Vision Research 49 (2009) 1729–1737

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Limitations of the ocular wavefront correction with contact lenses

Norberto López-Gil [a,*], José Francisco Castejón-Mochón [b], Vicente Fernández-Sánchez [a]

[a] *Grupo de Ciencias de la Visión, Instituto Universitario de Investigación en Envejecimiento, Universidad de Murcia, 30100 Murcia, Spain*
[b] *Escuela Politécnica Superior, IE Universidad, Segovia, Spain*

ARTICLE INFO

Article history:
Received 26 September 2008
Received in revised form 25 March 2009

Keywords:
Aberrations
Contact lens
Keratoconus
Keratoplasty

ABSTRACT

We analyze theoretically, by means of both computer simulations and laboratory experiments, the limitations of correcting aberrations with ideal customized contact lenses. Four experiments are presented: In the first one, we have analyzed the limitations of a static correction on the dynamic wavefront. In the second one, we studied the rotations of a contact lens on the eye using an optical method. The third one researched the limitations of the wavefront correction, focusing on a group of normal and highly aberrated eyes, when the correction suffers from a permanent rotation or translation. The fourth one estimates, under a simple approximation, the error made when applying on the corneal plane the correction corresponding to the wavefront measured at the entrance-pupil plane. Results show that a static correction of the wavefront leaves a residual aberration of 0.15–0.25 μm for a 5 mm pupil. Rotation of the contact lens (up to ±4°) diminishes the effectiveness of the correction. Horizontal or vertical translations of 0.5 mm could generate a high-order-aberration RMS that is higher than the remaining one after a standard low-order correction. In particular, the group of eyes having normal values of high-order aberrations are more sensitive to translations than the one having higher values. Most of the results could be applied to other methods of aberration correction, such as refractive surgery or correction by means of intraocular lenses.

1. Introduction

During the last decade, experimental systems for the correction of monochromatic ocular aberrations have been studied and developed. The main goal is to improve visual quality (Hofer et al., 2001; Liang, Williams, & Miller, 1997; Yoon & Williams, 2002) or to obtain high-resolution retinal images (Liang et al., 1997; Roorda & Williams, 1999).

There are different methods to correct the ocular wavefront; among them, adaptive optics by means of a deformable mirror applied to the eye (Liang et al., 1997; Roorda & Williams, 1999) is probably the most popular one and provides precise and rapid corrections (dozens of hertz) (Diaz-Santana, Torti, Munro, Gasson, & Dainty, 2003). These technologies have been successfully implemented in research laboratories, but the experimental systems are too large and heavy to be used daily with the aim of improving visual quality, in the same manner a pair of ideal glasses does.

Static correction of the aberrations might be more practical for daily use. At a given plane, it can be attained by inducing aberrations of equal value but opposite sign. In the case of contact lens correction, the aberration pattern that is induced has to be complementary to the eye aberration measured in that same plane, so that the wavefront coming from an axial point object to the retina will be totally spherical and centered at the fovea. Fig. 1 shows this idea schematically.

One way to produce a static correction is, for instance, through the use of a phase lens mounted onto an ophthalmic frame. For some normal eyes, 80% of the RMS has been compensated using this method (Navarro, Moreno-Barriuso, Bará, & Mancebo, 2000). The distance to the entrance-pupil plane (EPP) and the eye movements might limit the field of vision inside which visual quality improves (Bará & Navarro, 2003). Moreover, eye rotations give rise to a decentration of the optical system (ophthalmic lens-eye) and lead to residual aberration (López-Gil, Chateau, Castejón-Mochón, Artal, & Benito, 2003). As an example, a 3rd-order coma correction might induce tilt, residual defocus and residual astigmatism (Fernández-Sánchez et al., 2008).

In theory, another correction method showing a great potential is customized refractive surgery (Awwad, El-Kateb, Bowman, Cavanagh, & McCulley, 2004; Mrochen, Kaemmerer, & Seiler, 2000). This method does not have the problem of eye movements, because the compensation is located on the ocular globe. Some authors state that these results are better than those obtained using the standard non-customized surgery (Sarkisian & Petrov, 2002), but a satisfactory correction of ocular aberrations has not been achieved yet. Different factors affected the process: decentrations, accuracy of the ablation procedure (Guirao, Williams, & MacRae, 2003), cicatrization, etc. Moreover, this method is irreversible, and does not account for the ocular wavefront changes

---

* Corresponding author.
E-mail address: norberto@um.es (N. López-Gil).

0042-6989/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2009.04.016

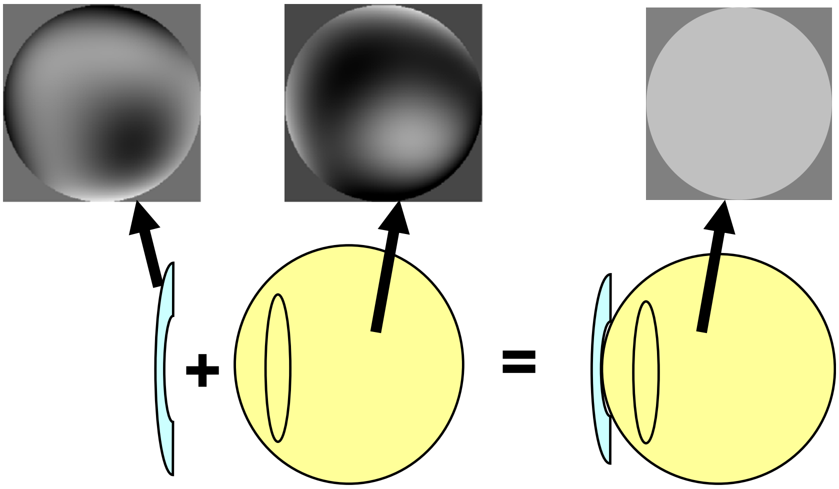

Fig. 1. Principle of aberration correction using contact lenses. The ocular aberration, as well as the aberration pattern induced by the contact lens are shown above.

that occur with accommodation, those due to microfluctuations (Atchison, Collins, Wildsoet, Christensen, & Waterworth, 1995; Cheng et al., 2004; López-Gil, Iglesias, & Artal, 1998) or those that develop with age (Brunette, Bueno, Parent, Hamam, & Simonet, 2003; Marcos, 2002).

There also exists the possibility of correcting the wavefront by means of custom contact lenses (CL) designed to compensate the specific aberrations of each eye. This one is a feasible option at present, made it possible by the new manufacturing technologies. The idea was already proposed by Smirnov (1961) as the only possible option for ocular correction, since it can follow the movements of the eye. Smirnov wrote almost half a century ago: "*In principle, it is possible to manufacture a lens compensating the wave aberration of the eye in the complex form of the plates of error. The lenses must obviously be contact ones. Otherwise, even small turns of the eye will produce sharp increase in aberration of the system*".

As ocular aberrations change with age, surgery, pathologies, etc., the main advantage of contact lenses over surgery is its reversible character, which allows the user to try several designs in order to obtain the highest-possible visual improvement. In addition, there are particular cases in which these contact lenses could be adapted if surgical solutions were unviable or very complicated.

The standard rigid gas-permeable contact lenses (RGP CL) are designed without taking high-order aberrations into account. However, the mechanism of adaptation inherently entails a compensation of the corneal aberrations, because the first surface of the lens acts practically as a new "artificial" first corneal surface. The contribution of the cornea to the aberrations of the human eye is important (Lu et al., 2008), in particular, in the presence of those pathologies that affect this organ (López-Gil et al., 2003). As a result, total or partial correction of the aberrations induced by this first surface could improve the visual quality, especially in highly aberrated eyes (Lu, Mao, Qu, Xu, & He, 2003).

A standard hydrophilic (soft) CL changes slightly its own shape when it is adapted to the cornea, which implies that, in principle, with this type of lenses a lower correction level with respect to the RGP ones (Lu et al., 2003) could be expected. On the other hand, soft CLs provide higher comfort levels than RGP ones, and they have proved to be more stable under eye movements and blinks (Cox & Lagana, 2004, chap. 33). Therefore, it would be necessary to introduce special designs based on each subject's high-order aberrations. Customized soft contact lenses with an aspheric and asymmetric first surface have lead to the generation of high-order aberrations having opposite sign to the corresponding aberrations that are present in the eye. First, López-Gil et al. (2003) obtained an improvement of the visual quality in keratoconus eyes. More recently, Yoon and Jeong (2005) have proposed the use of this technique not only in the presence of keratoconus, but also in post-keratoplasty and normal eyes, where both contact lens surfaces were customized.

Although the generation of high-order aberrations in soft CL is technically possible (López-Gil et al., 2002), ocular wavefront correction by means of soft contact lenses can be impaired due to several problems that limit the chances to attain a total compensation (López-Gil et al., 2003; Thibos, Cheng, & Bradley, 2003). Ocular aberrations change over time, even at relatively high frequencies (Legras & Rouger, 2008) due to physiological effects such as accommodation (Cheng et al., 2004; López-Gil et al., 1998) or tear film changes (Ho, 2003; Montés-Micó, Alio, Muñoz, & Charman, 2004). The plane where the eye aberrations are usually measured, the eye's entrance-pupil plane (or just pupil plane), is not the plane where the correction takes place, approximately at the first corneal surface (or just corneal plane). Moreover, realistic correction could also differ from the ideal case, since soft CL could suffer from shape distortions once it is placed on the eye. Besides, there are changes in the tear film that could modify the overall optical properties of the eye. Lateral movements of the lens relative to the center of the cornea could affect the effectiveness of the correction by generating residual aberrations (Bará, Mancebo, & Moreno-Barriuso, 2000; Guirao, Williams, & Cox, 2001). Blinks could cause a lateral translation and/or a rotation of the soft contact lens of up to 0.6 mm and 6°, respectively (Bará et al., 2000; Tomlinson, Ridder, & Watanabe, 1994) thus preventing the perfect coupling between the customized lens and the eye wavefront.

In the present article we study four limitations (i.e., limiting factors) to the static wavefront correction carried out in the corneal plane, as it is the case when using customized CLs. We performed four experiments, where the first two were related to dynamic changes (Experiments I and II). Simulations of rotations/translations of the wavefront correction in the pupil plane (the plane where the aberration pattern is usually measured) were carried out in Experiment III. Finally, in Experiment IV we developed a simple theoretical method to assess the effect of carrying out the wavefront correction in a different plane (corneal plane) to that where the measurement was done (pupil plane). Ocular wavefronts were measured using a custom-made wavefront sensor, as described in the next subsection. Wavefront data and other details of the subjects were also described in a subsection. For the sake of clarity, for each of the four experiments included in the present