Source: Cologne College of Optometry
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Wavefront Correction of Higher Order Aberrations with Contact Lenses

For more than 150 years, optometrists have measured the best spherocylindrical correction of their patients. Higher-order aberrations of the human eye have not been taken into account. In recent years, scientists have started to discuss whether or not an individually designed, customized wavefront correction with contact lenses will be possible in the near future. This debate was initiated by LASIK surgeons, who had accidentally created serious higher-order aberrations through refractive surgery, and is now being continued among spectacle lens and contact lens designers. The following article addresses basic optical properties and important physiological aspects connected to the wavefront correction of higher-order aberrations.

Aberrations of the Human Eye

According to the laws of geometrical optics, a perfect (non-aberrated) eye focuses a bundle of parallel light rays into a point inside the photoreceptor plane of the retina. In reality, the human eye is not a perfect optical system, but has a number of aberrations which degrade image quality.

Light Diffraction

Light diffraction limits spatial resolution of the human eye, when the pupil diameter is smaller than 2.5 mm. Even in the absence of other aberrations, each bright point in the image plane is surrounded by diffraction rings - the Airy disk - which blur the image. With pupil diameters larger than 2.5 mm, diffraction at the circular pupil is less disturbing, because the diameter of the Airy disk decreases and the spacing of retinal photoreceptor mosaic becomes the essential factor which limits visual acuity.

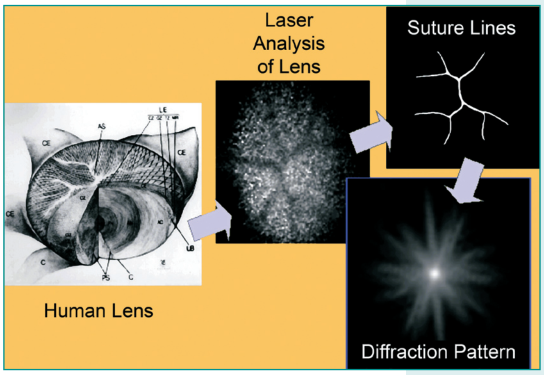

Fig. 1: Due to diffraction at interior structures of the eye lens, a point source of light is imaged as a starburst diffraction pattern on the retina (from Navarro and Losada, 1997, with kind permission)

Diffraction, however, is also responsible for light streaks many people observe around bright light sources. These starburst patterns can be caused by diffraction at biological structures such as eyelashes, the iris and the fissures inside the onion-skin-like human eye lens (Fig.1.) Image defects due to diffraction cannot be compensated by wavefront correction.

Chromatic Aberration

The focal length of the eye increases with wavelength. The difference in refractive power between 400 nm (blue) and 700 nm (red) is astonishingly large (> 2 D, Fig.2.) Optometrists use the image blur caused by chromatic aberration for the red-green test in subjective refraction.

Spectacles or contact lenses correct the human eye only for a single wavelength. In daily life, however, we are always confronted with multi-colored or white light objects. The different wavelengths emitted by visual objects cannot be focused on the retina simultaneously.

It is clear that chromatic aberration cannot be corrected with wavefront correction because a true color correction requires an achromatic optical system consisting of several lenses with different Abbe numbers.

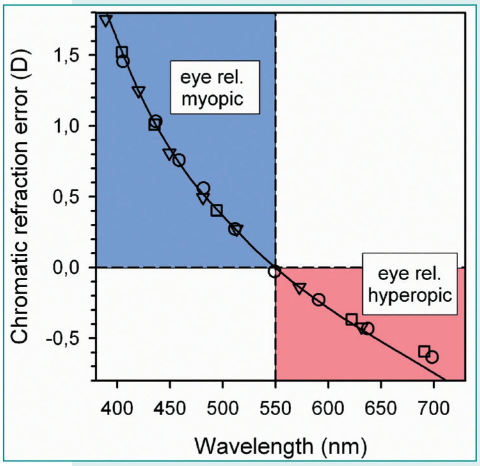

Fig.2: Chromatic aberration: Y-axis: spherical refractive error relative to the "reference wavelength" of 550 nm. The eye is -1.5 D short-sighted for a wavelength of 400nm. For red light of 700 nm, the eye is 0.7 D farsighted. Spectacles or contact lenses can correct the eye only for a single wavelength.

Light Scatter and Fluorescence

Scars in the cornea, oedema or an incipient cataract reduce the transparency of the optical media and scatter parts of the incoming light. In addition, blue or UV-light causes a disturbing fluorescence inside the human lens. Scattered and fluorescent light both reduce the image contrast on the retina. These effects cannot be compensated by wavefront correction.

Higher-Order Aberrations

In addition to the image defects mentioned above, the eye has numerous other aberrations. They can be divided in two classes of image defects. Prismatic, spherical and cylindrical refractive errors are lower-order (first- and second-order) aberrations. Coma, trefoil, spherical aberration and numerous other errors are higher-order aberrations. These two classes of aberrations are classified as "monochromatic" aberrations, because they deteriorate retinal image quality even when the scene is illuminated by monochromatic light. The magnitude of the image degradation increases with the pupil diameter.

Zernike Polynomials

Today, many optical scientists analyze monochromatic aberrations in terms of Zernike polynomials. Each Zernike polynomial represents a single elementary aberration such as coma, trefoil or spherical aberration. Each Zernike polynomial characterizes an "aberration mode" similar to the "acoustical modes" (i.e. higher harmonics) of a vibrating membrane.

The advantage of Zernike formalism is that the three traditional refractive errors (prism, sphere and cylinder) used in optometry can be associated with the lower-order Zernike polynomials. Therefore, the Zernike formalism is a vivid description that fits ideally into the conceptual framework of optometry.

The complete monochromatic refractive error of a real eye can be written as a weighted sum of elementary Zernike polynomials. This sum is a mathematical description of the total wavefront aberration and is measured in units of microns.

Total wavefront aberration = prismatic effect + spherical ametropia + astigmatism + coma + spherical aberration + trefoil + 2nd order coma + quadrefoil + …+ ….

An example of the Zernike polynomial Z_3^{-1} which characterizes vertical coma is visualized in Fig. 3. The colored circle in the upper right panel is a frontal view onto the pupil of the eye. The color at every point denotes the wavefront error. Blue indicates that the actual wavefront is attenuated compared to an ideal, non-aberrated wavefront. The color saturation is a measure of the size of the wavefront error. More saturated colors indicate larger errors. Red means that the actual wavefront reaches this point of the pupil earlier than an error-free reference wavefront. Green denotes points inside the pupil where the error is close to zero. An eye with this kind of vertical coma has a positive refractive power in the middle of the upper half of the pupil which is caused by the convex wavefront visible in the upper left panel of Fig. 3. In the lower half of the pupil we find a concave wavefront which is associated with a negative refractive power. An eye which has no errors except vertical coma creates a retinal image of a point light source that resembles the tail of a comet as illustrated in the lower right panel of Fig. 3.

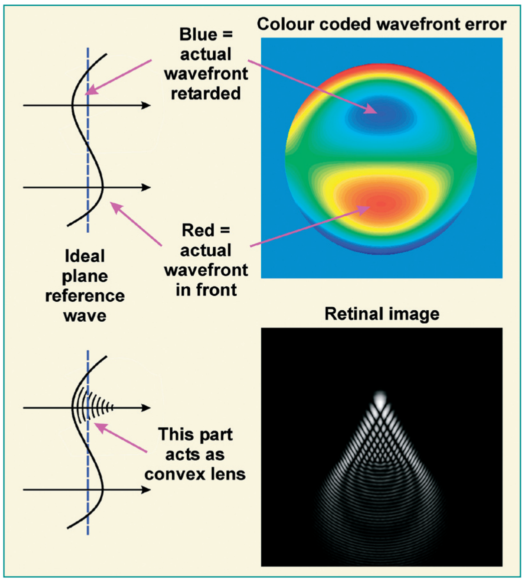

Fig. 3: Top right panel: Color-coded illustration of vertical coma. Left panels: vertical sections through the centre of the pupil. Lower right panel: Retinal image obtained with vertical coma.

Measurement of Wavefront Aberrations

For a few years now, it has been possible to measure the eye's higher-order aberrations with commercially available instruments, which incorporate a wavefront sensor such as the Hartmann-Shack sensor. These aberrometers measure the deviation of the actual wavefront from an ideal wavefront and decompose the wavefront error into Zernike polynomials. Stated in a simplified manner, the result of an aberrometer measurement is an individual "fingerprint" of the wavefront error distribution across the pupil of the eye. The question of how to compute the best objective refraction from the wave aberration data is still debated (Guirao and Williams, 2003, Thibos et al., 2004, Iskander et al., 2007, Pesudovs et al. (2007).) At present, different scientists prefer different algorithms to transfer Zernike polynomials into sphere, cylinder and axis values.

How large are Higher-Order Aberrations?

Higher-orderaberrations of human eyes are usually fairly small. Wavefront errors in patients with healthy eyes are normally smaller than 1 micron. However, patients with pathological disorders of the eye →

such as keratoconus may have wavefront errors of up to 10 micron. Thus, keratoconus patients do have a large spherocylindrical ametropia as well as large and irregular higher-order aberrations.

In recent years, the magnitude of higher-order aberrations has been measured in a number of population studies. Results are plotted in Fig. 4. The x-axis indicates the Zernike mode number (Z_3^{-3} to Z_5^{-5}) corresponding to the 6th to 20th Zernike polynomial. The lower-order aberrations (prism, sphere and cylinder) have been omitted. The y-axis plots the magnitude of the particular aberration (RMS error.)

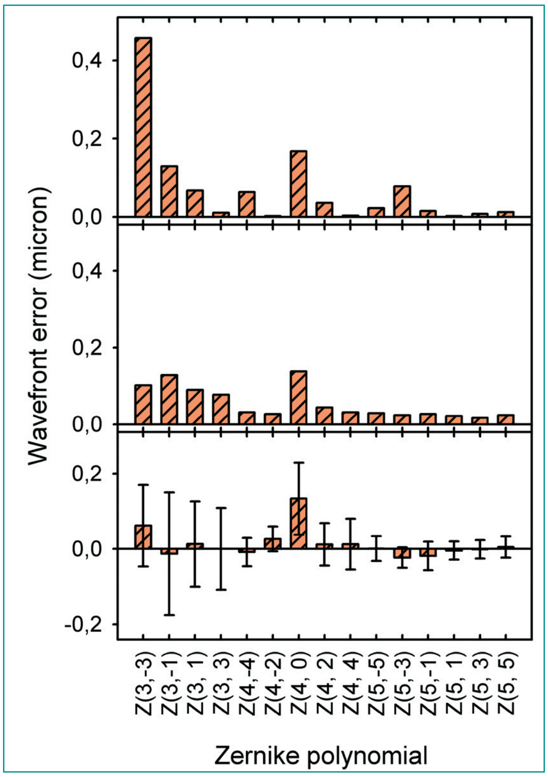

Fig. 4: Magnitude of higher-order aberrations. Upper panel: Aberrations of a single subject. Middle panel: Average values of 109 subjects (absolute values.) Lower panel: Average values of 109 subjects (signed data.) (Redrawn from Porter et al., 2001)

The upper panel in Fig. 4 depicts the higher-order aberrations of the author's right eye. An unusually strong trefoil component (Z_3^{-3}) is clearly visible. Spherical aberration (Z_4^{0}) and second-order trefoil (Z_5^{-3}) stand out against the other Zernike components as well.

The middle and lower panel of Fig. 4 plot results by Porter et al. (2001) which were obtained on 109 normal eyes. The histogram in the lower panel depicts the average of all 109 eyes. It tells us that the average of most higher-order aberrations is almost zero. Apparently, the average human eye does not have any significant higher-order aberrations. The one exception from this rule is spherical aberration (Z_4^{0},) which is present in most unaccommodated human eyes. The large error bar of the Z_4^{0} component, however, indicates large inter-individual variations. This leads to the conclusion that it is obviously impossible to correct spherical aberration of all human eyes with a single aspheric contact lens geometry.

All higher-order aberrations are much smaller than the normal sphere and cylinder powers optometrists have to take care of. According to Williams et al. (2001,) spherical and cylindrical refractive errors amount to 93% of the total refractive error. On average, only 7% of the total refractive errors are caused by higher-order aberrations. Coma and spherical aberration seem to be the most important higher-order components (Charman, 2006.)

It is interesting to note that the higher-order aberrations of the complete eye are normally smaller than the aberrations of the cornea alone. The aberrations of the cornea appear to be partially corrected by the aberrations of the crystalline lens. The positive spherical aberration of the cornea for example, is substantially diminished by the negative spherical aberration of the lens in most eyes. Therefore, a contact lens that neutralizes spherical aberration of the cornea is not a good choice, as a substantial portion of the spherical aberration is already compensated by the eye lens. Even coma of cornea and lens seem to partially neutralize each other (Artal et al., 2006.) Artal assumed that this compensation may be driven by an active growing-process similar to emmetropisation.

Dietze and Cox (2003) found that spherical soft contact lenses with negative power induced a negative spherical aberration. Spherical contact lenses with positive power tended to induce a positive spherical aberration. As most eyes have a positive spherical aberration, a myopic patient appears to profit from the induced aberration, whereas hyperopic patients experience a reduced image quality.

Effect on Visual Quality

The impact of higher-order aberrations on visual quality is quite small. Thibos (2002) investigated the aberrations of 200 healthy eyes corrected with spherocylindrical lenses. In 49% of all eyes, the higher-order aberrations reduced image quality less than the residual astigmatic error, which could not be corrected with the traditional 0.25 D stepsize used in optometry. In addition, Thibos evaluated the equivalent defocus with spherical lenses that reduced image quality as much as the combined higher-order aberrations. He found a mean equivalent defocus of only +0.125 D for a pupil diameter of 3 mm and +0.25 D for a 7.5 mm pupil size, respectively. According to Coletta (2005) the higher-order aberrations for a 6 mm pupil are typically smaller than 0.3 µm, which equals about +0.25 D of defocus.

Contact Lens Correction of Higher-Order Aberrations

The correction of higher-order aberrations is often called "wavefront correction," because the distorted, aberrated wavefront has to be transformed into an ideal, flawless wavefront.

In easy terms, the "dents" in the optical system of the eye have to be compensated by appropriate "inverse dents" in the contact lens.

A wavefront correction with contact lenses can be performed in a multistage procedure that contains the following steps:

1. Assessment of the patient's needs and motivation
2. Full routine eye examination and refraction (biomicroscopy, corneal topography, aberrometry, visual acuity (VA,. contrast sensitivity (CSF,. tear film assessment, etc..
3. Fitting of trial lenses
4. Fitting of the "optimal" rotationally stabilized spherocylindrical lenses with "perfect" back surface geometry and optimal visual acuity. These lenses must have peripheral laser engravings which allow a video evaluation of the CL orientation on the cornea
5. Video evaluation and documentation of the exact position and orientation of the lenses on the cornea of the patient
6. Calculation of a patient-specific, "customized" contact lens with the same back surface geometry which incorporates all data about the actual orientation and centration obtained in step 5
7. Transmission of calculated data to manufacturer, fabrication of CL
8. Fitting of customized CL, video verification and documentation of CL position on the cornea
9. After a waiting period: measurement of VA and CSF and assessment of residual higher-order aberrations by aberrometry with the contact lenses in place.
10. If necessary, fabrication of new optimized wavefront-correcting contact lenses and continuation of the fitting procedure from step 4

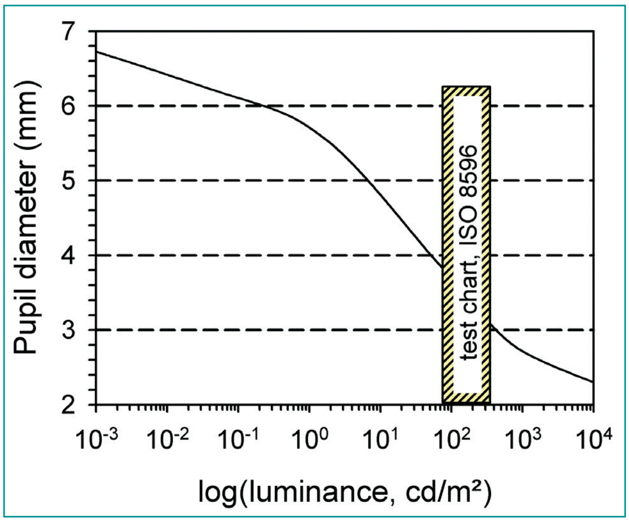

Fig. 5: Pupil diameter as function of stimulus luminance. (Redrawn from Farrel und Booth, 1984)

Optical and Physiological Aspects

Pupil Diameter

According to Wilson (2002) and Howland (2002) higher-order aberrations depend strongly on pupil diameter (Fig. 5.) Below pupil diameters of 2.5 mm wavefront errors seem to be completely unimportant for visual quality.

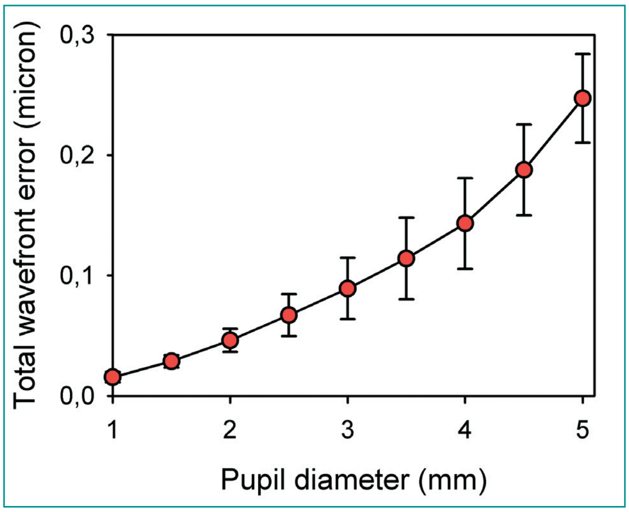

Fig. 6: Magnitude of total higher-order aberrations as function of pupil diameter (Redrawn from Wilson, 2002)

Farell and Booth (1984) measured the pupil diameter as a function of field luminance (Fig. 6.) They found a pupil diameter of about 3.5 mm for the luminance proposed for standardized indoor visual acuity tests (80 to 320 cd/m², ISO 8596.) In this context, Charman (2006) wrote: "It appears that the pressures of evolution have left the typical uncorrected human eye with only modest levels of axial higher-order aberrations for the small pupil diameters (< 4 mm) found under photopic daylight conditions."

On the other hand it is well known that the optical performance of the eye is not optimal at large pupil diameters so that retinal image quality may benefit from a correction of higher-order aberrations. Large pupil diameters, however, occur only at low mesopic or scotopic light levels, where visual acuity and contrast sensitivity are reduced due to the limited neural performance of the visual system. In addition, human eyes tend to become more myopic when viewing a distant object at low light levels (night myopia) and accommodation becomes less stable and less accurate. An example of intrinsic steady-state errors of the accommodative response is presented in Fig. 7. At short viewing distances (i.e. dioptric stimulus values lower than 2 D in Fig.7,) a substantial "under-accommodation" →

occurs that increases with decreasing luminance and is responsible for a serious image blur.

It is not clear how an improved retinal image quality and a reduced neural performance will interact. At present further experimental investigations with real patients and under real life conditions seem to be necessary. These might reveal to what extent visual quality can be improved by a higher-order correction at low light levels.

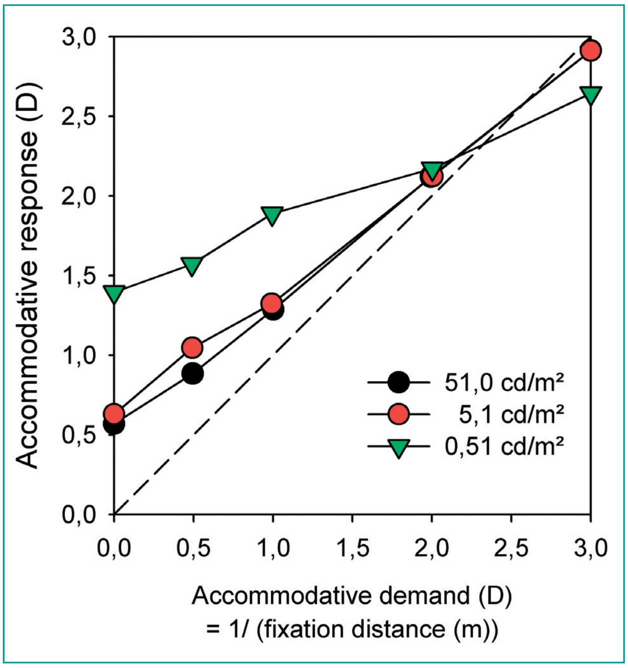

Fig. 7: Lag and lead of accommodation for three luminance levels. The retinal image is only in perfect focus when the data points fall exactly onto the dashed diagonal line. This is obviously not the case for most viewing distances and mesopic light levels. (Redrawn from Johnson, 1976)

Accommodation

Williams et al. measured higher-order aberrations of patients who fixated targets at different distances and found substantial changes with accommodation (Fig. 8.) He commented his findings with the words: "It is clear, that for each subject there are substantial, systematic changes in the aberrations that depend on accommodative state. This means that a higher-order correction tailored for distance vision would not be appropriate for near viewing and vice versa" (Williams et al., 2001, p.25.) The conclusion that can be drawn from their results is that it is impossible to correct higher-order aberrations for far and near distances simultaneously with contact lenses.

Williams' results were confirmed by Plainis et al. (2005) who demonstrated that a higher-order correction for distance led to reduced image quality for near objects. The most systematic change occurred for spherical aberration. The magnitude of the change was linearly related to the accommodative response. The average change was 0.048 µm/D.

It is interesting to note that overall image quality was varyingly affected by accommodation. Some subjects had their best image quality at far, others at near, and others at intermediate accommodative levels.

Image Quality Fluctuations

Hofer et al. (2001) found rapid changes of higher-order aberrations. Planis et al. (2005) observed that these fluctuations are smallest for distance (< 0.1 D) and increase with accommodative demand to values of ≈ 0.3 D. The fluctuations are caused by a feedback instability of the accommodative control circuit. It has been suggested that the fluctuations may play a functional role in optimizing image quality by producing continuous changes in retinal image contrast.

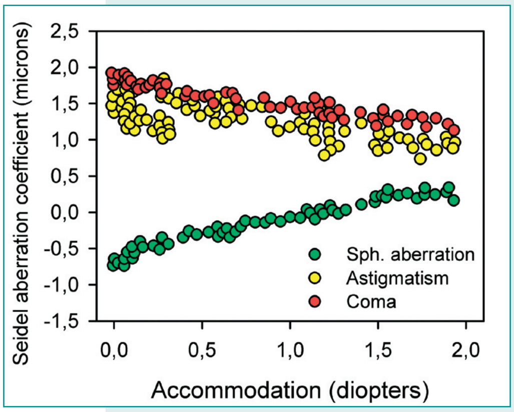

Fig. 8: Change of three higher-order aberrations with accommodation. (Redrawn from Williams et al., 2001)

Koh et al. (2006) investigated changes in higher-order aberrations associated with blinking. In a subgroup of patients, they identified a substantial increase of coma-like aberrations after blinking, which was probably caused by asymmetric changes in tear film thickness.

In addition, higher-order aberrations are known to change with the time of day and with age. In elderly patients studied by Jahnke et al. (2006,) coma was ten times stronger than in the younger subjects.

CL Decentration and Orientation

A spherocylindrical ametropia can be corrected with a spherocylindrical spectacle lens or contact lens even when the patient does not look exactly through the centre of the optical zone of the lens. A contact lens sitting on the eye in a decentred position exhibits a prismatic effect, which can be estimated by Prentice's formula. The prismatic deviation alters the apparent position of a visual object, but does not reduce image quality.

A correction of higher-order aberrations with a spectacle lens or a contact lens, however, works only, if the design reference point of the correcting lens is perfectly aligned with the eye's line of sight. Even a small decentration generates new aberrations that deteriorate retinal image quality. This problem is illustrated in Fig. 9.

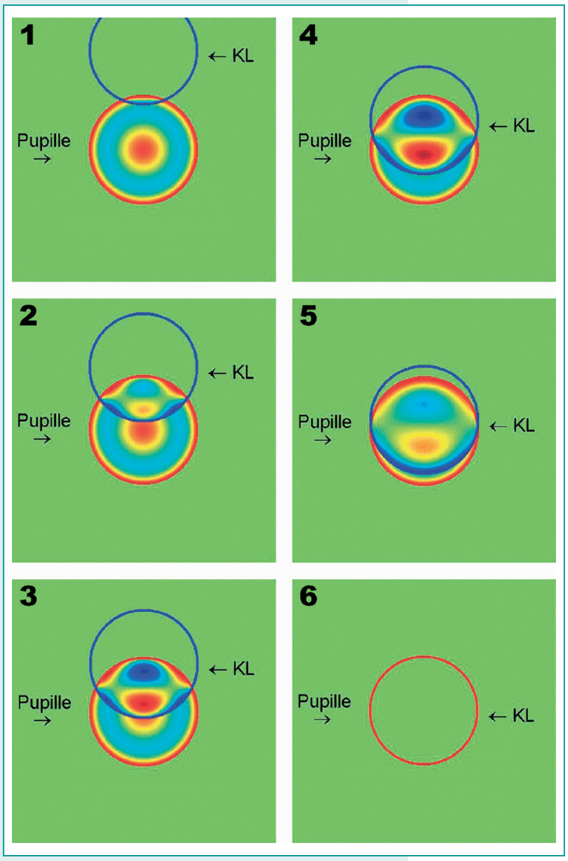

Fig. 9: Correction of spherical aberration with a customized contact lens. When the optical zone of the contact lens is decentred, vertical coma becomes visible in the overlapping area.

In order to simplify the interpretation of the computer simulations presented in Fig. 9, it was assumed that the eye under consideration has no spherocylindrical ametropia and no higher-order aberrations except spherical aberration. The colored circle marked "Pupille" represents a front view onto the pupil plane of the eye. The colors inside the pupil represent the wavefront errors of the eye as would be "perceived" by an aberrometer that looks straight into the eye.

Fig. 9 visualizes the correction of spherical aberration with a contact lens that has the appropriate inverse spherical aberration which neutralizes the spherical aberration of the eye. The circle marked "KL" denotes the central portion of the contact lens with a diameter equal to the pupil diameter that "carries" the higher-order correction. The six panels in fig. 9 show the contact lens in six different positions. In panel 1, the central zone of the CL is located outside of the pupil and the aberrations of the eye are not corrected. In panel 6, the contact lens is centred to the pupil and the wavefront errors of the eye are perfectly compensated by the CL. This is visualized by the evenly green color inside the circle denoting zero wavefront error. Panels 2 to 5 show four different amounts of decentration[1]. It is clearly visible that the spherical aberration of the eye and the inverse spherical aberration of the decentred contact lens interact in an undesired manner. As a result, artificial coma is generated in the overlapping area, which substantially reduces retinal image quality. The magnitude of artificial coma is strongest in panel 4 corresponding to a decentration of 1/4 of the pupil diameter.

Contact lens specialists are aware of this phenomenon. Coletta writes in her very interesting article of 2005: "Studies of visual performance with aspheric vs. spherical GP lenses, however, have shown that subjects prefer spherical GPs. One reason for this paradoxical result may be that on-eye positioning and stability are more critical for aspheric lenses than for spherical GPs."

The findings presented in Fig. 9 are not only valid for spherical aberration, but for all other higher-order aberrations as well. A small contact lens decentration destroys the desired wavefront correction and produces new aberrations. In the decentred position, retinal image quality can be worse than without any wavefront correction at all. According to the results of these computer simulations, a decentration of less than 0.3 mm and a rotation of less than 3 degrees seem to be tolerable.

Current Status

Technical Problems

The fabrication of a wavefront correcting contact lens is a highly demanding task because higher-order aberrations of healthy patients are normally smaller than 1 µm. A manufacturing precision like this cannot be achieved with traditional grinding and surfacing methods. Kruesi (2007) modified the front surface of contact lenses with an Excimer laser and managed to reduce the higher-order aberrations of the eye considerably. He was, however, somewhat disappointed about the increase in visual quality being very small and not significant.

Visual Acuity in normal Subjects

Yoon and Williams (2002) carried out laboratory experiments in order to measure the potential increase in visual acuity and contrast sensitivity. They used an adaptive optics system that incorporated a Shack-Hartmann wavefront sensor to measure the eye's imperfections and a deformable mirror to correct them. With this system, they were able to provide the eye with the best possible image quality and obtained an increase in visual acuity of about 0.05 log MAR units. Jeong et al. (2003) found a visual acuity increase of 0.04 log MAR units. The increase was statistically →

significant, but definitely not "eagle vision."

Visual Acuity in Keratoconus

Jeong et al. (2003) measured the visual acuity increase after wavefront correction in a patient with keratoconus. In cooperation with a contact lens manufacturer, they were able to fabricate an individually designed contact lens, which corrected the strong wavefront aberrations of the patient. With this lens, Jeong et al. found a fascinating visual acuity increase of 4 lines on a visual acuity chart.

Contact Lenses which correct Spherical Aberration

Considering the enormous technical, optical and physiological problems that impede a perfect wavefront correction with contact lenses, a couple of manufacturers have decided to simplify the problem. They try "wavefront correction light" by correcting spherical aberration only. This attempt has two essential advantages. Firstly, these lenses do not have to be rotationally stabilized. Secondly, different patients do have at least similar spherical aberrations (cf. Fig. 4). Such a contact lens has to sit in a position exactly centred to the optical axis of the eye. Otherwise the patient will observe a reduction in image quality because of coma-like aberrations as discussed in Fig. 9. Dietze and Cox (2004) reported results of experiments with different aspheric soft contact lenses. They measured that these lenses did in fact cut down the spherical aberration of the eye, whereas a significant increase in visual acuity was not found. Lindskoog Petterson et al. (2007) fitted two types of commercially available aberration controlled contact lenses to 42 patients and found that these contact lenses did not correct spherical aberration, but changed the originally positive spherical aberration into a negative spherical aberration of almost equal magnitude. A significant correlation between aberration and contrast sensitivity or visual acuity was not found.

Summary and Conclusion

Under daylight conditions, retinal image quality is mainly reduced by ordinary spherocylindrical ametropia, diffraction and chromatic aberration. These problems affect visual quality far more than the combined effect of all higher-order aberrations. Diffraction and chromatic aberration cannot be corrected by wavefront correction.

Higher-order aberrations change with accommodation, blinking and the time of the day. The lag of accommodation leads to a substantial image blur under dim lighting conditions. These physiological phenomena cannot be corrected with contact lenses.

Higher-order aberrations in healthy subjects are normally very small. They may be much larger in pathological cases such as keratoconus patients. In addition, there are some healthy subjects with larger higher-order aberrations than normal. The identification of such individuals by routine aberrometry should prove to be clinically valuable in order to establish which subjects can sufficiently benefit from higher-order correction.

According to experimental results available at present, we cannot expect major changes in visual acuity and contrast sensitivity with wavefront correcting contact lenses under daylight conditions. Normal patients experienced an increase of up to half a line on a standard visual acuity chart, when all higher-order aberrations were perfectly corrected in a laboratory setting. With an incomplete correction, the acuity increase will be correspondingly smaller.

Higher-order aberrations definitely play a progressively more important role the more the pupil dilates, but it is yet unknown to what extent visual acuity and contrast sensitivity can be improved in real life situations under low light levels.

Practical problems arise when the aberration-corrected contact lens decentres during blinks or when it rotates on the cornea, as a decentred lens introduces fairly strong new aberrations that degrade retinal image quality.

In summary, wavefront correction is an interesting challenge that fascinates visual scientists and manufacturers alike. Many scientists hope for a future increase in visual quality.

On the basis of our present knowledge, however, the gain in visual performance will be fairly small in normally sighted subjects with healthy eyes. Therefore, it is still unclear if the small visual benefit justifies the expensive contact lens fabrication and the time-consuming fitting procedure. For the overwhelming majority of our patients, the visual benefits of wavefront correction will probably be less valuable than one might think.

End note

1. If a pupil diameter of 4 mm is assumed, the decentration of the contact lens with respect to the centre of the pupil is 1.8 mm, 1.1 mm and 0.4 mm in panel 3 to 5 respectively.

A list of references can be obtained from the author's website: http://www.hfak.de/dozenten/Wesemann2.htm

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