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Review

Clinical applications of wavefront aberrometry – a review

Naoyuki Maeda MD
Department of Ophthalmology, Osaka University Medical School, Osaka, Japan

ABSTRACT

One of the most powerful clinical applications of aberrometry is wavefront-guided refractive surgery. This concept led to a paradigm shift in refractive error correction, and the same ideas were applied to design the power and shape of intraocular and contact lenses. Other applications are the diagnosis of irregular astigmatism and the assessments of the optical quality of the eye. Because the higher-order aberrations of the eye are expressed as the total root mean square errors, a set of coefficients for the Zernike terms, Strehl ratio, point spread functions, modulation transfer functions, and other types of metrics can be determined, hence the deterioration in the quality of vision can be easily estimated. Simulations of the retinal images are also useful to understand some of the symptoms in patients with irregular astigmatism. With corneal topographic analyses, the origin of irregular astigmatism from the cornea or internally, or both, can be specified by aberrometry.

Key words: aberration, aberrometry, corneal topography, irregular astigmatism, wavefront.

INTRODUCTION

Irregular astigmatism was considered to be a refractive error that could not be corrected with conventional spectacles. Corneal topography was used to diagnose corneal irregular astigmatism, and rigid gas permeable (RGP) contact lenses or corneal transplantations were used to treat these eyes. On the other hand, irregular astigmatism due to the crystalline lens or an intraocular lens (IOL) was not studied in detail because of the difficulties, until recently, in measuring irregular astigmatism caused by the internal optics.

In 1961, the higher-order aberrations (HOAs) of the human eye were first measured by Smirnov using a psychophysical method. He predicted that customized lenses would be made to compensate for the HOAs of individual eyes.[1] A modified technique was developed by Howland,[2] and the wavefront aberrations of the human eye were measured objectively using a Hartmann–Shack sensor in 1994.[3] After the HOAs were successfully corrected using adaptive optics which led to better optical quality of normal eyes,[4] the ability to provide supernormal vision and high-resolution retinal imaging[5] attracted a great deal of attention.

The beginning of the wavefront era began with the development of wavefront-guided refractive surgery,[6] and a paradigm shift occurred in the clinical definition of irregular astigmatism and the concepts of refractive error correction. It was generally assumed that normal eyes did not have irregular astigmatism; however, wavefront analysis showed that there was a small degree of irregular astigmatism even in normal eyes. In addition, the degree of irregular astigmatism was changed by different factors such as blinking, accommodation and ageing. Although there is no obvious influence of mild HOAs on the conventional visual acuity obtained with high-contrast optotypes, the contrast sensitivity and mesopic vision can be worsened.

In this article, the current roles played by aberrometry in the eye clinic will be described by reviewing earlier studies.

PRINCIPLES

Aberrometry uses wavefront sensing, which is a technique of measuring the complete refractive status, including irregular astigmatism, of an optical

■ **Correspondence:** Dr Naoyuki Maeda, Department of Ophthalmology, Osaka University Medical School, Room J7, Yamadaoka 2-2, Suita 565-0871, Osaka, Japan. Email: nmaeda@ophthal.med.osaka-u.ac.jp

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system. Light is defined differently in geometrical and physical optics. In geometrical optics, the rays from a point source of light radiate out in all directions. Light coming from infinity is considered to be linear bundles of light rays. In physical optics, on the other hand, light is expressed as a wave, and the light waves spread in all directions as a spherical wave. The wavefront is the shape of the light waves that are all in-phase.[7] Light coming from infinity is expressed as proceeding as a plane wavefront.

The differences in the concepts of a lens or an optical system in geometrical and physical optics are shown in Figure 1a. Although the lens is usually defined as the object that refracts the light rays, it can also be considered as the one that transforms the shape of the wavefront. The refractive status of the eye, for example emmetropia, myopia, hyperopia and eyes with HOAs (irregular astigmatism), can be displayed using wavefronts as shown in Figure 1b.

A wavefront aberration is defined as the deviation of the wavefront that originates from the measured optical system from reference wavefront that comes from an ideal optic system. The unit for wavefront aberrations is microns or fractions of wavelengths and is expressed as the root mean square or RMS.

The purpose of wavefront analyses of the eye is to evaluate the optical quality of the eye by measuring the shape of its wavefront as wavefront aberrations. For this, an aberrometer or wavefront sensor is used, and for measuring the corneal wavefront aberrations, a corneal topographer is used.

Aberrometers are usually classified into three types. The first type is the outgoing wavefront aberrometer as in the Hartmann–Shack sensor,[8] and the second type is the ingoing retinal imaging aberrometer as in the cross-cylinder aberrometer,[2] Tscherning aberrometer[9] and the sequential retinal ray tracing method.[10] The third type is the ingoing feedback aberrometer as used in the spatially resolved refractometer[11] and the optical path difference method.[12]

The shape of the wavefront can be analysed by expanding it into sets of Zernike polynomials. The Zernike polynomials are a combination of independent trigonometric functions that are appropriate for describing the wavefront aberrations because of their orthogonality. The first to sixth orders Zernike polynomials are shown graphically in Figure 1c. The zero order has one term that represents a constant. The first order has two terms that represent tilt for the *x*

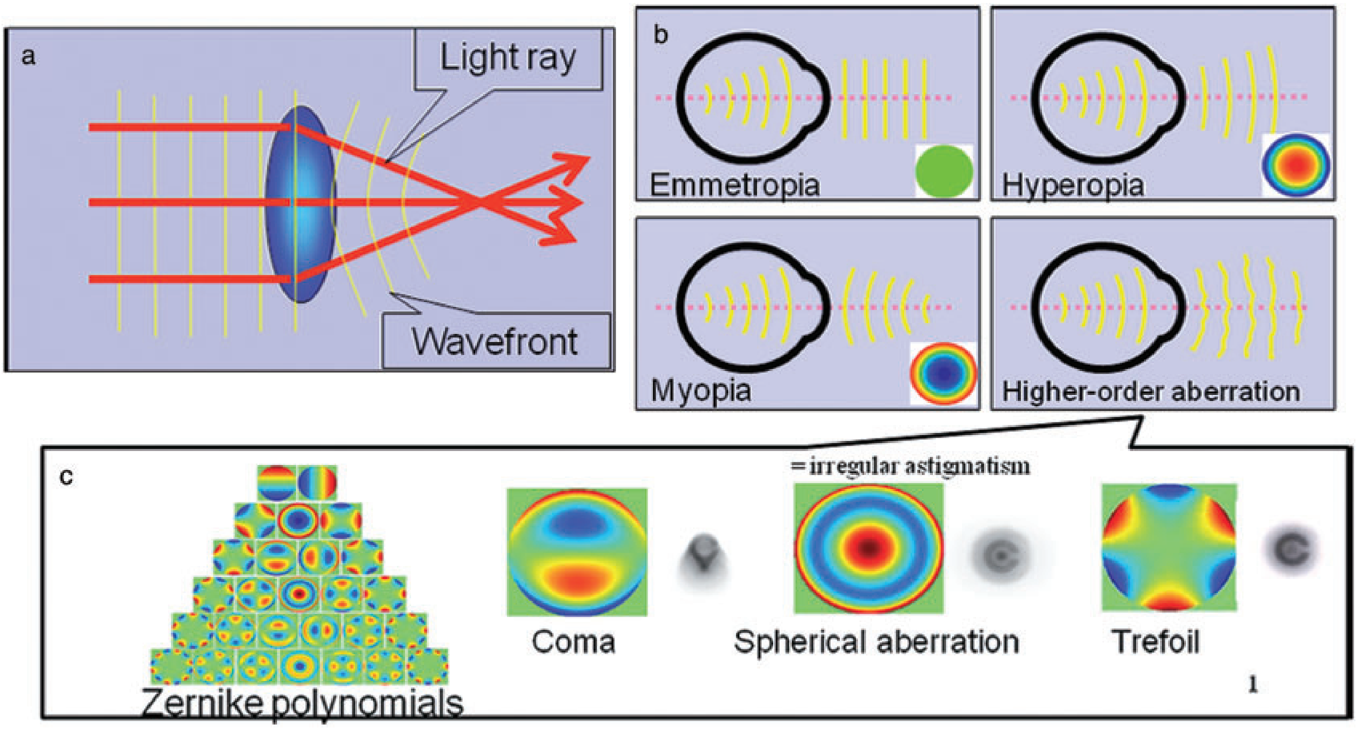

Figure 1. The differences in the concepts of a lens or an optical system in geometrical and physical optics (a). Effect of refractive errors on the wavefront (b). The wavefront of the perfect eye, that is an emmetropic eye without any aberrations, is shown as a perfect plane that is perpendicular to the line of sight. The wavefront in a myopic eye has a bowl-like (concave) shape with the peripheral wavefront more advanced than the central wavefront. The wavefront of the hyperopic eye has a hill-shape (convex shape) with the central wavefront more advanced than the peripheral wavefront. The wavefront of an eye with irregular astigmatism has an irregular and complex shape. The first to sixth orders Zernike polynomials shown graphically (c).

and *y* axes. The second order includes three terms that represents defocus and regular astigmatism in the two direction. The third order has four terms that represent coma and trefoil, and similarly, the fourth order has five terms that represent tetrafoil, secondary astigmatism and spherical aberration.

The polynomials can be expanded up to any arbitrary order if a sufficient number of measurements are made for the calculations. Spectacles can correct for only the second order aberrations, and not the third- and higher-orders that represent irregular astigmatism. Monochromatic aberrations can be evaluated quantitatively using the Zernike coefficients for each term.

Although the total HOAs can be used to estimate the severity of deterioration of optical quality of the eye as the diagnostic purposes, it will be essential for the surgical treatments to quantify the details of wavefront of the eye using Zernike expansion or Fourier expansion.

Wavefront aberrations caused by the anterior and/or posterior corneal surfaces can be calculated using the height data of the corneal topographers such as videokeratoscopes or slit-scanning corneal topographers.[13]

WAVEFRONT-GUIDED REFRACTIVE SURGERY

One of the most important roles of aberrometry in the clinic is to provide aberration data of the eye to the excimer laser for customized ablation. With the development of wavefront analyses, the increase of the HOAs of the eye following conventional photorefractive keratectomy (PRK) has been confirmed.[14,15] Therefore, customized ablation that can correct irregular astigmatism or that can reduce the surgically induced irregular astigmatism might solve some of the problems that are induced by the conventional keratorefractive procedures.

Wavefront-guided refractive surgery is a technique using excimer or other lasers to correct not only the spherical and cylindrical refractive errors but also the HOAs. Seiler *et al.* reported the first application of wavefront-guided laser *in situ* keratomileusis (LASIK) using a Tscherning aberrometer to measure the HOAs.[6] At about the same time, McDonald performed the first wavefront-guided LASIK using data obtained from the Hartmann–Shack wavefront sensor.[16] Wavefront-guided LASIK is safe and effective for primary myopia or myopic astigmatism, and it results in equal or better refractive accuracy and uncorrected visual acuity than conventional LASIK.[17]

Theoretically, correcting irregular astigmatism and eliminating the inherent optical aberrations of normal human eyes should result in obtaining super-normal vision.[18] The theoretical limits of visual performance have been estimated to be between 6/3.6 and 6/1.5 depending on the pupillary diameter.[19] Although the HOAs were only reduced after wavefront-guided LASIK in some cases, they were still less than that after conventional LASIK where the HOAs were generally increased.[17]

There are still so many factors that should be solved to improve the results of wavefront-guided refractive surgery. Those include errors of wavefront registration between measurement and treatment, unpredictable changes of corneal shape due to wound healing and/or biomechanics, fluctuation of HOA, fluctuation of beam profile, and so on.

AGEING

Wavefront analyses have shown that normal eyes not only have small degrees of HOAs, but also that the degree of the HOAs was positively correlated with age. This increase was consistent with the decrease of contrast sensitivity with increasing age.[20] In addition, the total ocular HOAs were lower than the corneal aberrations in most of the younger subjects, whereas the reverse was true in older subjects.[21,22] This indicated that the internal optical surfaces compensated, at least in part,[23] for the aberrations associated with the cornea in most of the younger subjects. However, this compensation was not present in the older subjects.

Another analysis of the effects of ageing on the HOAs showed that the ocular coma increased with age, mainly because of the increase in the corneal coma.[24] On the other hand, the increase in the ocular spherical aberration with age was caused mainly by an increase in the spherical aberration of the internal optics.[24] The ocular aberrations increased abruptly especially after 50 years of age due to the increase of lenticular HOAs. Therefore, customized ablation should be carefully considered especially in presbyopic eyes.[25]

KERATOCONUS

The characteristic HOA finding in keratoconic eyes is the prominent increase of vertical coma due to a corneal component.[26,27] In addition, the trefoil, tetrafoil and secondary astigmatism are higher in keratoconic eyes. When the directions of each term were analysed by Zernike vector analysis, keratoconic eyes tend to have a reverse coma pattern, that is, a prominent vertical coma with an inferior slow pattern.[28] In addition, the trefoil aberration was the reverse of that of normal eyes.[28] Although the total HOAs were significantly reduced with an RGP lens, the total HOA was still higher than that of normal eyes with an RGP lens.[28,29] Interestingly, the patterns

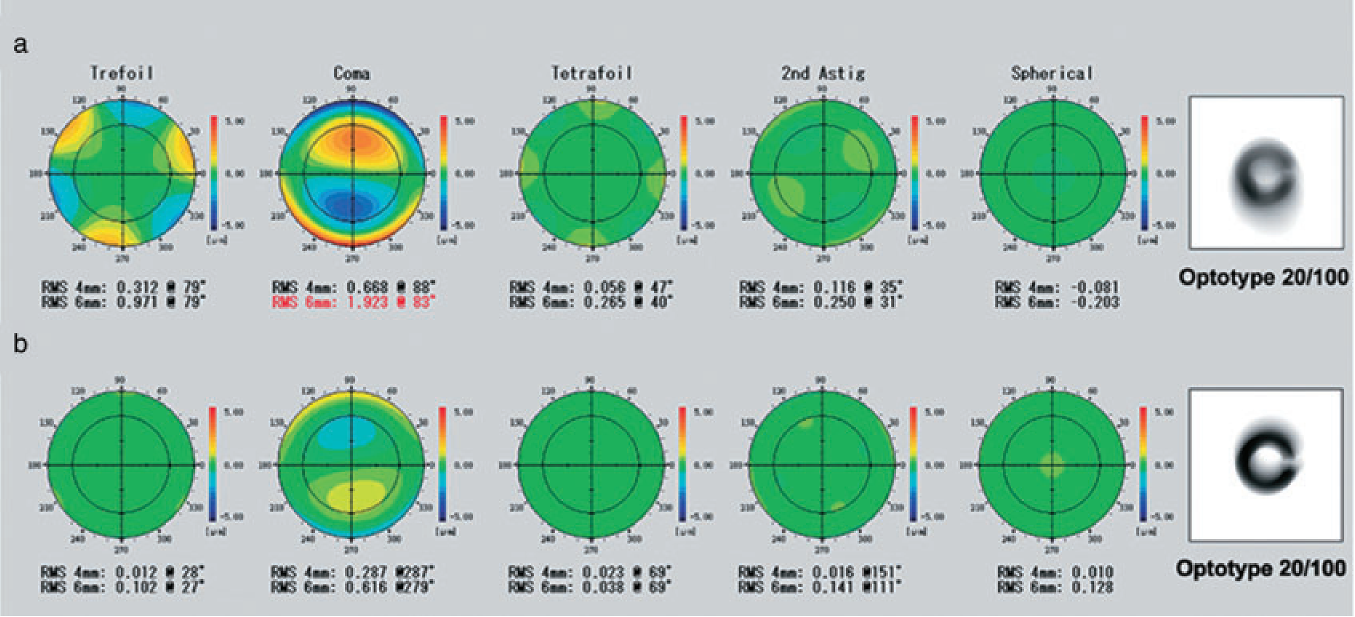

Figure 2. Zernike vector analyses and simulated retinal image of a typical keratoconus case without (a) and with (b) a rigid gas permeable lens (from Kosaki *et al.*[28]). RMS, root mean square.

of the axes of the coma and trefoil were reversed with the RPG lens.[28] The RGP lens corrected the irregular astigmatism; however, smaller comet-like retinal images oriented in the opposite direction remained as a result of the residual vertical coma possibly due to the posterior corneal surface (Fig. 2).

Higher-order aberrations are also used for grading the severity of keratoconus[30] or for detecting keratoconus or keratoconus suspect.[31,32]

PELLUCID MARGINAL CORNEAL DEGENERATION

Although pellucid marginal corneal degeneration and keratoconus are categorized as non-inflammatory corneal thinning disorders, the patterns of the HOAs in the two types of eyes differ, possibly owing to differences in the position of the corneal apex.[33] Similar to keratoconic eyes, the mean axes of the coma in eyes with pellucid marginal corneal degeneration are the reverse of that of normal eyes. However, the magnitude of the coma is significantly weaker than that in eyes with keratoconus. The mean axis of the trefoil in this disease or in normal eyes is opposite that in eyes with keratoconus. Also, the sign of the spherical aberration in eyes with pellucid marginal degeneration (plus) is opposite that in eyes with keratoconus (minus).

Periodic examinations of the corneal HOAs in a case of pellucid marginal degeneration showed a gradual and slight increase of the coma-like aberration and stable spherical-like aberration throughout the 11-year observation period.[34]

POST-REFRACTIVE SURGERY

Corneal wavefront aberrations have been investigated in patients following radial keratotomy,[35] PRK[36–38] and LASIK.[38,39] The results of several studies have shown that refractive surgeries tended to increase the total HOAs for both day (small pupil) and night vision (large pupil), and the increase was more prominent for night vision than for the day vision.[40] Also, refractive surgeries shifted the aberrations from mainly coma-like aberrations to mainly spherical-like aberrations. The increase in the HOAs was correlated with the amount of refractive correction.[41] These results were directly confirmed by aberrometry as changes in the ocular HOAs (Fig. 3).[42–44]

In terms of wavefront-guided LASIK, a reduction of the HOAs by wavefront-guided PRK or LASIK was found in only some cases, but the residual HOAs were generally lower than that following conventional LASIK.[45–49] Although the HOAs tended to increase,[46,47,50] wavefront-guided ablation also had the advantage over conventional ablation from the standpoint of corneal tissue conservation by some of the instruments.[51]

Wavefront analyses have shown a strong correlation between the visual symptoms and ocular aberrations, for example monocular diplopia in eyes with coma and starburst and glare in eyes with spherical aberration. Thus, aberrometry can also be used to determine the cause of symptomatic LASIK-induced aberrations.[52] To avoid such visual complications, methods that reference the aberration measurements

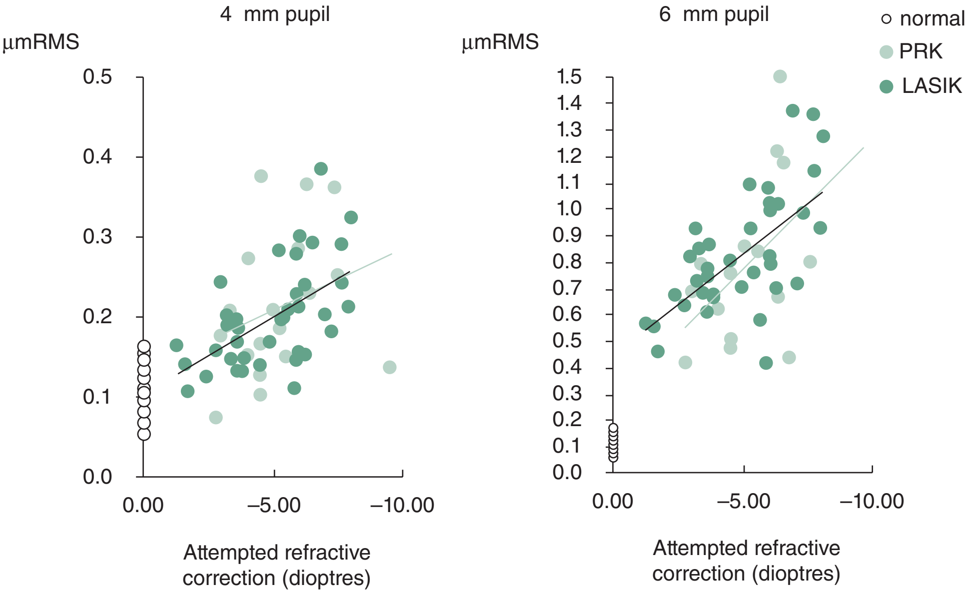

Figure 3. Correlation between the attempted refractive correction and ocular higher-order aberration for a 4 mm and a 6 mm pupillary diameter. The ocular higher-order aberrations increase in proportion to the attempted refractive correction for both photorefractive keratectomy (PRK) and laser *in situ* keratomileusis (LASIK) (from Ninomiya *et al.*[43]).

and treatments[53] to a fixed topological feature of the eye will reduce the potential for inducing aberrations due to shifts in the centre of the pupil.[54]

TEAR-FILM BREAK-UP AND DRY EYES

The first optical surface of the eye is not the surface of the corneal epithelium but the surface of the precorneal tear film. Therefore, it is easy to accept the fact that changes in the tear volume and tear fluid dynamics can induce changes in the HOAs even if the corneal shape is completely ideal. It has been shown that a break-up in the tear-film induces an increase in the ocular HOAs.[55–57] Sequential measurements of the HOAs during a 10-s period after eye opening in normal eyes showed that the post-blink changes in the pattern of the HOAs could be classified into four groups by pattern: stable (Fig. 4a, 25%), small fluctuation (45%), sawtooth (Fig. 4b, 20%) and others (10%).[58] The sequential changes in the total HOAs in subjects with a short tear-film break-up time (TBUT) had a sawtooth pattern with a marked upward curve that increased after blinking.[59] From 5 to 9 s after blinking, the total HOAs were significantly higher than that immediately after blinking, indicating that the optical quality might deteriorate in subjects with a short TBUT by suppressing the blinking. This can arise when staring at a video display terminal even with sufficient tear volume.[59]

On the other hand, increased HOAs were observed in dry eye partially result from superficial punctate keratopathy above the optical zone.[60,61] The low tear volume in severe dry eyes may not cause the sequential increases in the HOAs after blinking,[61] and the time when the minimum RMS aberration occurred was correlated with the TBUTs in mild dry eyes.[62]

In contrast, the sequential post-blink changes in the HOAs had a reverse sawtooth pattern when there was an excessive tear volume in a patient with dry eye who complained of paradoxical visual impairment with epiphora despite an improvement of the dry eye after punctal plug insertion.[63] These results indicated that sequential aberrometry is a useful objective method to evaluate sequential changes of visual performance related to tear-film dynamics. They also indicate that careful measurements and selection of data should be made before wavefront-guided refractive surgery to avoid having used artifactual data because of abnormal tear-film dynamics.[55,64]

CONTACT LENS

Performing aberrometry during contact lens wear is useful for the fitting of contact lenses, and for determining the interaction of the contact lens with the tears, cornea and internal optics of the eye.[65] Even in eyes with identical Snellen visual acuities, the quality of vision can be different in individuals wearing spectacles, soft contact lens and RGP lens. Aberrometry during contact lens and spectacle wear can show the differences in the HOAs.[66] Some studies have shown lower HOAs with RGP lenses than with soft contact lens or spectacles.[65,66] Others have pointed out that vertical coma during RGP wear might be increased or decreased because of preexisting coma[67] or the resting position of contact lenses.

There tended to be an increase in the total HOAs during soft contact lens wear for myopia compared

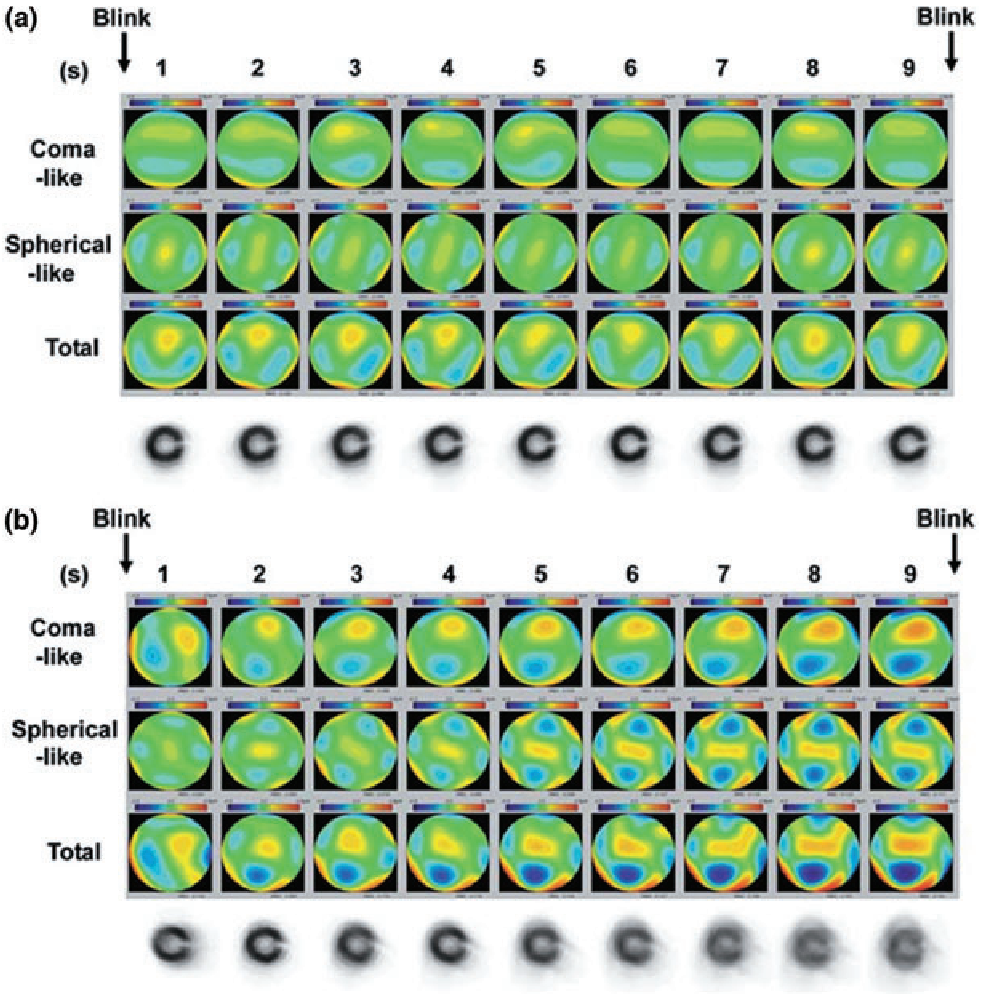

Figure 4. Representative sequential post-blink changes in (a) eyes with a stable pattern and with a (b) sawtooth pattern (from Koh *et al.*[58]).

with those without contact lens wear.[68] Differences in the HOAs can result from the methods used to manufacture the contact lenses,[69] the asphericity of the lenses, the power of the lenses[70] and the flexure of thin RGP lenses.[68] It is well-known that the pre-contact lens tear film is thinner and easier to break-up than the normal pre-corneal tear-film. In symptomatic wearers of disposable soft contact lenses, the use of internal lubricating agents was shown to improve the quality of vision by sequential measurements of the HOAs (Fig. 5).[71]

Because of these factors, for example lens flexure, lens movements, lens decentration and reduced stability of the pre-lens tear film, one needs to remember that there will be larger variability in on-eye than off-eye measurements.[72]

Aberrometry provides a better understanding of the optical effects of contact lenses *ex vivo*[73] or *in situ*, and can be useful for optimizing future designs of contact lenses such as customized soft contact lenses for keratoconic eyes.[74]

ORTHOKERATOLOGY

Corneal HOAs are significantly increased after orthokeratology even in clinically successful cases. The increase in the HOAs was correlated with the magnitude of the myopic correction.[75] Orthokeratology results in reduced low-contrast best-corrected visual acuity because of the increased HOAs.[76,77] A relationship between subclinical decentration and increase of horizontal coma has been suggested to be the cause of the decreased best-corrected visual acuity.[78]

LENTICONUS

One of the most interesting applications of wavefront measurements is in the evaluation of lenticular irregular astigmatism qualitatively and quantitatively. This is accomplished by comparing the total HOAs of the eye and those of cornea. Anterior lenticonus due to Alport syndrome had large amount of ocular HOAs with small amount of

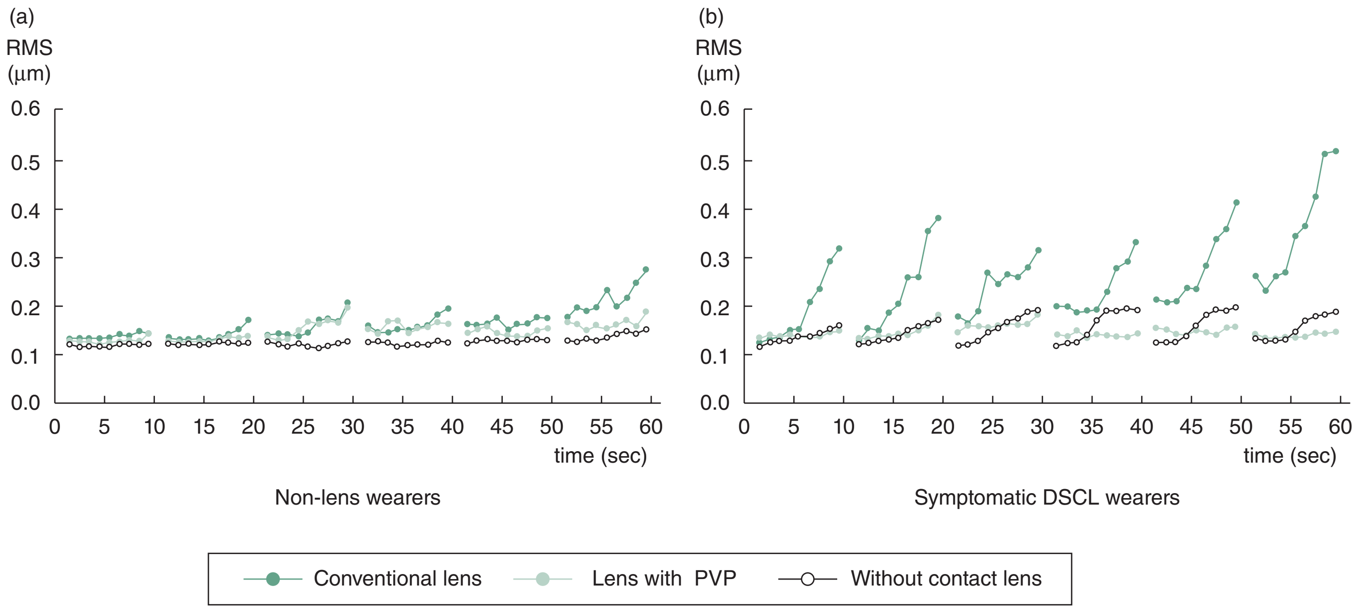

Figure 5. Sequential changes in higher-order aberrations during 60 consecutive measurements for 60 s consisting of six post-blink intervals in a non-contact kens wearer (a), and in a symptomatic disposable soft contact lens (DSCL) wearer (b). (From Koh *et al.*[71]). RMS, root mean square.

corneal HOAs. Spherical-like aberration is dominant compared with coma-like aberration in eyes with anterior lenticonus.[79] A large degree of negative spherical aberration is characteristic of the lenticular astigmatism in eyes with lenticonus.[80] During the screening process of refractive laser surgery, not only the transparent deformation of the cornea seen in keratoconic eye, but also a transparent deformity of the lens should be avoided.

CATARACTS

In mild nuclear or cortical cataracts, not only light scattering but also optical aberrations of the lens contribute to the loss of contrast sensitivity.[81] In eyes with mild nuclear cataracts, the spherical aberration tends to become negative, and the spherical-like aberration is dominant over coma-like aberration. Monocular triplopia has been reported in middle-aged patients with mild nuclear cataracts and high myopia (Fig. 6). This was caused by the combined increase of the trefoil and spherical aberration of the crystalline lens.[82,83]

In contrast, positive spherical aberration and dominance of coma-like aberration are characteristics of eyes with mild cortical cataracts.[84,85] Monocular diplopia probably results from the combined effects of spherical aberration and secondary astigmatism caused by cortical cataracts.[86]

The HOAs and forward light scattering of the lens can be calculated from the displacement and size of the aberrometer spot images.[87] The backward light scattering can be calculated from the optical density of the Scheimpflug images, and it is possible to predict the visual deterioration of the eyes with cortical or nuclear cataracts from these three parameters. The loss of contrast sensitivity was predominantly due to backward light scattering and HOAs in eyes with nuclear cataracts, and forward light scattering and HOAs in eyes with cortical cataracts.[88]

INTRAOCULAR LENSES

The first wavefront analyses in patients with an IOL showed that the HOAs were different from that of normal eyes.[14] Since then, many studies have been conducted to determine the effects of the materials and design of the IOL, asymmetrical preoperative corneal aberrations, incision-induced aberrations, and other factors on the HOAs.[89,90]

A modified, prolate-shaped aspherical IOL was designed with a fixed amount of negative spherical aberration that partially compensated for the average positive spherical aberration of the cornea. This was done to determine if there was an improvement of the ocular optical quality of pseudophakic patients.[91] The clinical results confirmed that the aspherical IOL compensated for the positive spherical aberration in older eyes, and some improvements were found in the quality of vision especially in contrast sensitivity and mesopic visual quality.[92,93]

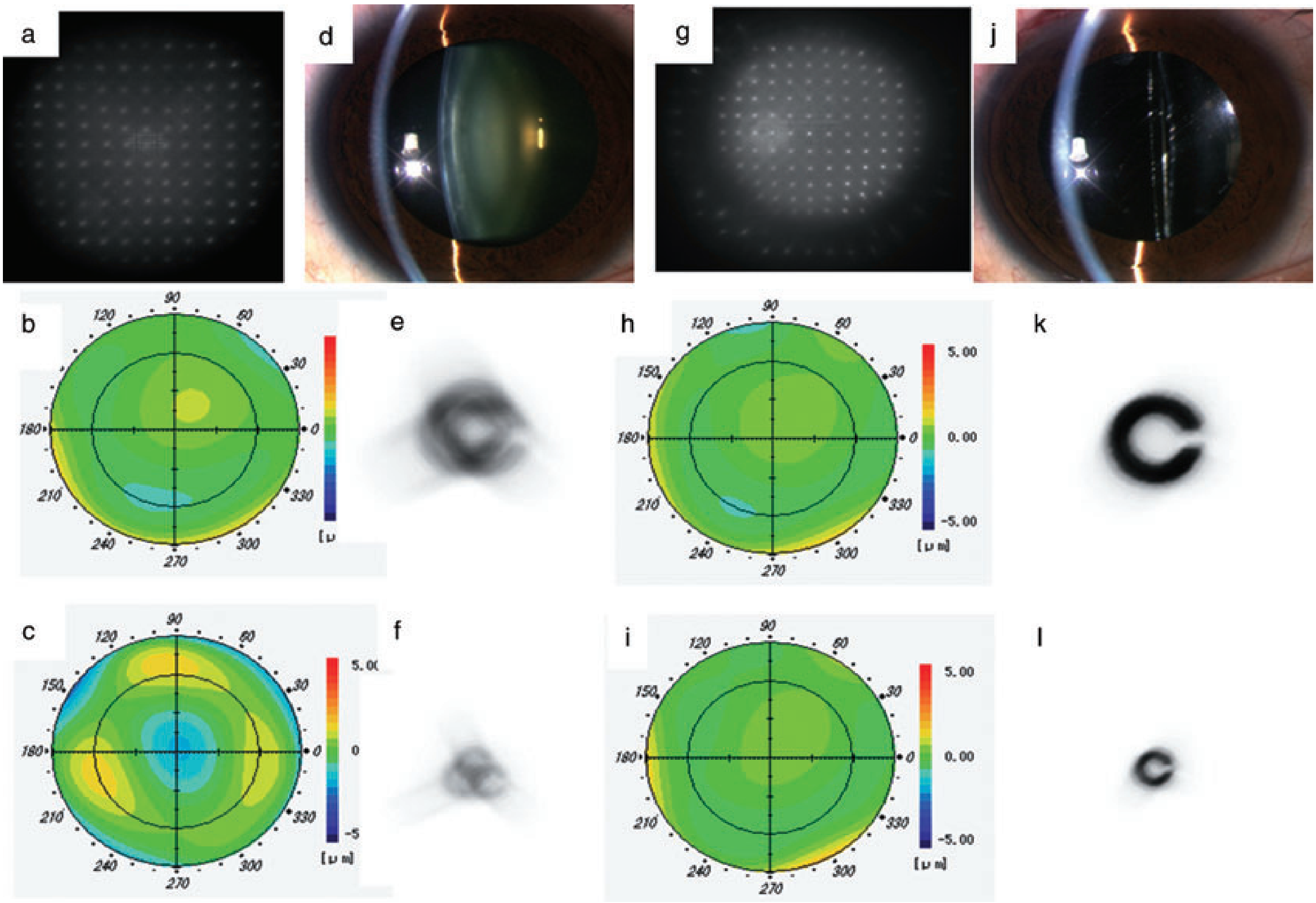

Figure 6. Hartmann–Shack aberrometer images and the maps of corneal and ocular higher-order aberrations before and after cataract surgery (from Fujikado *et al.*[83]). Hartmann images show a concave pattern before surgery (a), and a normal pattern after surgery (g). The maps of ocular higher-order aberrations show a delayed wavefront in the center and trefoil pattern in the peripheral area before surgery (c) and normal pattern after surgery (i). The maps of corneal higher-order aberrations show almost normal pattern before (b) and after (h) surgery. The simulated retinal images for a Landort C show triple configuration before surgery (e, f) and normal pattern after surgery (k, l). Slit lamp photographs before surgery (d) and after surgery (j).

The concept of aberration-correcting IOL has been proposed.[94] Excellent centration[95] and minimum tilt are required to maximize the visual effects of aspherical or wavefront-corrected IOLs. Even with conventional spherical IOLs, excellent centration and minimum tilt are important factors to reduce the surgery-induced HOAs.[96] The tilting of the lens induces considerable amount of ocular coma-like aberrations in cases of scleral-sutured IOLs.[97]

On the other hand, the coma-like aberrations of the cornea contribute to an apparent accommodation in pseudophakic eyes.[98] Although it is important to reduce the HOAs for better optical quality of the image, the depth of field might be reduced. Therefore, a trade-off between a sharper image and an increase in the depth of focus should be considered while selecting an IOL based on the expectations of the patient.

ACCOMMODATION

Aberrometry before and during accommodation in young adults showed that spherical aberration changed significantly towards negativity without a significant increase of the total HOAs.[99–101] As a matter of course, only small changes in the spherical aberration occur in older subjects.[102] So, spherical aberration can be used as an index of accommodation, and the increased aberration results from a change in the shape of the lens during accommodation. Also, accommodative miosis is useful for ameliorating the increase in the HOAs during accommodation.[103]

Therefore, it is possible to diagnose cases of accommodation spasm by the amount of negative spherical aberration during far vision. Excessive accommodative tone can be detected objectively by the negative spherical aberration, and the effect of a cycloplegic agent can be easily judged by noting that the spherical aberration recovers towards normal positive values.[104]

SCLERAL BUCKLING PROCEDURES

It is possible to evaluate the effects of various ocular surgeries on the quality of vision by aberrometry. For example, scleral buckling surgery was found to increase the HOAs significantly. Segmental buckling increased the HOAs to a greater extent and for a longer duration than the encircling procedure, and the direction of coma aberration corresponded to the location of the segmental buckle.[105]

CLINICAL SETTING

It is important to understand the characteristics of wavefront measurements. Wavefront refractions are not as precise as standard autorefractions; however, it is not clinically significantly worse.[106] Similar to the corneal power map, the usefulness of an absolute scale compared with a floating scale for the interpretations of the wavefront map has been suggested.[107] In terms of stability, the increased variability in the aberration maps between days and months indicates biological fluctuations.[108]

CONCLUSIONS

In spite of the widespread use of wavefront-guided refractive surgery, the application of wavefront technology is still at an early stage in ophthalmology. Most of the aberrometers in the eye clinics are not used to evaluate the optical quality of the eyes but mainly for wavefront-guided refractive surgery.

Still, there are limitations and rooms for improvements in currently available wavefront sensors. Most of them cannot do serial measurements, and also cannot measure wavefront aberrations for eyes with sever irregular astigmatism. With the advances in the evaluation of optical quality of the eye, the answers for the current controversies such as topography-guided *versus* wavefront-guided ablations, wavefront-optimized *versus* wavefront-guided ablations or Zernike expansion *versus* Fourier expansion or effectiveness of spherical aberration neutralizing IOLs will be shown.

As shown in this article, wavefront analyses provide a large amount of information on the quality of vision in normal eyes, in aged eyes, and in eyes with different pathological conditions. We believe that this technology has enormous potential to alter our way of thinking about visual functions, refractive errors and their correction. It has already contributed to the diagnosis and treatment of many ocular diseases in the clinic, and with the aid of basic research, it should improve the treatment of patients.

In the future, we believe that wavefront analysis will be performed at the clinic not only for refractive surgery but also for the diagnosing and treating most of the eye diseases that will influence to the quality of vision of the eye.

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