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Wavefront Technology- Applications in Ophthalmology

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ABSTRACT *A wavefront is defined as a locus of points that connect all the rays of light emanating from a point source that have the same temporal phase and optical path. Wavefront technology can be used in correcting aberrations of human eye and it has also got wide applications in astrophysics. Recent methods of refractive corneal surgeries like conventional Laser assisted in situ keratomileusis(LASIK) induces higher order aberrations(HOAs) compromising quality of vision of the patients. Wavefront guided laser ablations using Hartmann Shack's principle are shown to reduce HOAs in these patients. In addition to these, wavefront technology is emerging very rapidly as an extensive diagnostic modality for various clinical conditions like Keratoconus, Cataract, Glaucoma and Retinal disorders.*

Introduction:
The human eye, one of the most exquisitely constructed organs in all of nature, transmits information from the surrounding world to the brain by sensing the intensity and colour of the light. It is observed that optical system of the eye in human beings at many a times is not perfect. The imperfections of the optical system, because of faulty optics, are called as aberrations. Wavefront aberrations may be Lower order (LOA - defocus or astigmatism) or Higher order (HOA-coma, trefoil and spherical aberration). The LOA aberrations constitute about 90% of all aberrations of the human eye.[1] Therefore, images formed on the retina are blurred, resulting in degradation in visual performance. In routine clinical practice there is no method to detect and correct higher order aberrations, though lower order aberrations like astigmatism can be detected and corrected clinically.

Recently number of patients undergoing conventional LASIK surgery has increased. These LASIK surgeries give the quantitative vision, but the quality of vision is hampered because of iatrogenic induction of HOAs including root mean square (RMS) error, increased total HOAs, coma and spherical aberrations.[2,3] In order to overcome this problem of HOAs, recent technology of wavefront analysis is being incorporated in latest methods of LASIK surgeries. After analyzing the wavefront, cornea undergoes customized ablation by LASIK. Studies indicated wavefront optimized excimer laser ablations did not induce significant objective or subjective HOAs after LASIK or Photorefractive Keratectomy(PRK).[3]

Similar imperfections are observed in astrophysics when distant galaxies are observed through the earth based telescopes. They are mainly because of fluctuations in the refractive index of the atmosphere (changes in temperature, pressure etc.) and imperfections in the optical system of telescope. The use of wavefront technology was basically started in astrophysics. Above mentioned imperfections in the optical system of the eye or telescope can be measured by a technique called aberrometry. Aberrometry is based on principle of wavefront technology. The branch of physics which deals with this technology is called adaptive optics. Adaptive Optics (AO) is an emerging branch of optics wherein the optics modifies itself to changing environmental conditions to provide high resolution imagery. Recent developments in adaptive optics aid to analyse the wavefront in details by the development of wavefront sensors which then can be used effectively to rectify the aberrations. Aberration free optical systems greatly enhance the quality of resolution of the images.[4] The current paper aims at highlighting basics of wavefront technology in correcting optical errors of human eye as well as other optical systems.

Wavefront: In physics, a wavefront is the locus of points having the same phase: a line or curve in 2d, or a surface for a wave propagating in 3d.

Spherical Wavefront: Wavefronts emerging from a point source(S) are always spherical (divergent) as shown in fig.1a, and after being transformed by the stigmatic optical system, converging wavefronts are again spherical, but now centered around the image point. (fig. 1b) [5]. A lens can be used to change the shape of wavefronts. Here, plane wavefronts become spherical after going through the lens. Figure 1 about here,

Fig.1a - Spherical Wavefront

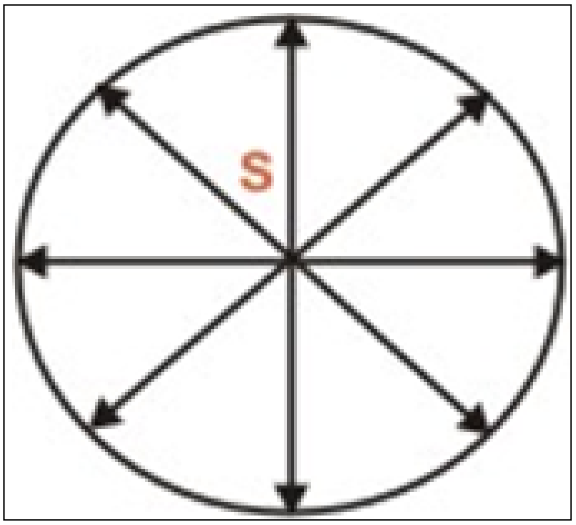

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Fig.1b - Wavefront after being transformed by the stigmatic optical system

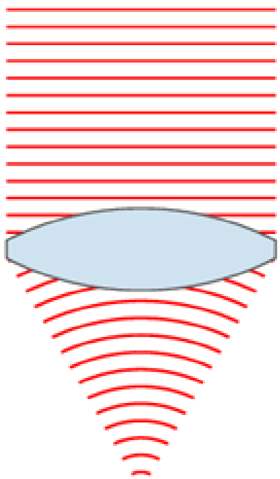


Fig.1c - Plane Wavefront

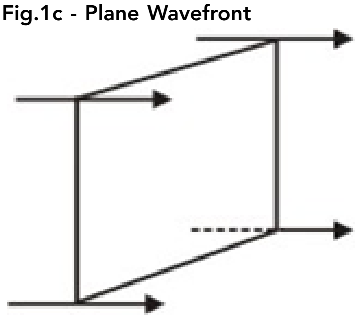
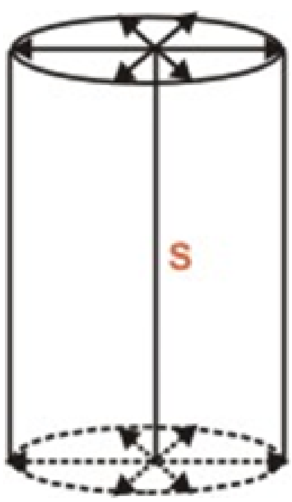


Fig.1d - Cylindrical Wavefront



Plane Wavefront: At a large distance from a source of any kind, the wavefront will appear plane as shown in figure 1c. Such a wavefront is called plane wavefront.

Cylindrical Wavefront: When the source of light is linear, all the points equidistant from the linear source lie on the surface of a cylinder as shown in figure 1d. Such a wavefront is called a cylindrical wavefront.

Simple wavefronts and propagation –Huygens Principle: Huygens wave theory is based on a geometrical construction that allows us to tell where a given wavefront will be at any time in the future if we know its present position. This construction is based on Huygens principle, which states that all points on a wavefront serve as point sources of spherical secondary wavelets. After a time t, the new position of the wavefront will be that of a surface tangent to these secondary wavelets.[6]

The simplest form of a wavefront is the plane wave, where the rays are parallel to one another. The light from this type of wave is referred to as collimated light. The plane wavefront is a good model for a surface-section of a very large spherical wavefront. For instance, sunlight strikes the earth with a spherical wavefront that has a radius of about 150 million kilometers (1 AU). For many purposes, such a wavefront can be considered planar.

Wavefront aberrations: Methods utilizing wavefront measurements or predictions can be considered an advanced approach to lens optics, where a single focal distance may not exist due to lens thickness or imperfections. Also for manufacturing reasons, a perfect lens has a spherical (or toroidal) surface shape though, theoretically the ideal surface would be aspheric. Shortcomings such as these in an optical system cause what are called optical aberrations. The best-known aberrations include spherical aberration and coma. However there may be more complex sources of aberrations such as in a large telescope due to spatial variations in the index of refraction of the atmosphere. The deviation of a wavefront in an optical system from a desired perfect planar wavefront is called the wavefront aberration. Wavefront aberrations are usually described as either a sampled image or a collection of two-dimensional polynomial terms e.g. Zernike polynomials. Minimization of these aberrations is considered desirable for many applications in optical systems.

The figure 2 below shows differently shaped wave-fronts leaving three types of eyes: myopic, hyperopic, and emmetropic. This is simply an alternate view of common eye aberrations, which are usually explained by drawing paraxial rays from outside to inside the eye. Here a point light source directed at the retina generates a spherical wavefront which leaves the eye. Because the emmetropic eye is a "perfect" optical system its refractive power is such that a spherical wave-front leaves the eye paraxially, i.e., in the form of a plane wave. The myopic eye has a "stronger" than necessary optical power so light rays leave the eye in converging manner. The opposite happens with the hyperopic eye, which refracts light less than necessary. [7]

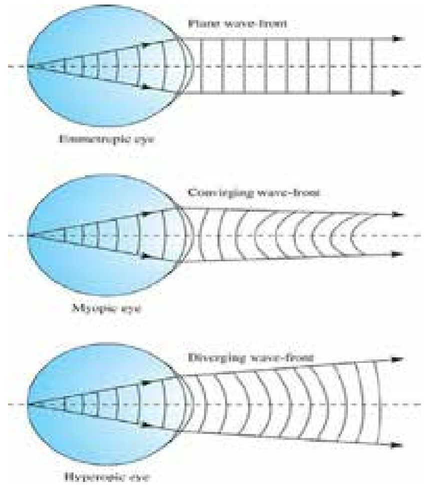


Fig. 2 - An alternate view of common eye aberrations

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In normal population, the dominant aberrations are the ordinary second-order sphero-cylindrical focus errors which are called refractive errors. Higher order aberrations are a relatively small component comprising about 10% of the eye's total aberrations, they increase with age and mirror symmetry exists between right and left eyes.

Wavefront sensor and reconstruction techniques –Shack –Hartmann Principle

A wavefront sensor is a device which measures the wavefront aberration in a coherent signal, to describe the optical quality or lack thereof in an optical system. A very common method is to use a Hartmann-Shack lenslet array.

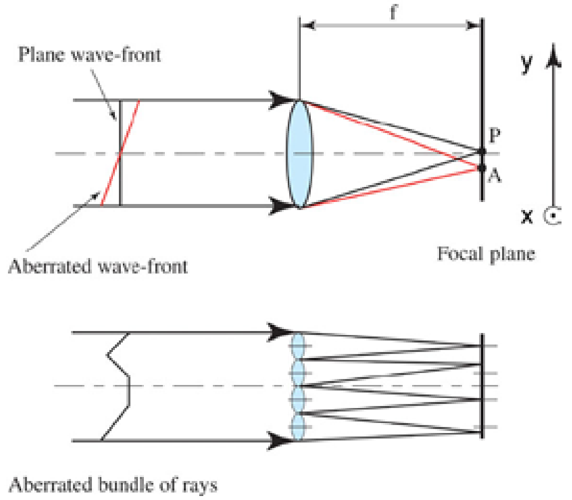

Fig. 3 - Principle of the Hartmann-Shack (HS) sensor

Principle of the Hartmann-Shack (HS) sensor (figure 3)- A plane wavefront hits a single micro-lens and focuses at a point P located over the optical axis and at a distance f from the lens; for the same micro-lens an aberrated wave-front focuses at point A, also on the focal plane but shifted away from the optical axis. Figure 3 lower diagram - For a set of micro-lenses, an aberrated wave-front will focus on unevenly spaced points (shifted away from the optical axis of each micro-lens) over the focal plane. It is the quantification of the individual shifts that allows one to determine the local slopes of the wave-front and then, from this information, retrieve the entire wave-front surface. The x,y arrows to the right of the upper diagram show the coordinate system directions.[7] It is believed that this is the most effective instrument for the measurement of human eye aberrations.[8]

Application of wavefront technology in corneal refractive surgery using Hartmann-Shack aberrometry: One of the most powerful clinical applications of aberrometry is wavefront guided refractive surgery. In 2002, the FDA approved the first wavefront-guided custom LASIK application. Today, there are many integrated wavefront-guided LASIK systems that first generate a wavefront map of a patient's unique optical imperfections and then send this information to an excimer laser that performs the custom LASIK procedure.

Wavefront analysis is a useful diagnostic tool, and wavefront based corneal surgery is an improvement over conventional techniques. Its use by an ophthalmologist is a clinical decision specific to an individual patient.[9] A low-power 1 mm laser beam is directed at the retina of the eye by means of a half silvered mirror. The retinal image of that laser now serves as a point source of light. From its reflection, a wavefront emanates and then moves towards the front of the eye. The wavewfront passes through the eye's internal optical structures, past the pupil, and eventually out of the eye. The wavefront then goes through a Shack-Hartmann lenslet array to focus the wavefront onto CCD array, which records it. The output from the Shack-Hartmann sensor is an image of bright points where each lenslet has focused the wavefront. Image processing algorithms are applied to determine the position of each image blur centroid to sub-pixel resolution and also to compute the deviation from where the centroid would be in, for an ideal wavefront. The local slope of the wavefront is determined by the lateral offset of the focal point from the center of the lenslet. Phase information is then derived from the slope. Figures 4 and 5 show the Shack-Hartmann output for eyes with and without aberrations.[8]

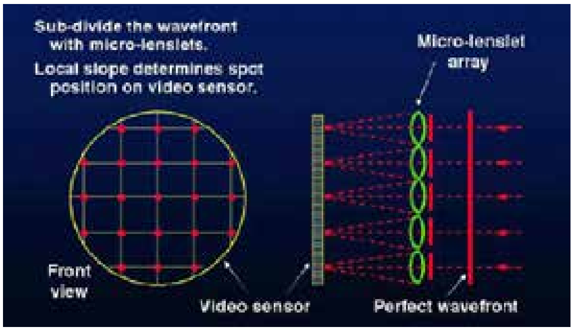

Fig. 4 - showing the Shack-Hartmann output for eyes without aberrations

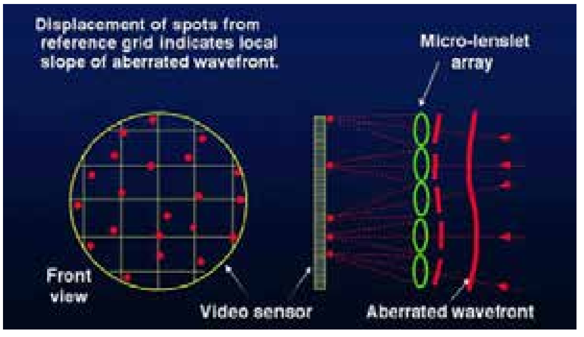

Fig. 5 - showing the Shack-Hartmann output for eyes with aberrations

The aberration data is collected and then the reconstruction of the wavefront using Zernike polynomials (modes) allows to extract useful information which is further converted into a treatment formula.[10] Each mode describes a certain three-dimensional surface and the Zernike polynomials correspond with ocular aberrations as shown below in figure 6. For instance, second-order Zernike polynomials represent the conventional aberrations such as defocus and astigmatism. Zernike polynomials above the second order represent the higher-order aberrations that are suspected of causing night glare and halos. Zernike polynomials help to simplify the wavefront technology by combining all aberrations into one simple map. This is called Zernike decomposition.

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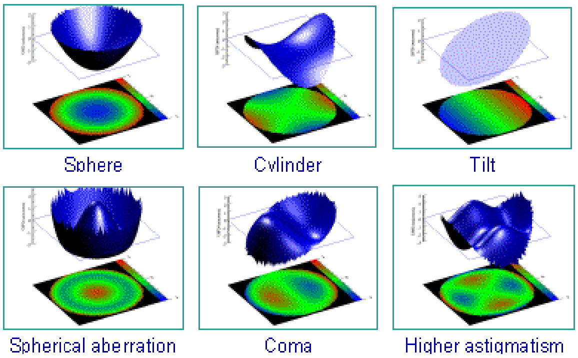

Fig. 6 - Zernike polynomial derived modes showing conventional aberrations

This map is then transferred to the laser, enabling treatment of the patient's lower and higher order aberrations.

OTHER APPLICATIONS:

1) Active and adaptive optics are techniques for improving the image quality of large astronomical telescopes. Active optics is concerned with correcting aberrations provided within the telescope and adaptive optics is concerned with correcting distortions introduced by the Earth's atmosphere.

2) Newer applications of wavefront technology as a diagnostic tool are emerging in retinal imaging, Glaucoma, aging changes, animal imaging in retinal research, Keratoconus, post-refractive surgery, analysis of tear film break-up and dry eyes, contact lens fitting, in orthokeratology, evaluation of lenticular irregular astigmatism, cataracts and aberration corrected intraocular lenses(IOLs).[11,12,13,14]

CONCLUSION:

Wavefront physics and adaptive optics have made it possible to detect, analyze and rectify different aberrations in the optical systems, right from human eye to earth based telescopes. As a result of this, resolution of the images has improved drastically which has wide applications in various fields including Ophthalmology.

REFERENCE

1) Battu R, Dabir S, Khanna A, Kumar A, Roy A. (2014). Adaptive optics imaging of the retina. Indian Journal of Ophthalmology, 62(1), 60-65. | 2) Yamane N, Miyata K, Samejima T, Hiraoka T, Kiuchi T, Okamoto F, Hirohara Y, Mihashi T, Oshika T. (2004). Ocular higher-order aberrations and contrast sensitivity after conventional Laser In Situ Keratomileusis. Investigative Ophthalmology & Visual Science, 45(11), 3986-3990. | 3) Randleman B, Perez-Straziota C, Hu M, White A, Loft E, Stulting D. (2009). Higher-order aberrations after wavefront-optimized photorefractive keratectomy and laser in situ keratomileusis. J Cataract Refract Surg, 35(2), 260-264. | 4) Ganesan AR. Indigenous development and characterization of a closed loop Adaptive Optics system for wavefront control.7 | 5) Lakshminarayanan V. (2013). What can we teach using adaptive optics? Education and Training in Optics and Photonics. | 6) Halliday D, Resnick R, Walker J. Fundamentals of Physics. | 7) Carvalho A, Castro J, Carvalho A. (2002). Measuring higher order optical aberrations of the human eye: techniques and applications. Brazilian Journal of Medical and Biological Research, 35, 1395-1406. | 8) Barsky BA. (2004). Vision-Realistic rendering: simulation of the scanned foveal image from wavefront data of human subjects. | 9) Lawless M, Hodge C. (2005). Wavefront's role in corneal refractive surgery. Clinical and Experimental Ophthalmology, 33(2), 199-209. | 10) Albert Jakobiec's principles and practice of Ophthalmology. | 11) Godara P, Dubis A, Roorda A, Duncan J, Carroll J. (2010). Adaptive Optics Retinal Imaging: Emerging Clinical Applications. Optom Vis Sci, 87(12), 930-941. | 12) Igor Kozak. (2014). Retinal imaging using adaptive optics technology. Saudi Journal of Ophthalmology, 28(2), 117-122. | 13) Naoyuki Maeda. (2009). Clinical applications of wavefront aberrometry – a review. Clinical and experimental ophthalmology, 37, 118–129. | 14) Liu H, Thibos L, Begley CG, Bradley A. (2010). Measurement of the time course of optical quality and visual deterioration during tear break-up. Invest Ophthalmol Vis Sci, 51(6): 3318–3326. |