance after refraction through the cornea and lens focus behind the retina without participation of accommodation (Figs. 2 and 3). Causes of hyperopia are typically genetic and involve an eye that is too short or a cornea that is too flat, so that images focus at a point behind the retina (2).

Hyperopia can be classified by: cause, clinical features and accommodative status. By cause hyperopia can be: *axial hyperopia*, attributed to a decrease in eyes axial length (less than 24 mm), and *refractive hyperopia*, attributed to the condition of refractive elements of the eye like decreased curvature of cornea (cornea plana). By clinical features hyperopia can be: *simple*, *pathological* (resulting in amblyopia or strabismus), and *functional*. By accommodative status hyperopia can be: *total*, *latent*, and *manifest*. Total hyperopia occurs in state of full paralysis of accommodation (after application of cycloplegics) and represents the amount of entire refractive error. Latent hyperopia is that part of the refractive error being corrected with

accommodation. Manifest hyperopia is the accommodation uncorrected part of hyperopia and becoming closer to the total one with age (2,3,4,5,6).

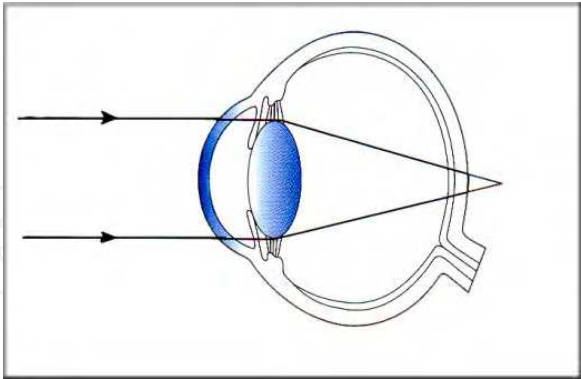


Fig. 2. Hyperopia with accommodation relaxed. Parallel light rays from infinity focus to a point posterior to the retina, forming a blurred image on the retina (6).

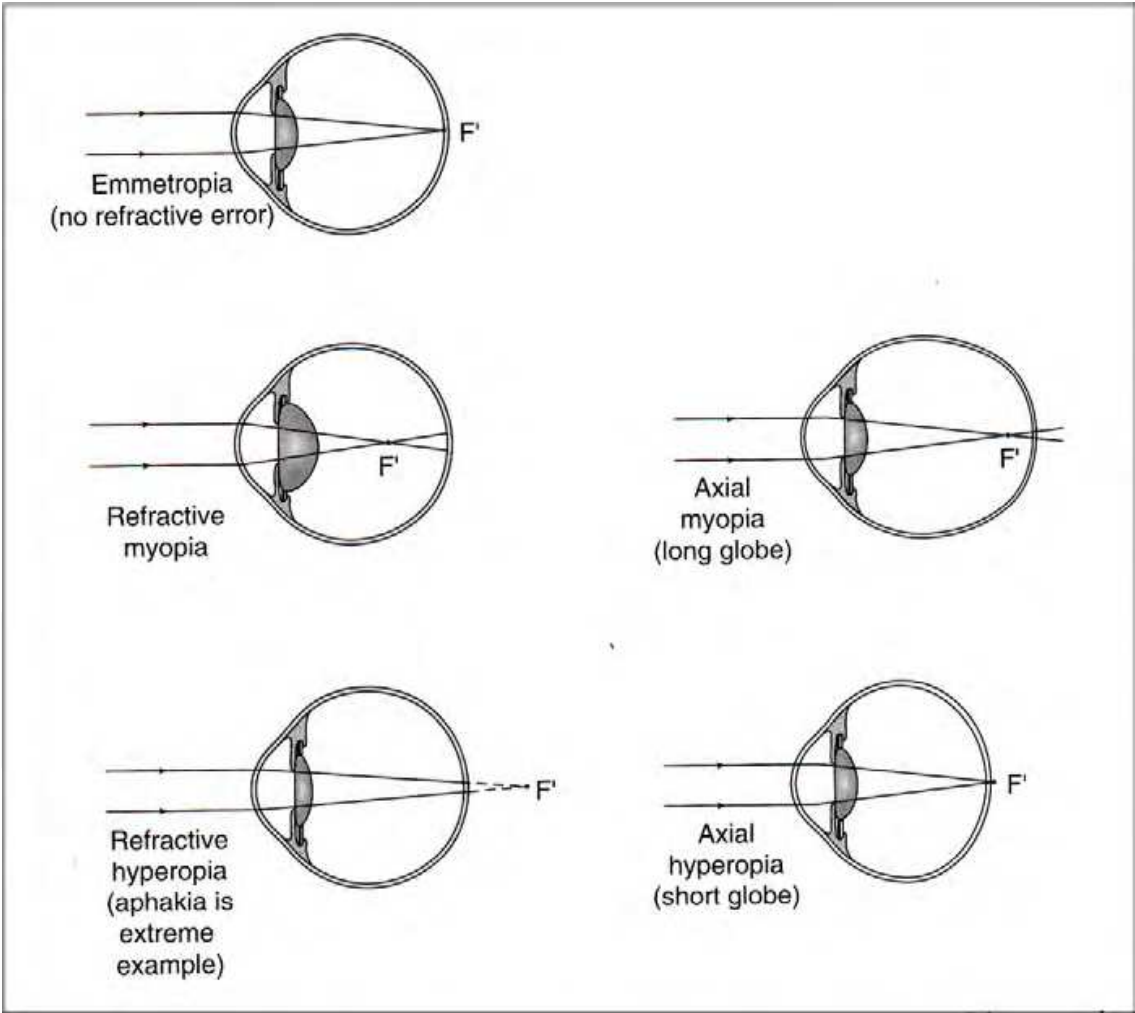


Fig. 3. Refractive errors (myopia and hyperopia) defined by the position of the secondary focal point with respect to the retina, with accommodation fully relaxed. The secondary focal point of a myopic eye is the front of the retina inside the vitreous, whereas the focal point of a hyperopic eye is behind the retina (7).

4. Astigmatism

Astigmatism is a refractive condition in which the eye optical system is incapable of forming a point image for a point object. This is because the refracting power of the optical system varies from one meridian to another. There are complex optical relationships in astigmatism: no focus (as in myopia and hyperopia), but the two focal lines corresponding to main meridians. The meridians of greatest and least refraction are defined as main (principal) meridians. Astigmatism is caused by the cornea or the crystalline lens. Clinically, most astigmatisms are corneal in origin and mainly related to the change in curvature of the cornea (3,4).

There are different types of astigmatism, according to the method of classification (2,3,4,5,6).

Astigmatism is *regular* when two main meridians are 90° to each other; it is correctable with cylindrical or spherocylindrical lenses. Otherwise, the astigmatism is *irregular*. Regular astigmatism is *with-the-rule (direct)* when the steepest corneal meridian is close to 90° ($\pm 20^\circ$) and *against-the-rule (indirect)* when the steepest meridian is close to 180° ($\pm 20^\circ$). When the astigmatism is regular but the main meridians do not lie close to 90° or 180° , it is *oblique*.

Astigmatic errors are also described by the location of secondary focal lines relative to the retina (with accommodation relaxed). *Compound myopic* astigmatism occurs when both of the main meridians are myopic, pulling the focal lines off the retina into the vitreous. In *simple myopic* astigmatism, one meridian is emmetropic and the other is myopic, one focal line is on the retina and the other is pulled into the vitreous. *Compound hyperopic* astigmatism occurs when both of the main meridians are hyperopic, pulling the focal lines behind the retina. In *simple hyperopic* astigmatism, one meridian is emmetropic and the other is hyperopic, one focal line is on the retina and the other is pulled behind the retina. *Mixed* astigmatism occurs when one meridian is hyperopic and the other is myopic (Fig. 4).

Astigmatism can be natural or surgically induced. *Natural* astigmatism is common, that is, around 15% of adult population have astigmatism $> 1D$ and 2% have astigmatism $> D$. Special group of astigmatisms are those surgically induced, *postoperative* astigmatisms. Any surgical intervention in the fibrous mantle of the eye (cornea, sclera) may result in major or minor postoperatively acquired astigmatisms. Classic and most common postoperative astigmatism occurs after cataract surgery, especially after extra- and intracapsular cataract extraction. It is very minimal after phacoemulsification (2).

As noted, the cornea is usually the source of clinically significant amounts of astigmatism. The amount of *corneal* astigmatism, along with the location of meridians of least and greatest refraction, can be easily determined with a keratometer. The vast majority of corneas have with-the-rule astigmatism; a small minority of corneas have against-the-rule or oblique astigmatism, and a small minority have no astigmatism. As compared to corneal astigmatism, *internal* astigmatism is relatively small in amount, tending to slightly vary from one person to another, and is almost always against-the-rule. Main causes of internal astigmatism are the toricity of the back surface of the cornea and the tilting of the crystalline lens. There is no clinical method of measuring internal astigmatism. *Refractive (total)* astigmatism includes both corneal and internal astigmatism and can be determined with refractometry (total determination of refraction) (3).

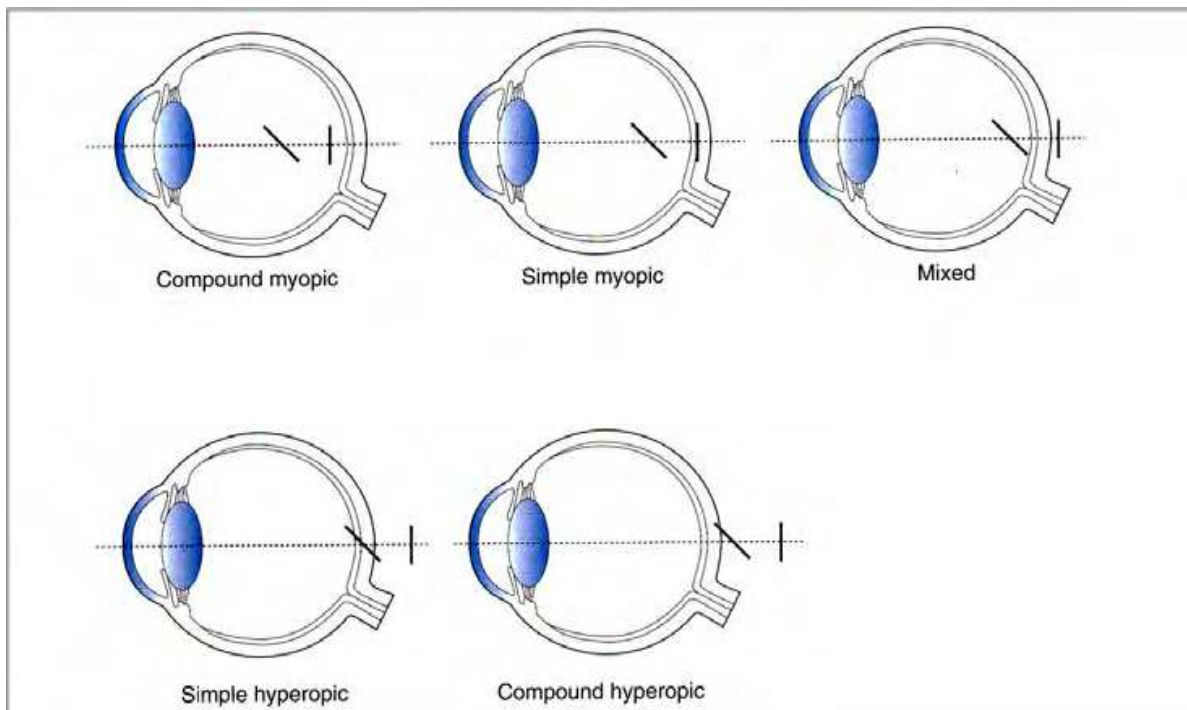


Fig. 4. The locations of focal lines with respect to the retina define the type of astigmatism (6).

5. Higher order aberrations (HOAs)

Within the past decade, rapid improvement in wavefront-related technologies, including the development of sensors for measuring optical properties of the eye in a clinical environment, allowed the ophthalmic community to move the wavefront theory of light transmission from an academic concept to one being central for better understanding of the effect of aberrations on visual performance and the corresponding image-forming properties of the eye. Imperfections in the optics of the eye are now measured and expressed as wave aberration errors. The wave aberration defines how the phase of light is affected as it passes through the eye's optical system, and is usually defined mathematically by a series of Zernike polynomials. Zernike polynomials are used to classify and represent optical aberrations because they consist of terms of same form as the types of aberrations observed when describing the optical properties of the eye, and can be used reciprocally with no misunderstanding. Moreover, the advantage of describing ocular aberrations using the normalized Zernike expansion, generally depicted as a pyramid (Figs. 5 and 6), is that the value of each mode represents the root mean square (RMS) wavefront error attributable to that mode. Coefficients with a higher value identify the modes (aberrations) that have the greatest impact on the overall RMS wavefront error in the eye and thus in reducing the optical performance of the eye (8).

The two most important HOAs are coma and spherical aberration. Coma is the distortion in image formation occurring when a bundle of light rays enters an optical system not parallel to the optic axis. Coma results in off-axis point sources such as stars appearing distorted, with a comet-like tail. Spherical aberration is the blurring of an image, occurring when light from the margin of a lens or mirror with spherical surface comes to a focus shorter than light from the central portion. The changing focal length is caused by deviations in lens or mirror surface from a true sphere.

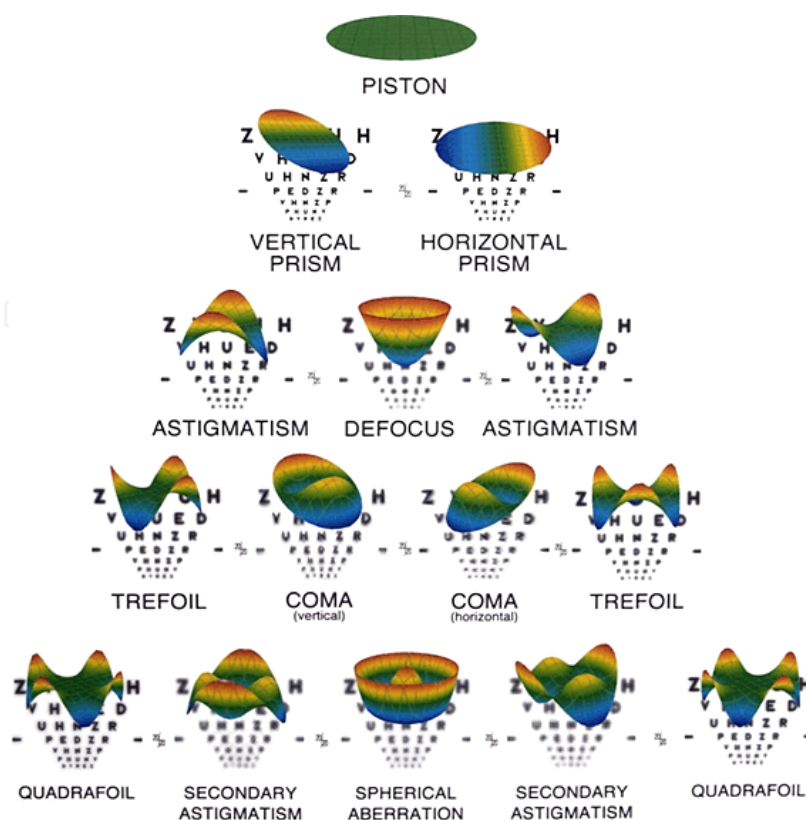


Fig. 5. This chart reveals more common shapes of aberrations created when a wavefront of light passes through eyes with imperfect vision. A theoretically perfect eye (top) is represented by an aberration-free flat plane known, for reference, as piston. (Image: Alcon Inc.)

HOAs are vision errors more complex than lower-order aberrations. HOAs have relatively unfamiliar names such as coma, spherical aberration and trefoil. These types of aberrations can produce vision errors such as difficulty seeing at night, glare, halos, blurring, starburst patterns or double vision (diplopia). No eye is perfect, which means that all eyes have at least some degree of HOAs. These aberrations are now more recognized because technology has been developed to diagnose them properly.

HOAs are measured by aberrometer (wavefront sensor). Aberrometers measure the distortion of a light wave as it is altered by passing through the optics of the eye. A plane wave of monochromatic light will be distorted by optical imperfections. Wavefront sensors do not measure light scatter (from stromal haze or corneal scars), chromatic aberrations or diffraction phenomena. Their effects on vision should be assessed by other means. A useful way to think of distortions in a wavefront is to think of the path length of parallel rays entering the pupil and projecting toward the retina. As light enters the eye from the air, its speed is retarded according to the refractive index of the material along its path to the retina. Arrival time is also influenced by the traveling distance. These two factors, refractive index and linear path variations, are measured with a wavefront sensor. A map can be made to show relevant retardation that a plane wave undergoes as it traverses the optics of the eye. Clinicians are now used to see this information displayed as Zernike polynomial expansion. In order to parcel the wavefront error into individual building blocks, a set of normalized Zernike polynomials is best fit to the measured wavefront error. The coefficient of each Zernike term reveals that term's relative contribution to the total root mean square (RMS) error (Fig. 7) (9).

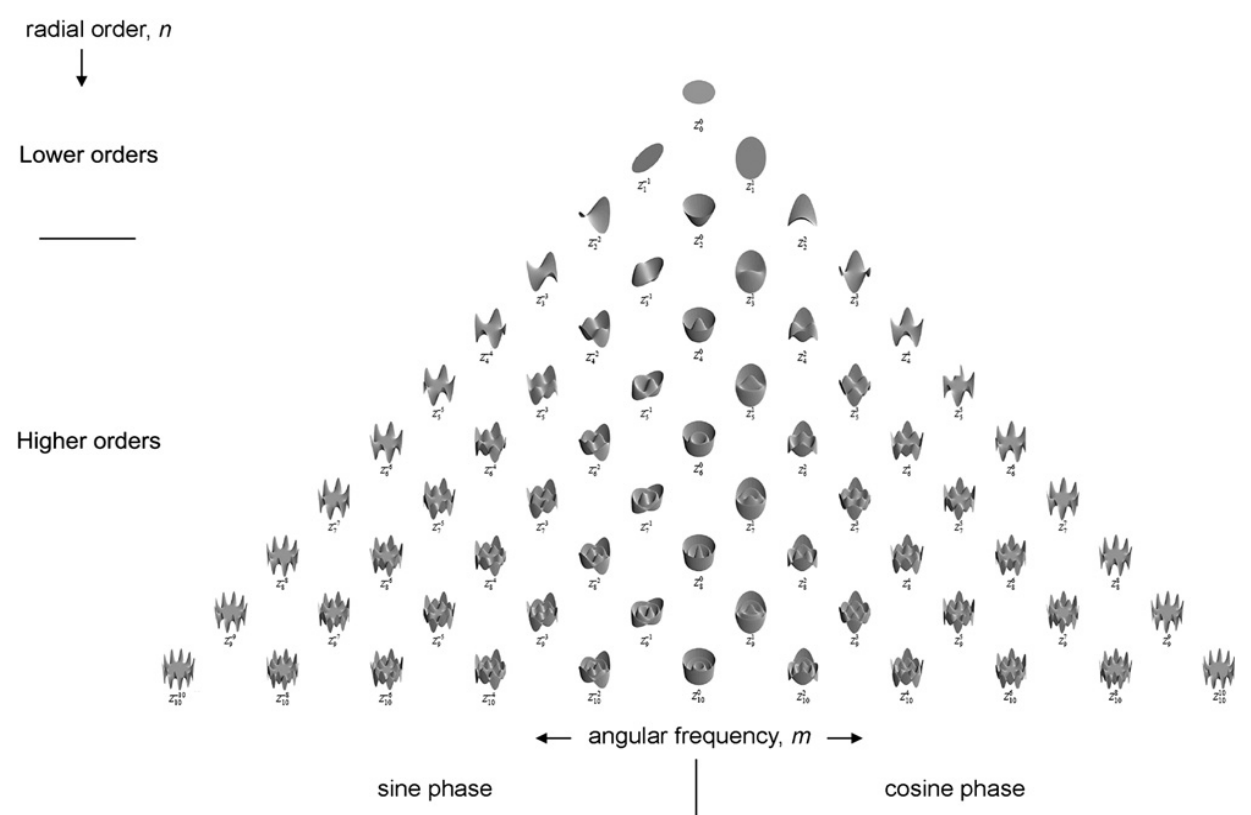


Fig. 6. The Zernike pyramid showing polynomials up to the 10th orders. The 0- to 2nd-order terms represent low optical aberrations in the eye, with 2nd-order terms (i.e. defocus and astigmatism) having the highest contribution to the overall wavefront aberration in the eye. Terms of the 3rd order and higher represent the HOAs. The 3rd- and 4th-order terms are the most prevalent HOA in the human eye (8).

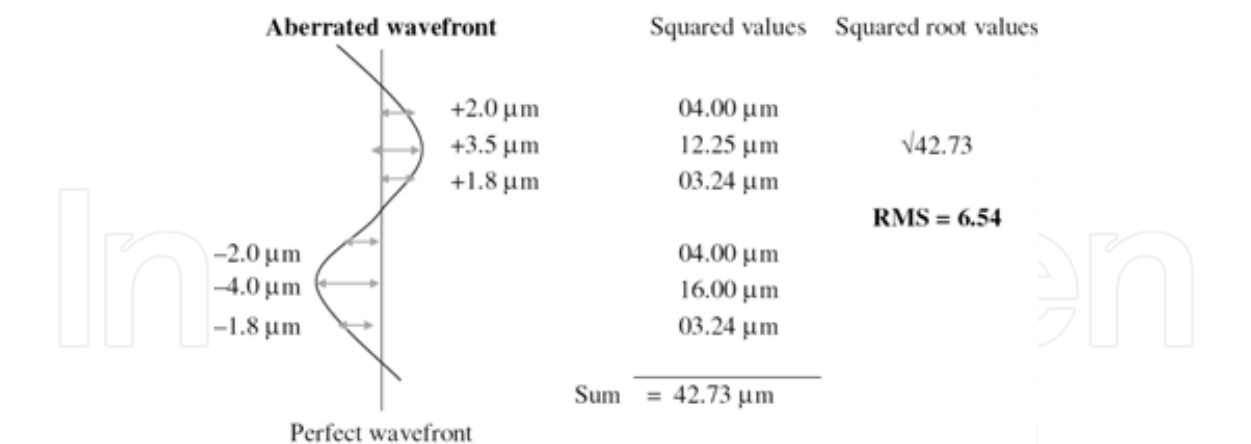


Fig. 7. Graphical representation of root mean squared wavefront error (9).

In the ametropic eye, defocus (i.e. myopia or hyperopia) is by far the largest aberration, followed by astigmatism. These are low order terms. The Zernike pyramid is useful (Table 1). As we follow down the rows from the top, we go from low order to high order. Low order encompasses the top three rows’ piston, tilt, tip, and sphere and astigmatism. Row three (i.e. sphere and astigmatism) is what we normally measure and prescribe in spectacles. The fourth row is called third order aberrations, and it continues from there. Anything

beyond lower order is lumped under the term of higher order aberrations (HOAs). As observed from the diagram, they have individual names such as coma, and spherical aberration. When interpreting data, we need to know whether the wavefront refers to total aberrations (9).

| Plot index | Term | Binomial representation | Polynomial (p,θ) |
|------------|-----------------------|-------------------------|---|
| 1 | Tip | (1,1) | $2p\sin(\theta)$ |
| 2 | Tilt | (1,1) | $2p\cos(\theta)$ |
| 3 | Defocus | (2,0) | $\sqrt{3} (2p^2 \angle 1)$ |
| 4 | Astigmatism | (2,2) | $\sqrt{6} p^2\sin(2\theta)$ |
| 5 | Astigmatism | (2,2) | $\sqrt{6} p^2\cos(2\theta)$ |
| 6 | Vertical coma | (3,1) | $\sqrt{8} (3p^3 \angle 2p)\sin(\theta)$ |
| 7 | Horizontal coma | (3,1) | $\sqrt{8} (3p^3 \angle 2p)\cos(\theta)$ |
| 8 | Trefoil | (3,3) | $\sqrt{8} p^3\sin(3\theta)$ |
| 9 | Trefoil | (3,3) | $\sqrt{8} p^3\cos(3\theta)$ |
| 10 | Spherical aberration | (4,0) | $\sqrt{5}(6p^4 \angle 6p^2 + 1)$ |
| 11 | Secondary astigmatism | (4,2) | $\sqrt{10} (4p^4 \angle 3p^2)\sin(2\theta)$ |
| 12 | Secondary astigmatism | (4,2) | $\sqrt{10} (4p^4 \angle 3p^2)\cos(2\theta)$ |
| 13 | Tetrafoil | (4,4) | $\sqrt{10} p^4\sin(4\theta)$ |
| 14 | Tetrafoil | (4,4) | $\sqrt{10} p^4\cos(4\theta)$ |

Table 1. Zernicke pyramid (9).

In the normal ametropic eye, HOAs are a relatively small component, comprising about 10% of eye’s overall aberrations. This varies between individuals. Figure 8a shows a 2-D wavefront of a normal ametropic eye with a low amount of HOAs (0.14μm), and Figure 8b shows a subtle form fruste keratoconic eye with a larger amount (0.42μm) of HOAs. Both images are for data at a 6 mm pupil size. It is important to know what the pupil size was when aberrometry was performed, and at what pupil size data was presented, as HOAs increase with increased pupil size (9).

Three different wavefront measuring principles are available to measure aberrations: (1) Hartmann-Shack, (2) Tscherning or ray tracing, and (3) automated retinoscopy. A Hartmann-Shack aberrometer is an outgoing wavefront aberrometer. It measures the shape of the wavefront that is reflected out of the eye from a point source on the fovea. An array of microlenslets is used to subdivide the outgoing wavefront into multiple beams which produce spot images on a video sensor. The displacement of each spot from the corresponding nonaberrated reference position is used to determine the shape of the wavefront. A Tscherning, or ray-tracing, aberrometer is an ingoing instrument. It projects a thin laser beam into the eye, parallel to the visual axis, and determines the location of the beam on the retina by using a photodetector. Once the position of the first light spot on the retina is determined, the laser beam is moved to a new position, and the location of the second light spot on the retina is determined. Aberrations in the optical system cause a shift in the location of the light spot on the retina. The third type, automated retinoscopy, is based on dynamic skiascopy. The retina is scanned with a slit-shaped light beam, and the reflected light is captured by an array of rotating photodetectors over a 360° area. The time difference of the reflected light is used to determine the aberrations. Visser et al. compared total ocular aberrations and corneal aberrations identified with four different aberrometers and

determined the repeatability and interobserver variability. In this prospective comparative study, 23 healthy subjects underwent bilateral examination with four aberrometers: the Irx3 (Hartmann-Shack; Imagine Eyes, Orsay, France), Keratron (Hartmann-Shack; Optikon, Rome, Italy), iTrace (raytracing; Tracey Technologies, Houston, TX), and OPD-Scan (Automated Retinoscopy; Nidek, Gamagori, Japan). Six images per eye were obtained. Second-, third- and fourth-order spherical aberrations were exported for 5.0-mm pupils. Results demonstrate that significant differences in measurements were found for several total ocular aberrations (defocus [2,0], astigmatism [2,2], trefoil [3,-3], trefoil [3,3], and spherical aberration [4,0]) and corneal aberrations (defocus [2,0] and astigmatism [2,2]).

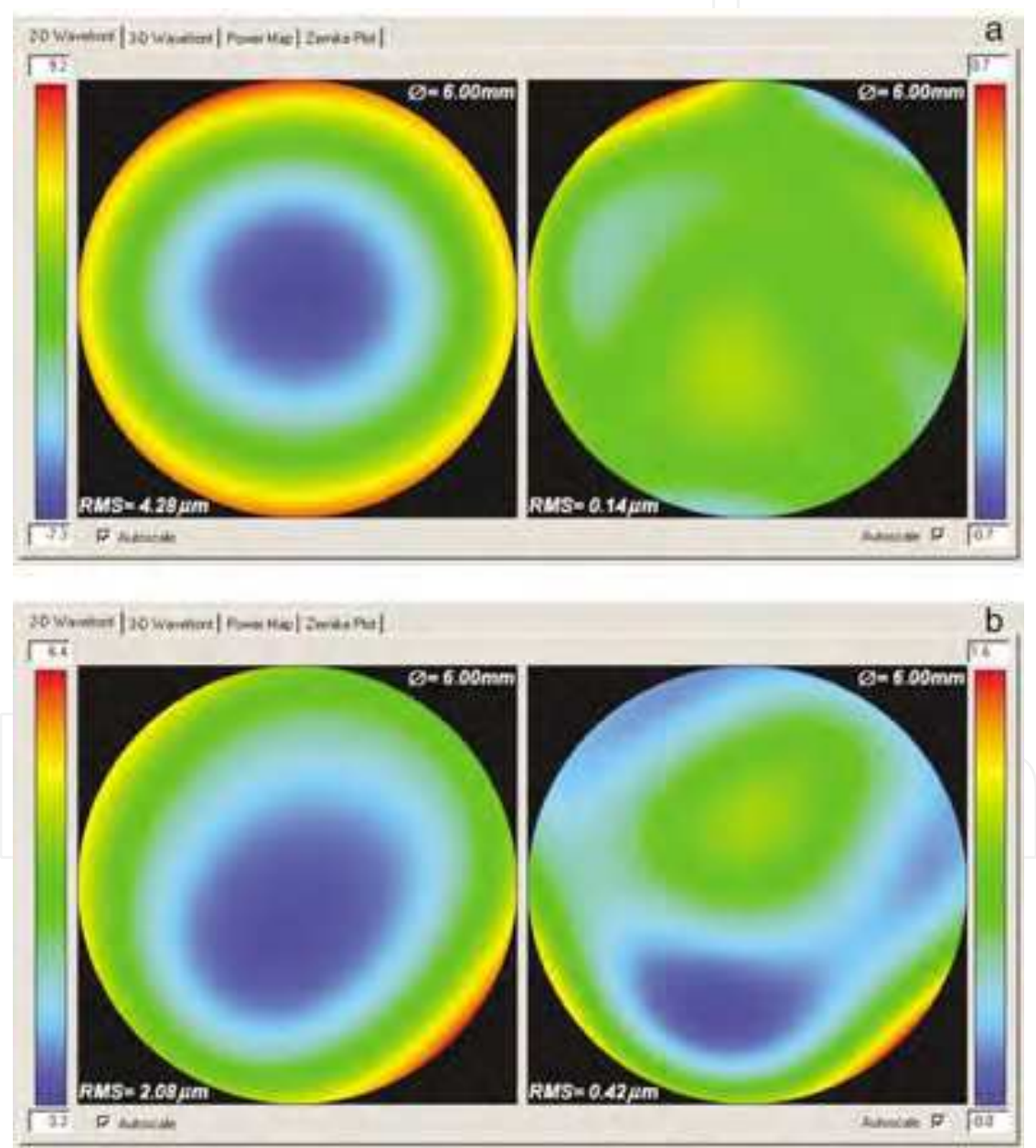


Fig. 8. HOAs represented by 2-D image: (a) eye with low degree, and (b) eye with high degree of HOAs (HOAs measured by Alcon LADARWave) (9).

The Irx3 showed the highest repeatability in measuring total ocular aberrations, followed by the Keratron, OPD-Scan, and iTrace. The repeatability of corneal aberration measurements was highest for the iTrace, followed by the Keratron and OPD-Scan. The OPD-Scan showed a lower interobserver variability, compared with the Irx3, Keratron, and iTrace. In conclusion, total ocular and corneal aberrations are not comparable when measured with different aberrometers. Hartmann-Shack aberrometers showed the best repeatability for total ocular aberrations, and iTrace for corneal aberrations (10).

In our clinic we use WaveLight Analyzer (WaveLight Germany) as aberrometer. Working in the same visible spectrum as the human eye, the WaveLight Analyzer is designed for wavefront measurements on the basis of the Tscherning principle. In order to perform measurements according to the Tscherning principle, an image of regular measurement spots is projected onto the retina and captured by a lightsensitive camera. The distortion of the light spots on the retina in relation to the reference light bundle is calculated and the wavefront error is displayed. Figure 9 shows HOAs in a male aged 32 with myopia on his left eye. Wavefront refraction: -6.54/-1.14 ax 72°, coma: 0.16µm, spherical aberration: 0.02 µm, and pupil diameter: 6.59 mm.

Can HOAs be corrected? Wavefront technology has been advanced enough only in the last few years to produce accurate measurements and diagnoses of HOAs. Some types of new wavefront designed glasses, contact lenses, intraocular lens implants and wavefront-guided laser vision correction can correct HOAs.

One of the most powerful clinical applications of aberrometry is wavefront-guided refractive surgery. With the development of wavefront analyses, the increase of the HOAs of the eye following conventional photorefractive keratectomy (PRK) has been confirmed (11). Wavefront-guided refractive surgery is a technique using excimer or other lasers to correct not only spherical and cylindrical refractive errors but also HOAs. Seiler et al. reported the first application of wavefront-guided laser *in situ* keratomileusis (LASIK) using a Tscherning aberrometer to measure the HOAs (12). McDonald performed almost simultaneously the first wavefront-guided LASIK using data obtained from the Hartmann-Shack wavefront sensor (13).

Several excimer laser platforms are available today. Although various terminology has been used to label, identify, and differentiate treatment modalities, the most commonly used include conventional laser *in situ* keratomileusis (LASIK); wavefront-guided treatments, which customize ablation patterns based on higher- and lower-order aberration profiles unique to the eye being treated; and wavefront-optimized treatments, which take some eye variables into account but use pre-programmed ablation profiles based on population analysis. Wavefront-guided treatments are intended to reduce preoperative HOAs, and wavefront-optimized treatments are intended to minimize the induction of postoperative HOAs; both modalities minimize significantly postoperative HOA changes compared with conventional LASIK treatments. There are some reported differences in the outcomes of wavefront-guided and wavefront-optimized platforms; however, few studies have directly compared the outcomes of these different technologies. The results in these studies are inconsistent, some indicating an advantage for wavefront-guided treatments and others finding no significant differences between the 2 treatment algorithms for patients without significant preoperative HOAs (14).

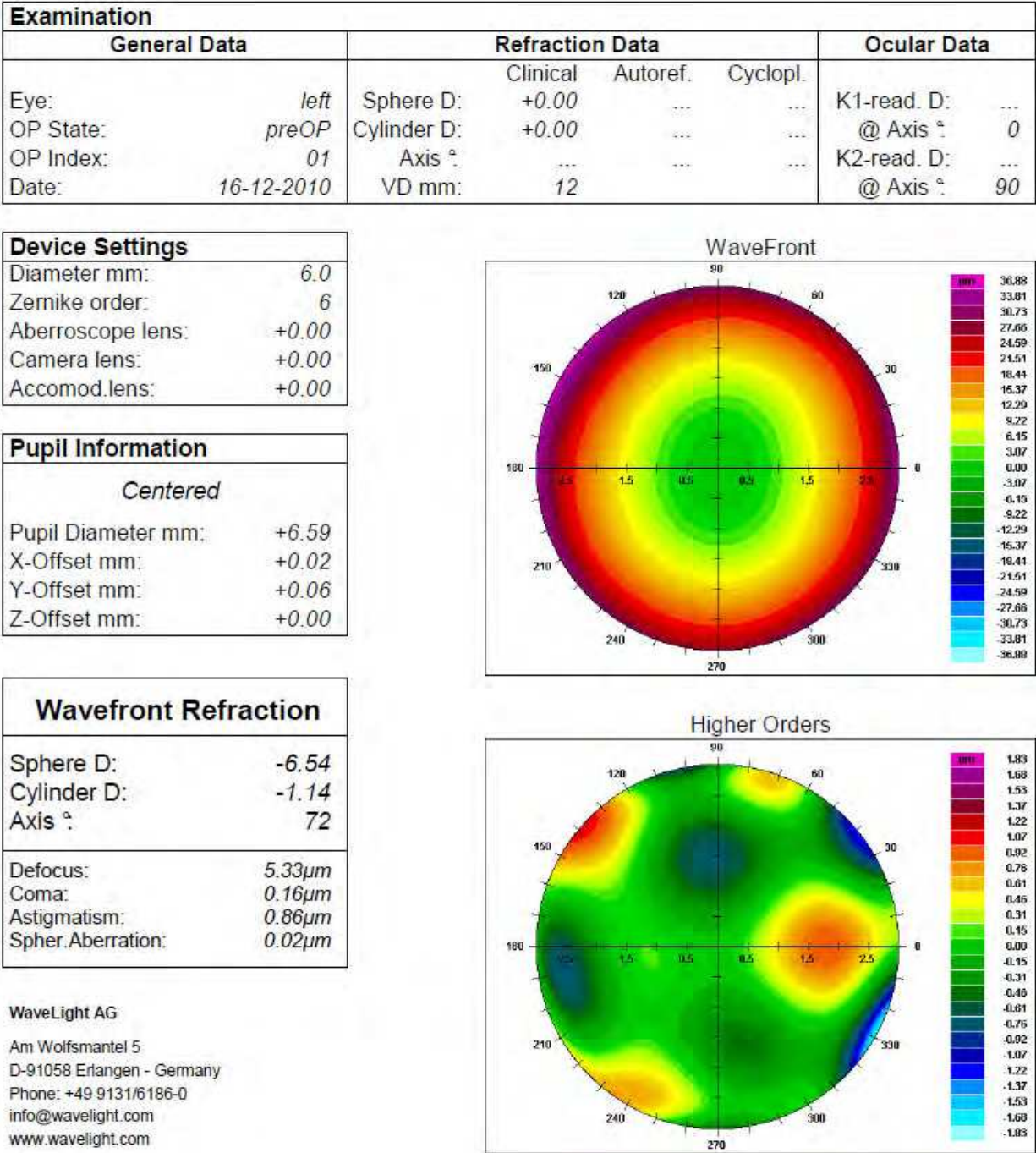


Fig. 9. Wavefront aberrations recorded on WaveLight Analyzer (WaveLight Germany).

Fares et al. compared the efficiency, predictability, safety, and induced HOAs between wavefront-guided and non-wavefront-guided ablations. Their meta-analysis showed that the increase in HOAs in patients who had wavefront-guided LASIK was lesser than in those who had non-wavefront-guided LASIK (15).

We experienced in our clinic that refractive surgical procedures (LASIK and PRK) induce HOAs and usually do not reduce visual acuity. Here is a brief overview of a case of increasing coma after successful correction of mild myopia using PRK: the patient was a male aged 27, and a PRK method was performed on his right eye with myopia. WaveLight Allegretto (400 Hz) excimer laser was used. HOAs were measured preoperatively and postoperatively on WaveLight Analyzer. Preoperative best spectacle corrected visual acuity of the right eye was with $-0.75/-0.25$ ax $134^{\circ} = 1.0$, and postoperative uncorrected visual acuity was 1.0. Optical zone of 6.5 mm and ablated zone of 9.0 mm were used. Coma was increased from $0.02\text{ }\mu\text{m}$ preoperatively to $0.15\text{ }\mu\text{m}$ postoperatively, and sperical aberration was the same ($0.08\text{ }\mu\text{m}$) (Figs. 10 and 11).

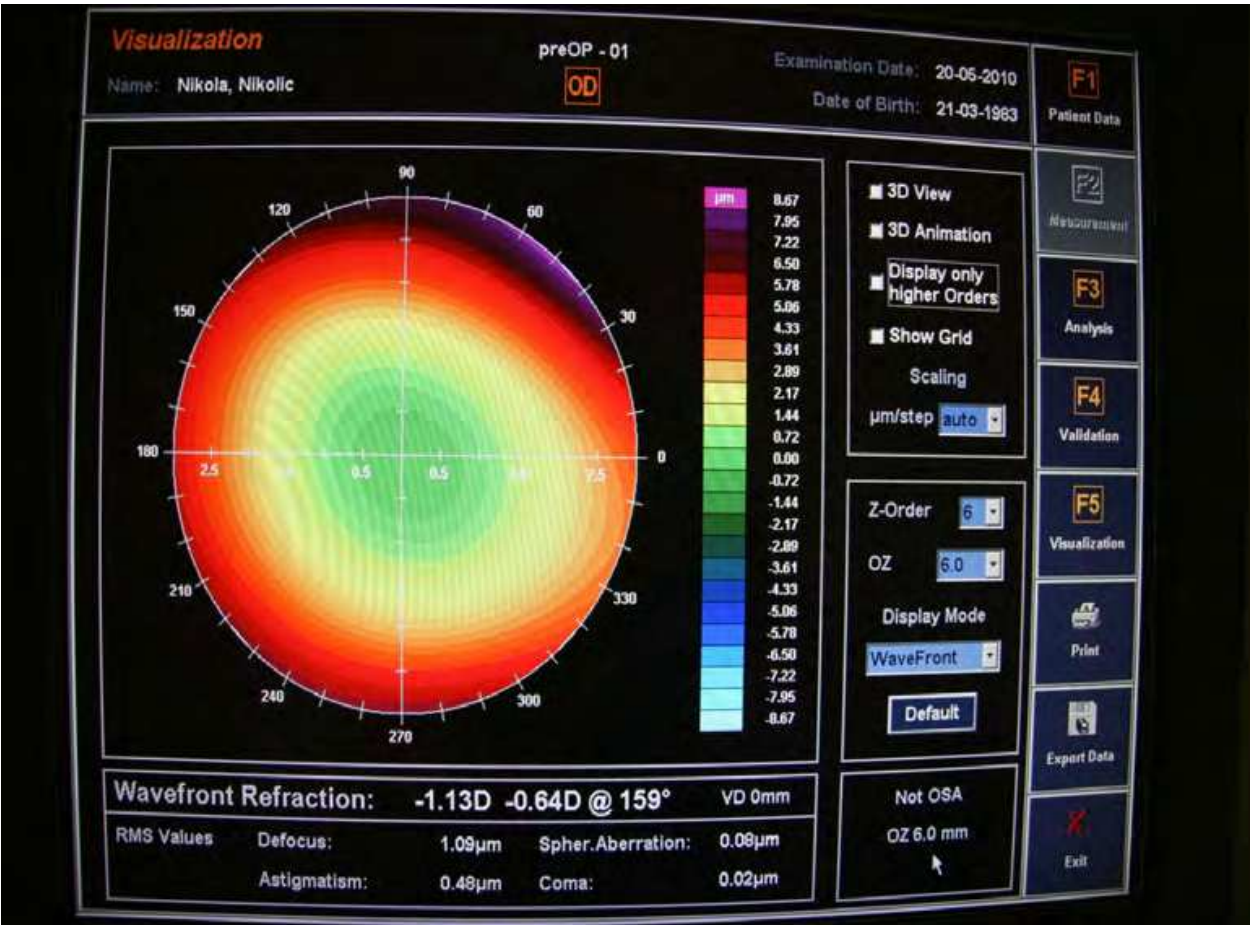


Fig. 10. Picture of wavefront aberrations preoperatively.

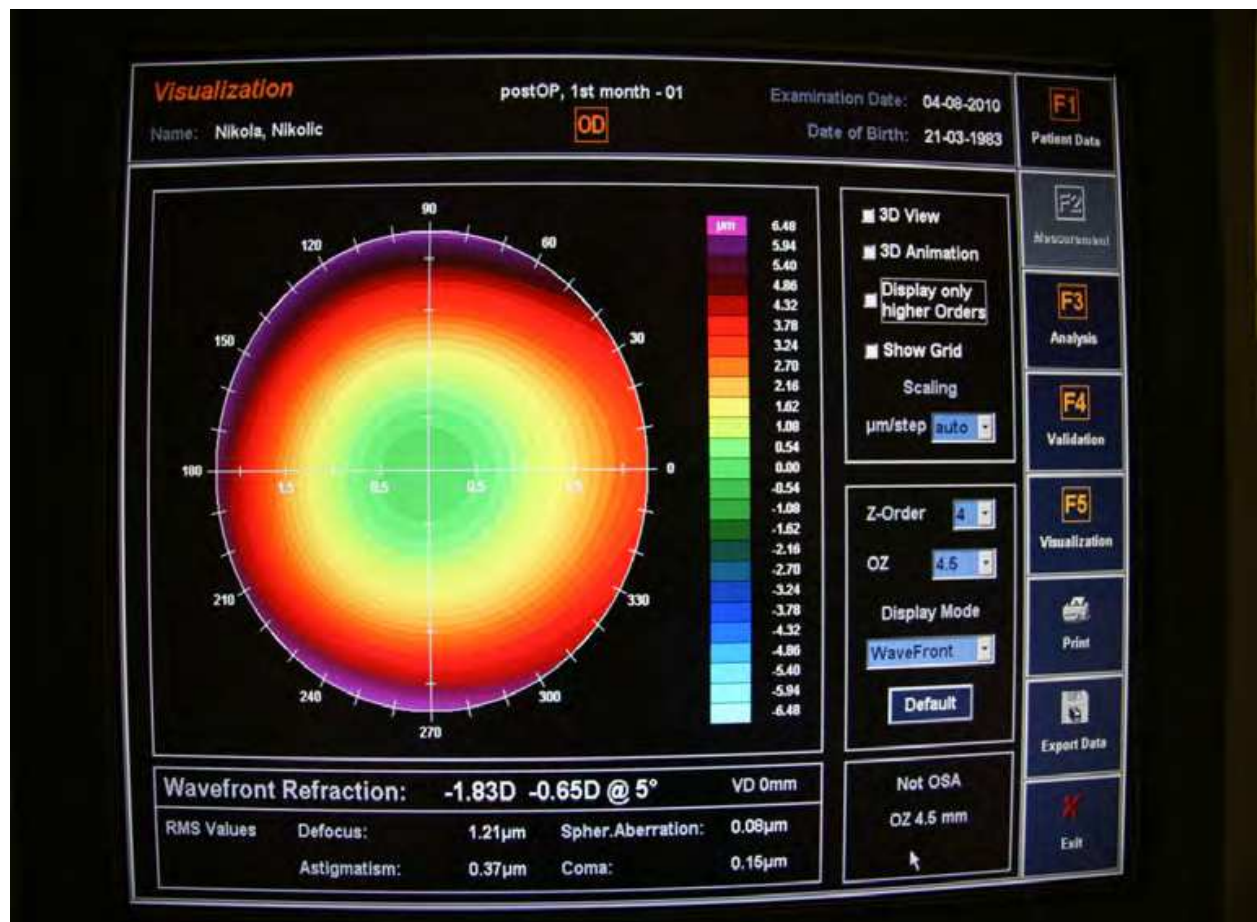


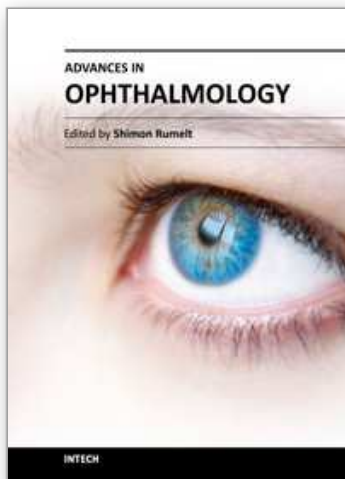
Fig. 11. Picture of wavefront aberrations postoperatively.

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Advances in Ophthalmology

Edited by Dr Shimon Rumelt

ISBN 978-953-51-0248-9

Hard cover, 568 pages

Publisher InTech

Published online 07, March, 2012

Published in print edition March, 2012

This book focuses on the different aspects of ophthalmology - the medical science of diagnosis and treatment of eye disorders. Ophthalmology is divided into various clinical subspecialties, such as cornea, cataract, glaucoma, uveitis, retina, neuro-ophthalmology, pediatric ophthalmology, oncology, pathology, and oculoplastics. This book incorporates new developments as well as future perspectives in ophthalmology and is a balanced product between covering a wide range of diseases and expedited publication. It is intended to be the appetizer for other books to follow. Ophthalmologists, researchers, specialists, trainees, and general practitioners with an interest in ophthalmology will find this book interesting and useful.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Mirko Resan, Miroslav Vukosavljević and Milorad Milivojević (2012). Wavefront Aberrations, Advances in Ophthalmology, Dr Shimon Rumelt (Ed.), ISBN: 978-953-51-0248-9, InTech, Available from: <http://www.intechopen.com/books/advances-in-ophthalmology/wavefront-aberrations>

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