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Mini Review

Advancements in Wavefront Aberrometry: Precision Measurement and Applications in Auto-Refractive Technologies

Ninos Georgios* and Vassiliades Panagiotis

Laboratory of Optical Metrology, Optics and Optometry Sector, Department of Biomedical Sciences, University of West Attica, Greece

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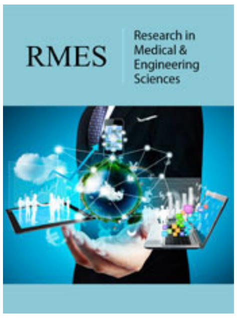

***Corresponding author:** Ninos Georgios, BSc (Phys.), MSc, PhD, Lecturer (Teaching), Optics and Optometry Sector, Department of Biomedical Sciences, University of West Attica, Greece, 28 Ag. Spyridonos str, 12243 Egaleo, Greece

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Abstract

The human eye's ability to form clear images on the retina can be compromised by aberrations arising from refractive errors such as myopia, hyperopia, and astigmatism. Wavefront aberrometry, facilitated by the Hartmann-Shack sensor, offers a promising solution for precisely measuring these aberrations. This sensor divides incoming light into multiple beamlets, enabling detailed assessment of aberrations through Zernike polynomials. Spherical aberrations, astigmatism, coma, and tilt are among the aberrations quantified by this method. The derived wavefront aberration coefficients inform the prescription of corrective lenses algorithmically. While wavefront aberrometry holds considerable potential for auto-refraction and initial eye examinations, its applicability may be limited in cases of highly distorted corneas, such as those found in keratoconus. High corneal curvature can lead to overlapping lighted spots on the sensor, potentially compromising accuracy. Nonetheless, advancements in technology promise enhanced processing power and detailed data representation, paving the way for the integration of wavefront aberrometry into modern auto-refractors. This abstract summarizes the principles of wavefront aberrometry, its potential applications, and considerations for its use in clinical practice.

Keywords: Wavefront Aberrometry; Auto-refraction; Hartmann-Shack sensor; Zernike polynomials; Refractive errors; Keratoconus; Corneal curvature; Aberrations; Lens prescription; Optical imaging

Abbreviations: CCD: Charge-Coupled Device; HOA: Higher Order Aberrations; HS: Hartmann-Shack; IOL: Intraocular Lens; ISO: International Organization for Standardization; LCD: Liquid Crystal Display; Z0-Z8: Zernike Polynomials Terms 0 to 8

Introduction

Human eye aberrations, including myopia, hyperopia, and astigmatism, challenge visual acuity and necessitate precise measurement for effective correction. Wavefront aberrometry, leveraging the Hartmann-Shack sensor, offers unprecedented precision in characterizing ocular aberrations through Zernike polynomials analysis [1,2]. This technology holds immense promise in revolutionizing auto- refraction and enhancing clinical decision-making in ophthalmology. By providing detailed insights into refractive status and guiding tailored lens prescriptions, wavefront aberrometry is poised to advance patient care significantly. This review aims to comprehensively explore the principles, applications, and implications of wavefront aberrometry in ocular diagnostics and treatment planning, emphasizing its significance in addressing refractive errors and improving visual outcomes.

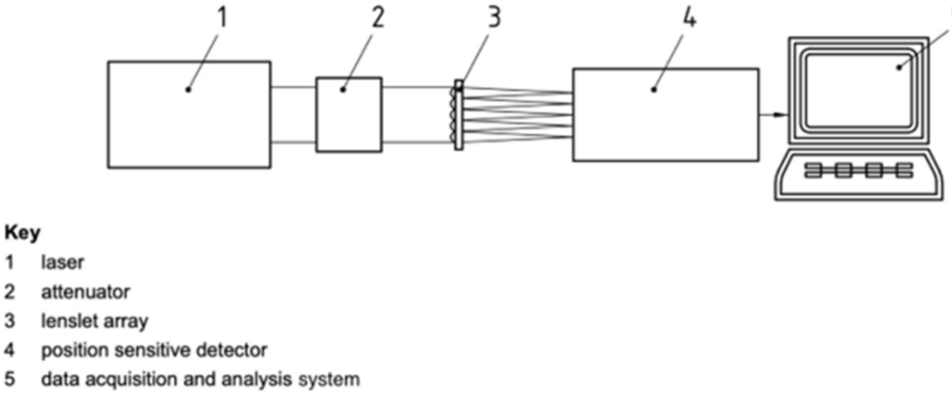
Discussion

The human eye

The human eye is designed to Forman image on the retina formed by the light rays which reach the eye from the outside. In order for the light to reach the retina it passes through multiple mediums where the light gets refracted. Except for the change of mediums, the light gets also refracted by the cornea and the IOL which both have their refractive power. Thus, it is perceived that the light can be aberrated in the process of refraction causing considerable image degradations [3]. If no geometrical aberrations occur the human eye is emmetrope and the light rays are converging on the retina. Otherwise, refractive errors result from the occurring aberrations like myopia, hyperopia and astigmatism.

Wavefront aberrometry

The Hartmann-Shack sensor: The Hartmann-Shack (HS) sensor, initially developed by Hartmann in 1900 and improved by Shack in 1971, measures aberrations by dividing the incoming light beam which reaches the setup into multiple beamlets using a lens let or micro-lens array [4,5]. The sensor comprises a lens let array, a positive sensor detector and a computer with a frame grabber which collects the data and processes data. The consists of a CCD or LCD panel which collects the light rays. The computer then receives an image of a black background and multiple light (white) spots. By assessing the size of the spots and the pixel gradient an initial calculation of Zernike polynomials can be performed (Figure 1) [5].



Key
1 laser
2 attenuator
3 lenslet array
4 position sensitive detector
5 data acquisition and analysis system

Figure 1: Shack-Hartmann sensor setup according to ISO 15367-2-2005 [5].

Aberrations calculation: Spherical aberrations can be calculated using term #8 which represents third-order spherical and focus while astigmatism is represented by terms #4 and #5. Terms #6 and #7 correspond to coma and tilt. First- order wavefront properties and third-order wavefront aberration coefficients are derived from the Zernike polynomial coefficients using the first nine Zernike terms Z_0 to Z_8. The aberrations and properties corresponding to these Zernike terms are shown in Table 1. This table lists the Zernike polynomial terms (Z_0-Z_8) and their corresponding aberrations, including piston, tilt, focus, astigmatism, coma, and spherical aberration. The power of the corrective lens pre-scripted in diopters both for sphere and cylinder can be calculated algorithmically using the first and third order Zernike polynomials [6,7].

Table 1: Z_0-Z_8: Zernike Polynomials Terms 0 to 8.

Aberrations Corresponding to the First Nine Zernike Terms	
Z_0	piston
Z_1	x-tilt
Z_2	y-tilt
Z_3	focus
Z_4	astigmatism @ 0° & focus
Z_5	astigmatism @ 45° & focus
Z_6	coma & x-tilt
Z_7	coma & y-tilt
Z_8	spherical & focus

Whilst younger patients tend to get measured with insignificant HOA, corneal aberrations and lower order aberrations are oftenly occuring, indicating refractive errors. HOA measuring can provide valuable insights into various conditions [8]. These include dry eye syndrome, pellucid marginal corneal degeneration and keratoconus, lenticonus and cataracts. Additionally, HOA measurements can assess the eye's condition after refractive surgery, orthokeratology, or IOL replacement [9].

Conclusion

The application of Hartmann-Shack sensor principles in wavefront aberrometry for auto-refraction shows great promise. Advances in technology provide tools with greater processing power and detailed sensor accumulated light data representation, suggesting that current autorefractors could be replaced by modern devices utilizing wavefront aberrometry for initial eye examinations and lens prescriptions [5,6].

However, while wavefront aberrometry is suitable for healthy eyes and normal corneas as an auto refracting method, it may not be as effective for highly distorted corneas, such as those with keratoconus. High corneal curvature can produce sensor images with overlapping light spots, leading to inaccurate measurements [8,9].

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