

High-order Aberrations in Keratoconus

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ABSTRACT

With all the technological advances today and the increasing number of people undergoing refractive surgery, the importance of detecting keratoconus (KC) prior to surgery has become evident. Although by using a topographer we can detect early stage KC, however, by using wavefront analysis technology, we are able to detect KC at an even earlier stage.

Every eye possesses a number of aberrations. However, in a KC patient's eye, there are approximately five to six times the numbers of high-order aberrations (HOAs) than in a healthy eye. Using this technology to detect and assess the HOAs, it was found that in a KC cornea, it is possible to detect at a very early stage a much higher value of vertical coma aberrations compared with a normal eye. By using this technology, it is possible to study and understand the characteristics of the quality of the image on the retina, thereby understanding its impact on the patient's visual quality.

Keywords: Aberrations, High-order, Keratoconus, Vertical coma, Wavefront.

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INTRODUCTION

The eyes of keratoconus (KC) patients have five to six times more high-order aberrations (HOAs) than in a healthy eye.^{1,2} Keratoconus patients complain of blurry vision, glare, and diplopia, even at the early stages of the disease. With progress in technology and the large number of people undergoing refractive surgery, the importance of detecting KC prior to surgery has become evident. Although we are generally assisted by the topographer, it seems that there is a different technology that enables us to detect KC at a much earlier stage.³ Over the years, many studies have researched HOAs in KC patients (Table 1).

Keratoconus is a bilateral progressive noninflammatory disease characterized by a bulge and thinning of the cornea. The incidence is approximately 1:2000 in the general population.⁴ As the disease progresses, the

Table 1: A list of selected research papers dealing with HOAs in KC patients

| Year published | Authors name | Title |
|----------------|---------------------|--|
| 2002 | Naoyuki et al | Wavefront aberrations measured with Hartmann–Shack sensor in patients with KC |
| 2005 | Marine et al | Corneal wavefront aberration measurements to detect KC patients |
| 2006 | Jorge et al | Corneal higher order aberrations: A method to grade KC |
| 2007 | Seth et al | Characterizing the wave aberration in eyes with KC or penetrating keratoplasty using a high-dynamic range wavefront sensor |
| 2007 | Okamoto et al | Higher-order wavefront aberration and letter-contrast sensitivity in KC |
| 2007 | Jafri et al | Higher order wavefront aberrations and topography in early and suspected KC |
| 2007 | Buhren et al | Defining subclinical KC using corneal first-surface higher-order aberrations |
| 2008 | Tan et al | How KC influences optical performance of the eye |
| 2009 | Pinero et al | Pentacam posterior and anterior corneal aberration in normal and KC eyes |
| 2009 | Sabesan et al | Visual performance after correcting higher-order aberrations in KC eyes |
| 2010 | Radhakrishnan et al | Dynamics of ocular aberrations in KC |
| 2010 | Atchison et al | Peripheral ocular aberrations in mild and moderate KC |
| 2011 | Mihaltz et al | Mechanism of aberration balance and the effect on retinal image quality in KC: Optical and visual characteristics of KC |
| 2013 | Colak et al | Comparison of corneal topographic measurements and high order aberrations in keratoconus and normal eyes |
| 2013 | Feizi et al | Correlation between corneal topographic indices and higher-order aberrations in KC |
| 2016 | Hashemi et al | Pentacam top indices for diagnosing subclinical and definite KC |

anterior corneal structure changes and causes an increase in the refractive powers of the central cornea, asymmetry in the curvature between the upper and the lower cornea (with the lower cornea having a higher curvature), and a shifting of the meridian of the curve away from the horizontal plane. These changes cause an irregularity of the cornea, resulting in high astigmatism and HOAs, causing the patient to experience distorted and decreased

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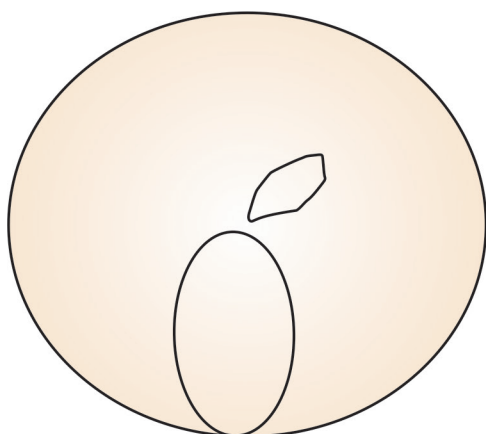


Fig. 1: The most common pattern in KC patients

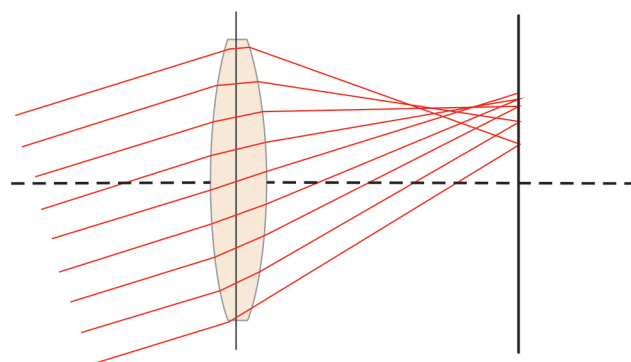


Fig. 2: Coma aberration; this is an aberration caused by a wide, oblique-angled bundle of light rays. The image created by a point far away from the optical axis is not sharp and is shaped like a coma (comet). The image created is of rings growing in size. Each ring is the image created from a specific area of the lens (cornea), thus creating a comet shape

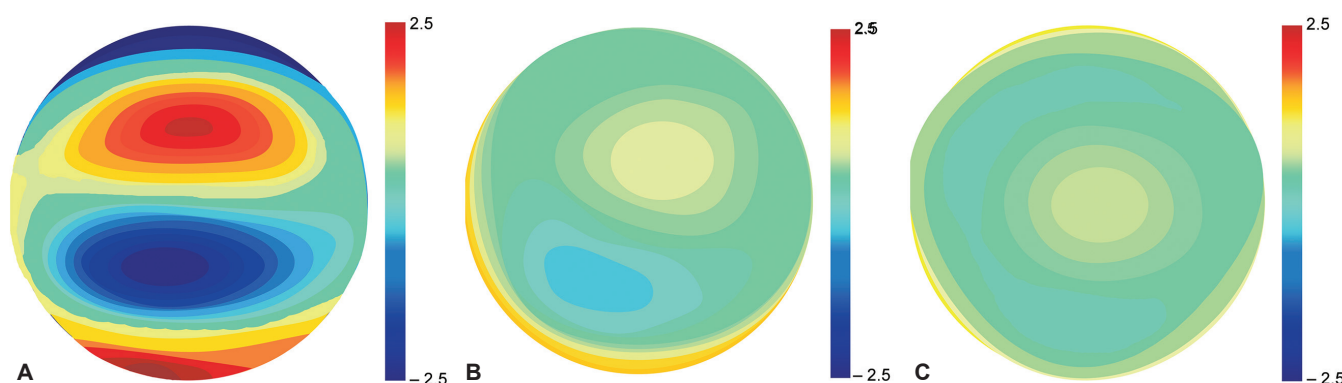
vision. The hallmark sign of KC is irregular astigmatism. Today, the most common method for early detection of KC is using a corneal topographer, where the most common pattern seen in KC patients is the asymmetric bowtie pattern with a skewed radial axis pattern (Fig. 1).^{4,5} This pattern is rarely seen in a healthy eye.

The topographer enables us to diagnose KC before clinical signs of the disease appear, i.e., Fleischer Ring, Vogt's Striae, etc.⁴ Despite its advantages, this method has many limitations as it only measures the anterior cornea, and a shift in the reference point or the visual axis can cause curvature reading errors. The posterior cornea's elevation function supplies more accurate data of the shape of the cornea and this method is now becoming popular as another screening tool for KC. In this article, we intend to explore another different method that enables detection of KC at an even earlier stage with wavefront analysis technology.³

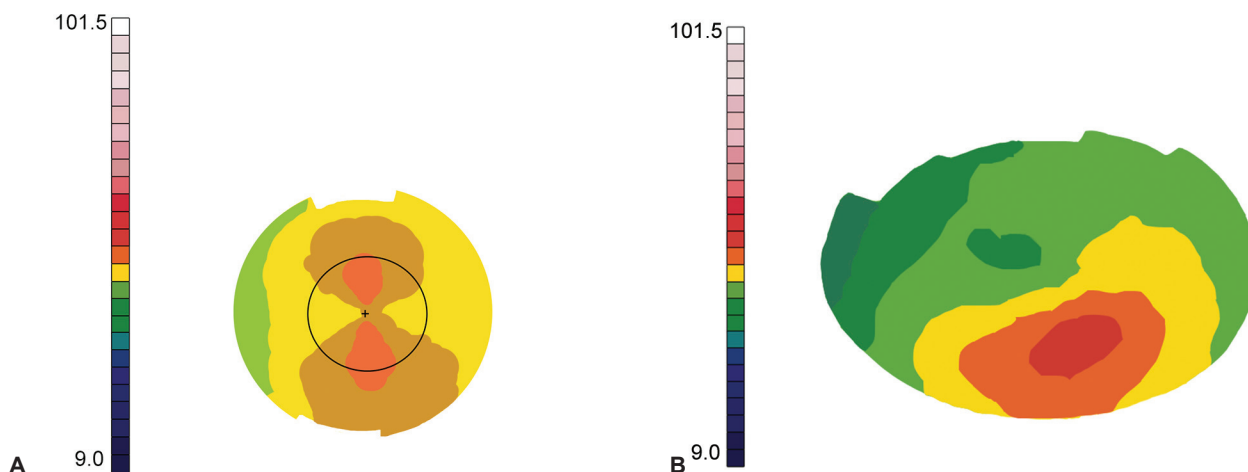
The anterior cornea has the largest impact on the eye's full refraction because of the large difference between the refractive index of air and that of the cornea. Therefore, in distorted corneas like in KC, the anterior surface is the main cause of optical errors. For this reason, analysis of anterior

corneal aberrations is an effective tool in detecting and grading KC. Every eye has aberrations including HOAs.⁵ However, a KC eye has five to six times the amount of HOAs than a normal, healthy eye.^{1,2} In order to assess and study the HOAs, wavefront analysis technology can be used.

Failure to detect early-stage KC can result in serious outcomes, for instance, the patient has to undergo refractive surgery. Retrospective studies have shown that the majority of people that have had laser-assisted *in situ* keratomileusis (LASIK) surgery and who have later been diagnosed with ectasia are actually KC or pellucid marginal degeneration sufferers, who were not diagnosed preoperative. Performing refractive surgery on such a cornea can evoke deterioration. It was also found that in these patients, topography mapping had been performed without a KC finding prior to surgery. These studies^{3,4,6-8} demonstrate the need to find and use a better diagnostic tool. Earlier diagnosis could have a great impact on clinical decision-making. Trials that were performed using wavefront technology in different aberrometric appliances, such as the Pentacam® (Oculus, Germany) and LADARWave® (Alcon, USA), found that in KC corneas, it is possible to



Figs 3A to C: Corneal HOAs measured by the Orbscan appliance. The left circle belongs to the early-stage KC. It is apparent that the coma aberration is very dominant. The center circle represents the fellow eye of patients from the first group of KC patients. This eye has suspected KC with no clinical signs. Using this examination, it is possible to see a small amount of coma aberration, even at a very early stage when there is only suspected KC. The right circle represents the control group with healthy eyes, showing no sign of the aberration⁶



Figs 4A and B: (A) Topography map of a normal eye demonstrates the asymmetric bowtie pattern consistent in with-the-rule astigmatism. (B) The topography map of an eye with suspected KC shows the AB/SRAX pattern. The patient showed no clinical signs of KC

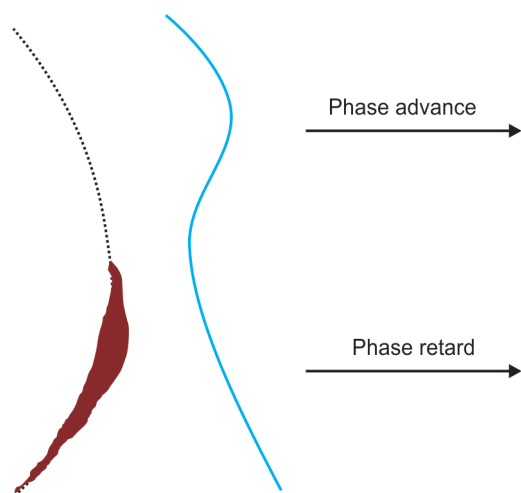


Fig. 5: (A) Diagram illustrating the theoretical cause of vertical coma in KC eyes – the actual cornea (represented by the solid line) – deviates from the ideal cornea (dotted line) via a relative depression on the superior portion and relative protrusion on the inferior portion of the cornea. Using a Shack–Hartmann sensor, it can be seen that light coming out of the eye exits first from the superior half of the cornea. The transition from the cornea to air increases the gap even more

detect, even at a very early stage, a significantly higher value of the vertical coma aberration (Figs 2 and 3A to C) compared with a normal eye.^{1,3-6,8} A normal value counts as 0.32 ± 0.28 , whereas in a suspected KC eyes, higher values are found (Figs 4A and B) due to the change in the shape of the cornea (Fig. 5).

In KC eye, the apex of the cornea is usually located in the inferior area of the cornea. Therefore, the superior area is flatter. When the aberrations are measured, light is returned from the retina and exits the eye faster from the superior area and is delayed leaving the inferior area. This gap is magnified further by the fact that when the light exits the superior cornea, it starts traveling even faster as air has a lower refractive index, thus creating the vertical coma aberration.¹ In a topographical map, we

regard a vertical asymmetry as indicating suspected KC; by using wavefront technology, it is possible to find this asymmetry earlier as this is the reason for the appearance of the coma aberration. Mihaltz et al³ reported findings included measuring horizontal asymmetries by aberrometric examinations, which was significant only in patients with subclinical KC. The authors suggested trying out a new topographical pattern, which is pattern D. Three patients with horizontal asymmetry developed ectasia after undergoing LASIK, with no risk factors apparent prior to surgery. These findings confirm the fact that horizontal asymmetry and horizontal coma can also be a significant sign of early-stage KC. The wavefront technology enables even earlier detection of KC and is also a way to grade the stages of KC (up to the late stage where the amount of aberrations is too high to measure). Obviously, the combination of topography and wavefront technology will give the most accurate diagnosis.

EFFECT OF HOAs ON THE QUALITY OF THE VISION

By using wavefront technology, it is possible to study and understand the correlation between the qualities of the image on the retina, which is affected by the HOA, thus enabling a deeper understanding of their effect on the patient’s visual quality outcome. The technology enables us to examine the point spread function (PSF). The scattering of the light from the original projection spots to the retina. This shows the amount of blur of the image appearing on the retina.

It is possible to see a decrease in the quality of the image portrayed on the retina due to the coma and astigmatic aberrations in a patient with suspected KC (subclinical) and PSF in KC patients, which is even more distorted, whereas in the control group, with normal eyes, the PSF found is small and round. This enables us to understand

why KC patients complain of glare and monocular diplopia, even with an early stage of KC.³ Researchers have shown a direct connection between HOAs and contrast sensitivity (CS). They found that CS was lower in KC patients. This is caused by the effect of the spherical aberration and the coma aberration in KC patients, especially the coma, which is extremely significant in KC patients.

LogMAR best spectacle-corrected visual acuity was measured and was significantly lower in KC eyes than in the normal control group. This is also directly linked to aberrations. However, in the normal control group, no connection was found between the LogMAR and the HOAs or between the CS and HOAs. We understand from this that the CS test is a very sensitive test in evaluating visual disturbances caused by HOA increases in the eye. (In cataract patients, there is also an increase in HOAs and as a result a decrease in CS).⁹

In another study,¹⁰ the effect of the position, shape, and size of the cone on the amount of HOAs and the quality of the vision was studied. The findings were as follows:

- When the cone is positioned in the center, between the center of the visual axis and periphery, the highest amount of HOAs is apparent.
- The larger the pupil, the more the HOAs.
- With a small pupil, a medium-sized cone will have the most HOAs, and with large pupils, a large cone will create the most HOAs.
- The most aberrations will be present when the cone is "off-center" and the cone's curve covers the majority of the vision area.
- A medium-to-large size cone located between the visual axis and the periphery with an irregular shape will cause the most HOAs. If the pupil is large, then a medium-sized cone located there will cause much less HOAs as less of the cone falls in the vision area. The ratio between the size of the cone and that of the pupil has a large effect.

The question of whether correcting the HOAs would cause an improvement in the vision of KC patients was studied. It seems that because of adaptation to a blurry retinal image, these patients' vision did not improve, even when correcting fully the highest aberrations. This was compared with a regular eye, where correcting the HOAs caused an improvement in both the CS and the VA.

The visual system consists of optic and neurological components. While the optical components can be corrected, it seems that the neurological parts restrict the improvement.

Studies comparing the correction of HOAs in myopic and emmetropic eyes (without KC) have been conducted. The findings showed that correcting the HOAs

in myopic eyes had much less visual improvement than in emmetropic eyes. The visual nervous system adapts to optical blurs. It may be possible to improve the vision by treating the neural adaptation by reducing the neural system's effect on the visual input. In KC patients, who have five to six times more HOAs as mentioned before, the adaptation to a blurry image is even higher, so it is harder to improve the vision. Some studies suggest that the adaptation to a blurry optical image causes the visual system to be less sensitive to diffraction and causes limited retinal quality. Therefore, the improvement in the visual quality outcome is limited. Improvement in the quality of the image on the retina after correcting the HOAs in KC patients can be seen. However, the actual visual acuity shows no improvement.²

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