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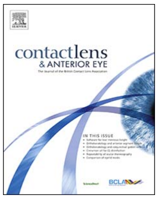

Short communication

Optical quality of rotationally symmetrical contact lenses derived from their power profiles

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ABSTRACT

Purpose: To present a methodology for evaluating the optical quality of rotationally symmetrical contact lenses (CLs) from a single power profile.
Methods: Simulated rotationally symmetrical power profiles corresponding to different CLs designs (monofocal, two-zone center-near bifocal, and four-zone center-distance bifocal) were used to calculate the wavefront error profile by means of numerical integration. Then, each lens wavefront error profile was spun around the center to obtain the lens wavefront error surface. From the surface, monochromatic optical transfer functions (OTF), simulated images and the visual Strehl ratio based on the OTF (VSOTF) were obtained for different distances and pupil sizes (3 and 5.5 mm) after performing a through-focus.
Results: VSOTF variations, taking into account both vergence and pupil size, were presented for the three CLs designs. The monofocal design showed excellent optical quality only for far vision, whereas the bifocal designs exhibited good optical quality for far and near vision. Modulation transfer function (MTF) from each lens design, pupil size, and work distance agreed with the previous results.
Conclusions: The methodology presented here allows for a rapid and thorough assessment of the optical quality of rotationally symmetrical CLs by means of optical quality metrics, with a special interest in simultaneous image contact lenses. This methodology may be useful for choosing the most suitable lens for each subject's visual demands.

1. Introduction

Simultaneous image contact lenses (CLs) are the most popular CLs for presbyopia compensation [1,2]. These lenses are based on the principle of simultaneous vision [1], where two or more images are formed simultaneously at the subject's retina. For this principle to work, the visual system must select the best focused image and supress the rest.

Currently, there is a fair amount of different simultaneous image CLs designs available in the market (e.g. center-near, center-distance designs) with different addition powers [1,2] and different number of zones or rings; thus knowing their power distribution is essential. In the last years, several studies have evaluated the power distribution of simultaneous image CLs based on their power profiles [3–7]. A power profile shows how the refractive power provided by a lens varies with the radial distance. Typically, the power profiles analysed are from rotationally symmetric CLs, since in this case a single power profile represents the refractive power distribution of the whole lens. If a CL does not present rotational symmetry (e.g. toric CL, angular patterns), then one power profile is not enough to know the refractive power distribution of the whole lens.

Power profiles, when interpreted correctly, offer useful information about the work distances that simultaneous image CLs can cover and about the effect of pupil size upon the power distribution [5,7]. However, power profiles cannot offer a thorough analysis regarding the optical quality of these lenses. For this reason, a methodology based on the vergence maps described by Nam et al. [8,9] was proposed. This methodology allows the assessment of the optical quality of rotationally symmetrical simultaneous image CLs by calculating the lens wavefront from a sole power profile.

2. Methods

2.1. Contact lenses designs

Three simulated power profiles were considered in this study. All the power profiles corresponded to CLs that had a nominal power of 0 D and a spherical aberration of $-0.075\ \mathrm{D/mm^2}$. A negative value of

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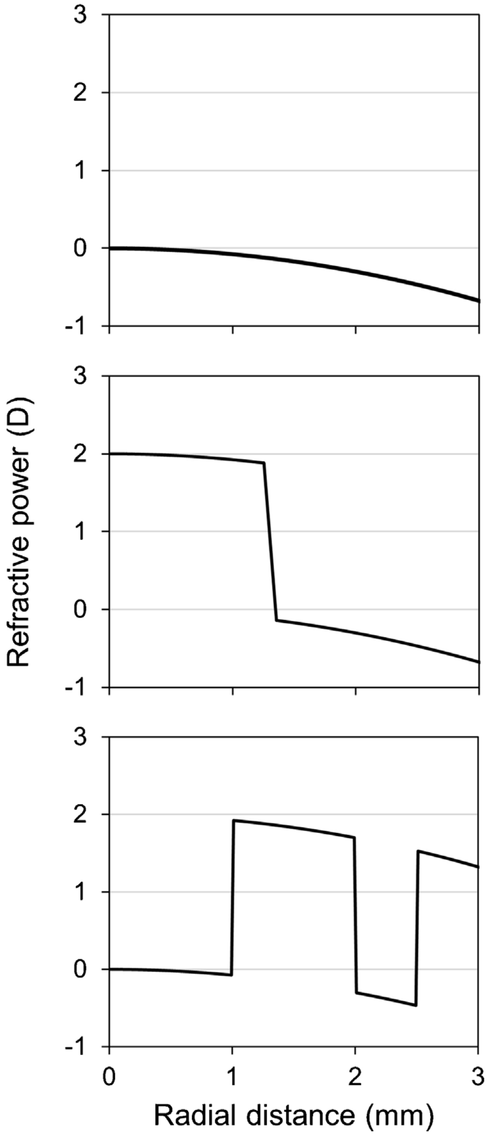

Fig. 1. Power profiles of the three CLs designs considered in this study. Upper panel shows the power profile corresponding to the monofocal CL. Mid panel shows the power profiles corresponding to the two-zone center-near design. Lower panel shows the power profile corresponding to the four-zone center-distance design.

spherical aberration is typically found in some CLs. The first power profile simulated a monofocal CL, the second a two-zone center-near [1,2] bifocal design with an addition power of 2 D, and the third a four-zone center-distance [1,2] bifocal design, also with an addition power of 2 D. The power profiles of these three CLs are shown in Fig. 1.

2.2. Procedure

From now on it will be assumed that the power maps present radial symmetry, hence it is enough to work with half of a power profile, also known as half-chord.

A wavefront vergence map (V), which is equivalent to a refractive power map, can be derived from a wavefront error map (W) as follows [8–10]:

$$V(r, \theta) = n\frac{\delta W/\delta r}{r} \tag{1}$$

where r and θ are polar coordinates and n is the refractive index. The refractive index is already taken into account in the measured vergence map. Assuming that, as mentioned before, the refractive power map presents rotational symmetry, Eq. (1) transforms into

$$V(r) = \frac{\delta W/\delta r}{r} \tag{2}$$

From Eq. (2), the profile of the wavefront error map can be calculated by integrating the profile along the radial direction, as:

$$W(r) = \int V(r)rdr \tag{3}$$

Since the power map was considered to have rotational symmetry, the resultant wavefront error profile can be spun around the origin of the radial coordinates to obtain the wavefront error map, which will be also rotationally symmetric.

Once the lens wavefront was obtained, a computational through-focus [11,12] was performed by adding wavefronts with pure defocus to the lens wavefront. The range of the through-focus was from −3 to 1 D of vergence, in steps of a fourth of 0.125 D. At each step of the through-focus, the optical transfer function (OTF) was obtained for a wavelength of 550 nm. Then, the visual Strehl ratio based on the optical transfer function (VSOTF) was calculated and used as a quality metric [13,14]. For each amount of defocus, the VSOTF was computed using Fourier methods [13]. This metric was chosen because it is known to correlate well with subjective measurements of visual performance [15]. This procedure was repeated for pupil diameters ranging from 0 to 6 mm, in 0.0625 mm steps.

A threshold for acceptable vision was set at VSOTF = 0.12, which has been used previously [16,17]. This threshold corresponds to a 0.2 logMAR visual acuity [18] and it can be considered as the limit where half of the people show difficulty in reading [19]. Therefore, values greater or equal than the mentioned threshold are considered to provide acceptable vision. In addition, retinal images were calculated by convolving the point spread function (PSF) of each design for far and near distances for pupil diameters of 3 mm and 5.5 mm, with a chart composed of four letters that corresponded to a visual acuity of 0.2 logMAR. The modulation transfer function (MTF) for the cases described before was also calculated and shown. All the computations were performed using MATLAB (MathWorks, Inc., Natic, MA, USA).

3. Results

The VSOTF values for each design, with respect to the vergence and the pupil diameter can be seen in Fig. 2. The white solid curves demarcate the zones where the VSOTF was equal or greater than 0.12. The upper panel corresponds to the VSOTF values obtained for the monofocal design, which presents only optimal VSOTF values at one vergence or working distance, in this case far. The peak got displaced to the right as the pupil diameter increased as a consequence of the negative spherical aberration [20]. The mid panel shows the VSOTF map for the center-near design. It is evident that for small pupils this design offered good optical quality only for near distances and the optical quality increased again for far when the pupil became larger than 3 mm in diameter. Lastly, the lower panel presents the VSOTF map for the center-distance design. This design showed opposite behaviour than the center-near design, and also slightly different optical quality distribution due to the complexity of the design.

Fig. 3 shows how the optical quality changed with respect to the vergence. These curves correspond to horizontal cuts in the maps showed in Fig. 2 for a 3 mm pupil size (left panel) and for a 5.5 mm pupil size (right panel). The solid gray curves stand for the monofocal design, while the black solid and dashed curves stand for the center-near and center-distance designs, respectively. The horizontal dotted black line indicates the 0.12 threshold, thus the lenses provide acceptable vision at the vergences where the curves are above this line.

Fig. 4 shows the variation in the optical quality provided by each one of the lenses when the pupil size changes. The left panel corresponds to the far distance, whereas the right panel corresponds