ADVANCEMENT IN OPTICS TECHNOLOGY FOR IMPROVING VISION CORRECTION: REVIEW ARTICLE

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Abstract:

Background: The evolution of refractive surgery techniques in ophthalmology led to the introduction of wavefront technology to address higher-order aberrations induced by laser refractive procedures. This technology, borrowed from astronomy, has revolutionized vision correction by providing customized treatment profiles through wavefront-guided procedures. Aberrometers, such as the Shack–Hartmann sensor, pyramid sensor, and diffuser wavefront sensor, have been instrumental in measuring ocular aberrations for precise treatments.

Objective: This review aims to explore the latest advancements in optics technology for enhancing the accuracy and effectiveness of vision correction procedures. It evaluates the potential benefits of these innovations in improving visual acuity, reducing complications, integrating new technologies into existing practices, and enhancing patient outcomes and satisfaction levels.

Conclusion: Optics technology, particularly wavefront-guided procedures like topography-integrated wavefront-guided LASIK, has significantly improved the predictability and outcomes of refractive surgeries. The utilization of diverse wavefront sensors, such as the Shack–Hartmann sensor and diffuser wavefront sensor, has enabled more accurate measurements of ocular aberrations, leading to enhanced vision correction. The integration of these technologies into ophthalmic practices has the potential to further advance the field of vision correction and improve the quality of life for individuals with visual impairments.

Keywords: wavefront sensing, adaptive sensors, optical aberrations, Shack–Hartmann sensor, wavefront-guided laser refractive surgery, ophthalmology.

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Introduction:

In the latter part of the 20th century, ophthalmologists embarked on a quest to diminish reliance on eyeglasses through the application of refractive surgery techniques [1]. This innovative approach involved utilizing an excimer laser to reshape the cornea, thereby altering its refractive properties to address various eye conditions. While the outcomes of refractive surgery were generally successful, patients frequently reported experiencing issues such as glare, halos, and starburst effects in their vision, both during the day and at night [2]. Clinical observations revealed that laser refractive surgery could induce higher-order aberrations (HOAs), prompting the need for a new field of study now known as "wavefront technology." The primary objective of this emerging area was to quantify and mitigate the emergence of these undesirable aberrations [3].

Wavefront technology finds extensive application in the realm of astronomy for correcting aberrations in the reflective mirrors of telescopes, leading to the capture of higher-quality images. This technology has been instrumental in enhancing the imaging capabilities of renowned instruments like the Hubble Space Telescope and NASA's James Webb Space Telescope, which have delivered exceptional images of celestial bodies [4]. In a similar vein, wavefront-guided refractive surgery has adopted a comparable methodology, incorporating an aberrometer into the surgical process to map the eye's wavefront errors and guide the excimer laser to achieve a customized treatment profile [5]. The insights and tools derived from these advancements have not only revolutionized wavefront-guided refractive surgery but have also had a profound impact on other areas of ophthalmology, including the development of corrective devices like contact lenses and intraocular lenses, as well as the assessment of eye disease progression [6].

More specifically, in the context of wavefront-guided (WFG) laser-assisted in situ keratomileusis (LASIK), also known as custom LASIK, an aberrometer generates intricate patterns that inform the laser ablation process. Numerous factors must be considered to optimize the outcome of the procedure in terms of optical correction, including patient selection, the acquisition of precise wavefront data, and the execution of a successful surgery that accounts for potential variations during the healing process. Consequently, WFG treatments facilitated by high-resolution aberrometers not only enhance visual acuity but also enable greater predictability in refractive outcomes and a reduction in post-operative higher-order aberrations (HOAs) [7]. One innovative approach, known as topography-integrated wavefront-guided (TI-WFG) LASIK, involves calculating the ablation profile by integrating topographical and ocular wavefront aberration data obtained from a validated high-resolution topographer–aberrometer system [8].

Objectives:

The main objectives of this review are:

1. To explore the latest innovations in optics technology that can enhance the accuracy and effectiveness of vision correction procedures.
2. To evaluate the potential benefits of these advancements in terms of improving visual acuity and reducing the risk of complications.
3. To investigate the feasibility of integrating these new technologies into existing vision correction practices.
4. To assess the overall impact of these advancements on patient outcomes and satisfaction levels.

Wavefront sensors for ophthalmological applications:

Wavefront sensors can be defined as aberrometers, revealing light wave distortion after it passes via the eye’s optical system. On the market, various wavefront sensing devices employing different technologies can be found [9]. The most widely used wavefront sensors, including the Shack–Hartmann sensor, the pyramidal prism, and the Tscherning aberrometer, are reviewed in the following:

1. Shack–Hartmann Sensor

The Shack–Hartmann (S–H) sensor stands out as the most widely utilized wavefront sensor in the fields of astronomy and ophthalmology [10]. This sensor comprises a lenslet array that generates spots from incoming light. The spatial shifts of these spots from a reference grid captured on a CCD camera serve as a direct indication of the tilts in the wavefront. Notably, the measurement involves determining the deviation of each spot from its expected position, which is then linked to the localized distortions within the eye's pupil caused by its optical elements.

Despite its popularity, the S–H sensor does have its limitations, primarily in terms of cost and its constrained dynamic range attributed to the lenslet array it employs. Some research has delved into ways to extend the dynamic range of the S–H sensor [11]. For instance, Shinto et al. introduced an adaptive spot search technique based on a dual microlens array, demonstrating expanded dynamic range capabilities for defocus, astigmatism, and coma. More recently, Akondi and Dubra proposed an algorithm to enhance the positioning of lenslet images in scenarios involving defocus and astigmatism [12].

The computation of the local wavefront slope over each lenslet aperture is facilitated by the individual displacements of the spots, a characteristic of the S–H sensor. However, this sensor overlooks the quality of the individual spots formed by the lenslet array, rendering it less accurate for highly aberrated eyes. In cases where the wavefront shape significantly varies within a single lenslet, the resulting spot pattern may appear blurred, thereby limiting the reliable measurement of maximum wavefront slopes. To mitigate the blurring effect of the lenslet focal spot, geometric optics principles can be applied, akin to the classical and quantum descriptions of a particle [13].

Another constraint of the S–H sensor stems from the lenslet spacing across the pupil and the focal length of the lenslet array. Notably, most higher-order aberrations are encapsulated within Zernike modes up to the 8th order Zernike coefficients, totaling 42 coefficients. This implies that a minimum of 42 lenslets is necessary to capture these higher-order aberrations (HOAs). The maximum displacement that each spot can undergo on the CCD camera utilized is equivalent to the distance within a lenslet's subaperture, corresponding to half of the lenslet's diameter [14].

2. Foucault Knife-Edge and Optical Differentiation Wavefront Sensor (ODWS)

Spatial filtering techniques, such as the Foucault knife-edge test and the linear amplitude filter, are utilized to process images by analyzing the intensity values within a specific pixel's neighborhood. Linear filtering, a highly effective method for enhancing images, involves modifying a portion of the signal frequency spectrum using the filter's transfer function. Typically, the filters used in this process are linear and shift-invariant, resulting in output images that are the convolution sum of the input image and the filter impulse response [15].

3. Pyramid Sensor

Since its inception in 1997, adaptive optics (AO) systems utilized S–H sensors for wavefront sensing in ophthalmic applications. While this method has proven successful, there is potential for alternative approaches to enhance efficiency and flexibility in wavefront sensing. The implementation of the pyramid sensor (PS) presents a viable option for ocular wavefront measurements due to its ability to measure a wide range of ocular aberrations. Similar to the Foucault knife-edge test [16], the pyramidal wavefront sensors (PS) detect aberration-induced inhomogeneities by positioning a four-facet pyramid refractive element in the focal plane with its tip aligned to the optical axis.

4. Diffuser Wavefront Sensor:

Numerous endeavors have been undertaken over time in the quest for cost-effective alternatives to conventional wavefront sensors. The utilization of a slim diffuser and its memory effect presents a promising avenue. This concept hinges on the correlation between a tip/tilt within an incoming wavefront and the consequent local displacement in the observed pattern [17]. Placing the diffuser in close proximity to the camera enables the numerical reconstruction of the wavefront through a specialized algorithm. Berto et al. advocated for the application of the renowned "Demon Algorithm," which has been fine-tuned for the non-rigid registration of biomedical images [18]. Gunjala et al., on the other hand, employed a faint diffuser at various illumination angles to reconstruct aberration profiles from multiple images using a statistical methodology [19]. Notably, McKay et al. have introduced a diffuser wavefront sensor (DWFS) tailored for ocular aberrometry, boasting a wider dynamic range compared to a Shack–Hartmann wavefront sensor (SHWFS) for wavefront assessments [20].

5. Tscherning Aberrometer, Ray-Tracing System, and Dynamic Skiascopy:

In a preceding section, it was elucidated that H–S aberrometers exhibit a high level of user-friendliness, boasting exceptional resolution, reproducibility, and accuracy, along with swift fundamental time in conducting measurements and analyzing ocular aberrations [1]. Despite these advantages, H–S falls short when it comes to reconstructing wavefronts in patients with significantly aberrated corneas. A similar constraint is observed with Tscherning aberrometers [2]. While Tscherning aberrometers are known for their rapid measurements and high accuracy, they are less user-friendly as they necessitate more time and effort to capture a usable image. Utilizing a laser beam, the Tscherning aberrometer projects a grid onto the target, with any deviations from the reference grid being depicted in the aberration map [21].

Another form of aberrometry is ray tracing, which operates on a principle akin to that of the Tscherning aberrometer. The key distinction lies in the fact that the ray-tracing system scans the retina sequentially rather than simultaneously. This sequential processing of each point offers the advantage of reducing the risk of intersecting light rays, thereby enabling the imaging of highly aberrated eyes. However, the efficacy of the ray tracing technique is contingent upon the resolution of the aberroscope. By scanning an unexpanded laser beam through different pupil locations, the system sequentially introduces light into the eye, with the displacement of the image relative to a reference being proportional to the local derivative of the wave aberration [22].

An intriguing system employs the skiascopic ocular wavefront-sensing device, also known as the retinoscopy technique, which represents a time-dependent rather than a position-dependent method for studying optical aberrations, particularly the refractive error of the eye. This technique involves measuring the time interval between reflected light beams using a rotating array of detectors, directly correlating this time gap to wavefront errors. The rapid rotation of a series of sensors enables the collection of over 1400 retinoscopic data points within a short timeframe [23]. Additional details on ophthalmological imaging methods and their applications are expounded upon in subsequent sections.

The impact of optics technology in improving vision correction:

Optics technology plays a crucial role in enhancing vision correction for individuals with diverse visual impairments. The evolution of sophisticated lenses, including progressive lenses and high-index materials, has enabled more refined and personalized vision correction [24]. Furthermore, the integration of wavefront technology in laser eye surgery has transformed the landscape of ophthalmology, offering precise and personalized treatments for conditions like myopia, hyperopia, and astigmatism. These breakthroughs in optics technology not only elevate the standard of vision correction but also elevate the overall quality of life for numerous individuals globally [24]. As technology progresses, we anticipate further advancements in optics that will continue to redefine the possibilities in vision correction.

Conclusion:

In conclusion, the utilization of wavefront technology in ophthalmology, particularly in the context of wavefront-guided refractive surgery, has significantly enhanced the accuracy and effectiveness of vision correction procedures. By integrating advanced wavefront sensors such as the Shack–Hartmann sensor, pyramid sensor, and diffuser wavefront sensor, ophthalmologists can now obtain precise wavefront data to tailor customized treatment profiles for patients undergoing procedures like LASIK. These innovations have not only improved visual acuity and predictability in refractive outcomes but have also led to a reduction in post-operative higher-order aberrations.

The review of optics technology advancements underscores the potential benefits of incorporating these innovations into existing vision correction practices. By exploring the latest developments in wavefront sensors and their applications in ophthalmology, this research article aims to evaluate the impact of these technologies on patient outcomes and satisfaction levels. As optics technology continues to evolve, we anticipate further enhancements in vision correction procedures that will elevate the standard of care and improve the quality of life for individuals with visual impairments.

References:

1. Kugler L.J., Wang M.X. Lasers in Refractive Surgery: History, Present, and Future. Appl. Opt. 2010;49:F1. doi: 10.1364/AO.49.0000F1. [PubMed] [CrossRef] [Google Scholar]
2. Maeda N. Clinical Applications of Wavefront Aberrometry—A Review. Clin. Exp. Ophthalmol. 2009;37:118–129. doi: 10.1111/j.1442-9071.2009.02005.x. [PubMed] [CrossRef] [Google Scholar]
3. Charman W.N. Wavefront Technology: Past, Present and Future. Contactlens Anterior Eye. 2005;28:75–92. doi: 10.1016/j.clae.2005.02.003. [PubMed] [CrossRef] [Google Scholar]
4. Perrin M.D., Acton D.S., Lajoie C.-P., Knight J.S., Lallo M.D., Allen M., Baggett W., Barker E., Comeau T., Coppock E., et al. Preparing for JWST Wavefront Sensing and Control Operations. In: MacEwen H.A., Fazio G.G., Lystrup M., Batalha N., Siegler N., Tong E.C., editors. Proc. SPIE 9904, Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave. SPIE; Bellingham, WA, USA: 2016. p. 99040F. [Google Scholar]
5. Maeda N. Wavefront Technology in Ophthalmology. Curr. Opin. Ophthalmic. 2001;12:294–299. doi: 10.1097/00055735-200108000-00009. [PubMed] [CrossRef] [Google Scholar]
6. Ryan D.S., Sia R.K., Rabin J., Rivers B.A., Stutzman R.D., Pasternak J.F., Eaddy J.B., Logan L.A., Bower K.S. Contrast Sensitivity After Wavefront-Guided and Wavefront-Optimized PRK and LASIK for Myopia and Myopic Astigmatism. J. Refract. Surg. 2018;34:590–596.

doi: 10.3928/1081597X-20180716-01. [PubMed] [CrossRef] [Google Scholar]

7. Piñero D.P., Soto-Negro R., Ruiz-Fortes P., Pérez-Cambrodí R.J., Fukumitsu H. Analysis of Intrasession Repeatability of Ocular Aberrometric Measurements and Validation of Keratometry Provided by a New Integrated System in Mild to Moderate Keratoconus. Cornea. 2019;38:1097–1104. doi: 10.1097/ICO.0000000000002034. [PubMed] [CrossRef] [Google Scholar]
8. Hampson K.M. Adaptive Optics and Vision. J. Mod. Opt. 2008;55:3425–3467. doi: 10.1080/09500340802541777. [CrossRef] [Google Scholar]
9. Lawless M.A., Hodge C. Wavefront's Role in Corneal Refractive Surgery. Clin. Exp. Ophthalmol. 2005;33:199–209. doi: 10.1111/j.1442-9071.2005.00994.x. [PubMed] [CrossRef] [Google Scholar]
10. Rasouli S., Dashti M., Ramaprakash A.N. An Adjustable, High Sensitivity, Wide Dynamic Range Two Channel Wave-Front Sensor Based on Moiré Deflectometry. Opt. Express. 2010;18:23906–23915. doi: 10.1364/OE.18.023906. [PubMed] [CrossRef] [Google Scholar]
11. Shinto H., Saita Y., Nomura T. Shack–Hartmann Wavefront Sensor with Large Dynamic Range by Adaptive Spot Search Method. Appl. Opt. 2016;55:5413–5418. doi: 10.1364/AO.55.005413. [PubMed] [CrossRef] [Google Scholar]
12. Akondi V., Dubra A. Shack-Hartmann Wavefront Sensor Optical Dynamic Range. Opt. Express. 2021;29:8417–8429. doi: 10.1364/OE.419311. [PMC free article] [PubMed] [CrossRef] [Google Scholar]
13. Rasouli S., Dashti M., Ramaprakash A.N. An Adjustable, High Sensitivity, Wide Dynamic Range Two Channel Wave-Front Sensor Based on Moiré Deflectometry. Opt. Express. 2010;18:23906–23915. doi: 10.1364/OE.18.023906. [PubMed] [CrossRef] [Google Scholar]
14. Platt B.C., Shack R. History and Principles of Shack-Hartmann Wavefront Sensing. J. Refract. Surg. 2001;17:S573–S577. doi: 10.3928/1081-597X-20010901-13. [PubMed] [CrossRef] [Google Scholar]
15. Gunjala G., Sherwin S., Shanker A., Waller L. Aberration Recovery by Imaging a Weak Diffuser. Opt. Express. 2018;26:21054–21068. doi: 10.1364/OE.26.021054. [PubMed] [CrossRef] [Google Scholar] [Ref list]
16. Shirai T., Barnes T.H., Haskell T.G. Adaptive Wave-Front Correction by Means of All-Optical Feedback Interferometry. Opt. Lett. 2000;25:773–775. doi: 10.1364/OL.25.000773. [PubMed] [CrossRef] [Google Scholar] [Ref list]
17. Qiao J., Mulhollan Z., Dorrer C. Optical Differentiation Wavefront Sensing with Binary Pixelated Transmission Filters. Opt. Express. 2016;24:9266–9279. doi: 10.1364/OE.24.009266. [PubMed] [CrossRef] [Google Scholar]
18. Sinjab M.M., Cummings A.B. Customized Laser Vision Correction. Springer International Publishing; Cham, Switzerland: 2018. Introduction to Wavefront Science; pp. 65–93. [Google Scholar]
19. Lombaert H., Grady L., Pennec X., Ayache N., Cheriet F. Spectral Log-Demons: Diffeomorphic Image Registration with Very Large Deformations. Int. J. Comput. Vis. 2014;107:254–271. doi: 10.1007/s11263-013-0681-5. [CrossRef] [Google Scholar]
20. Gunjala G., Sherwin S., Shanker A., Waller L. Aberration Recovery by Imaging a Weak Diffuser. Opt. Express. 2018;26:21054–21068. doi: 10.1364/OE.26.021054. [PubMed] [CrossRef] [Google Scholar]
21. Haffert S.Y. Generalised Optical Differentiation Wavefront Sensor: A Sensitive High Dynamic Range Wavefront Sensor. Opt. Express. 2016;24:18986–19007. doi: 10.1364/OE.24.018986. [PubMed] [CrossRef] [Google Scholar]
22. Moreno-Barriuso E., Lloves J.M., Marcos S., Navarro R., Llorente L., Barbero S. Ocular Aberrations before and after Myopic Corneal Refractive Surgery: LASIK-Induced Changes Measured with Laser Ray Tracing. Investig. Ophthalmol. Vis. Sci. 2001;42:1396–1403. [PubMed] [Google Scholar]
23. Tan B., Chen Y.-L., Baker K., Lewis J.W., Swartz T., Jiang Y., Wang M. Simulation of Realistic Retinoscopic Measurement. Opt. Express. 2007;15:2753–2761. doi: 10.1364/OE.15.002753. [PubMed] [CrossRef] [Google Scholar]
24. Sekine R., Shibuya T., Ukai K., Komatsu S., Hattori M., Mihashi T., Nakazawa N., Hirohara Y. Measurement of Wavefront Aberration of Human Eye Using Talbot Image of Two-Dimensional Grating. Opt. Rev. 2006;13:207–211. doi: 10.1007/s10043-006-0207-2. [CrossRef] [Google Scholar]