Original article

Halos and multifocal intraocular lenses: Origin and interpretation

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ABSTRACT

Objective: To present the theoretical and experimental characterization of the halo in multifocal intraocular lenses (MIOL).

Method: The origin of the halo in a MIOL is the overlaying of 2 or more images. Using geometrical optics, it can be demonstrated that the diameter of each halo depends on the addition of the lens (ΔP), the base power (Pb), and the diameter of the IOL that contributes to the “non-focused” focus. In the image plane that corresponds to the distance focus, the halo diameter (ΔHd) is given by: 

$$\Delta H_d = d_{pm} \cdot \Delta P / P_d$$

where $d_{pm}$ is the diameter of the IOL that contributes to the near focus. Analogously, in the near image plane the halo diameter ($\Delta H_n$) is:

$$\Delta H_n = d_{pd} \cdot \Delta P / P_d$$

where $d_{pd}$ is the diameter of the IOL that contributes to the distance focus. Patients perceive halos when they see bright objects over a relatively dark background. In vitro, the halo can be characterized by analyzing the intensity profile of the image of a pinhole that is focused by each of the foci of a MIOL.

Results and conclusions: A comparison has been made between the halos induced by different MIOL of the same base power (20D) in an optical bench. As predicted by theory, the larger the addition of the MIOL, the larger the halo diameter. For large pupils and with MIOL with similar aspheric designs and addition (SN6AD3 vs. ZMA00), the apodized MIOL has a smaller halo diameter than a non-apodized one in distance vision, while in near vision the size is very similar, but the relative intensity is higher in the apodized MIOL. When comparing lenses with the same diffractive design, but with different spherical-aspheric base design (SN60D3 vs. SN6AD3), the halo in distance vision of the spherical MIOL is larger, while in near vision the spherical IOL induces a smaller halo, but with higher intensity due to the spherical aberration of the distance focus in the near image. In the case of a trifocal-diffractive IOL (AT LISA 839MP) the most noticeable characteristic is the double-halo formation due to the 2 non-focused powers.

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Halos y lentes intraoculares multifocales: origen e interpretación

RESUMEN

Objetivo: Caracterización teórica y experimental del halo en lentes intraoculares (LIO) multifocales.

Método: El halo producido por una LIO multifocal (LIOM) se origina cuando sobre una imagen enfocada se superpone otra desenfocada. Mediante óptica geométrica se demuestra que el diámetro de cada halo depende de la adición de la lente ($\Delta P$), de la potencia base ($P^b$) y del diámetro de la lente iluminada que contribuye al foco «no-enfocado». En plano imagen que corresponde al foco de lejos, el diámetro del halo ($\delta H$) viene dado por: $\delta H = d^m \Delta P/P^d$ donde $d^m$ es el diámetro de la LIO que contribuye al foco cercano. Análogamente, en el plano imagen del foco de cerca el diámetro del halo ($\delta H$) viene dado por $\delta H = d^c \Delta P/P^d$, donde $d^c$ es el diámetro de LIO que contribuye al foco lejano. Los pacientes perciben halos cuando observan objetos luminosos sobre un fondo relativamente oscuro. In vitro, el halo se puede caracterizar analizando el perfil de intensidad de la imagen de un pinhole que forma cada uno de los focos de una lente multifocal.

Resultados y conclusiones: Hemos comparado los halos producidos por varias LIOM de la misma potencia base (20D) en un banco óptico. Tal y como predicen la teoría, cuanto mayor es la adición de la LIOM de lentes asféricas (SN6AD3 vs. ZMA00), las lentes apodizadas presentan un halo de menor diámetro que las no-apodizadas en visión lejana, mientras que en visión cercana el halo es del mismo tamaño pero la intensidad relativa es mayor en el caso de las apodizadas. Comparando lentes esféricas y asféricas con igual diseño difractivo (SN60D3 vs. SN6AD3) el halo en visión lejana en la lente esférica es mayor, mientras que en visión cercana la lente esférica produce un halo de menor tamaño pero de mayor intensidad debido a la aberración esférica del foco lejano en el plano imagen del foco cercano. En el caso de una lente trifocal (AT LISA 839MP) la característica más distintiva es la aparición de un doble halo debido a los focos lejano e intermedio de la LIO, sobre la imagen enfocada en visión cercana.

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only the central MIOL area, with \( d_{pm} \) diameter, sends light to the near focus.

For calculating halo diameter, the object-image correspondence formula through the optic system (the eye) in paraxial optics will be used:

\[
\frac{n_i}{f_i} = \frac{n_v}{f_v} + \frac{n_o}{f_o}, \quad \text{con} \quad i = [n, d] \tag{1}
\]

where \( n_v \) is the vitreous refraction index \((n_v = 1.336)\), \( n_o \) is the refraction index of air \((n_o = 1)\), \( i \) can be "\( d \)" or "\( n \)" for the far or near focus respectively, \( a \) is the distance of the object to the main plane object \((H)\) of the system (the eye), \( a' \) is the distance of the main plane image \((H')\) at the far or near image, and \( f \) is the focal distance of the eye for the \( i \)-focus. It will be assumed that planes \( H \) and \( H' \) do not change significantly in near and far vision and that:

\[
P_d = \frac{n_o}{f_d}, \quad P_n = \frac{n_v}{f_n} \quad \text{and} \quad \Delta P = P_n - P_d. \tag{2}
\]

where \( P_d \) and \( P_n \) are the refractive powers of the far and near focus of the eye, and \( \Delta P \) is the addition.

In far vision conditions (Fig. 1a) and with the paraxial approach (not taking into account the contribution of high order aberrations or scattering), the halo is formed due to the unfocused image in the near focus. In this case \( a_d = -\infty \), therefore \( f'_d = a'_d \) and \( f'_n = a'_n \). Accordingly, the result is:

\[
\delta H_d = d_{pm} \frac{\Delta P}{P_d} \tag{3}
\]

Fig. 1 – (a) Halo formation scheme in far vision in eyes implanted with MIOL. (b) Same in near vision. An apodized lens is considered in which only the central part of the MIOL contributes to the near focus. Applying Eq. (2) in Eq. (3), under these conditions the halo diameter is given by:

\[
\delta H_d = d_{pm} \frac{\Delta P}{P_d} \tag{4}
\]

On the other hand, when the object is at a finite distance from the eye, i.e., in near vision conditions (Fig. 1b) the halo is formed due to the unfocused image of the far focus (also in paraxial approach which ignores the contribution of high order aberrations). In this situation \( a'_n = f'_d \) and, as the position of the main near and far vision planes does not change significantly, the distance to the object both for the near and far focus is \( a = n_o d/\Delta P \); and \( d_{pd} = n_o/\Delta P \), and accordingly the halo diameter in near vision \( (H_n) \) can be calculated starting from:

\[
\delta H_n = \frac{d_{pd}}{P_d} \Delta P \tag{5}
\]

where \( d_{pd} \) is the diameter of the IOL lighted area which contributes to the far focus. Again, applying Eq. (2) in Eq. (5) the product is:

\[
\delta H_n = d_{pd} \frac{\Delta P}{P_d} \tag{6}
\]

As shown in Eqs. (4) and (6), halo diameter in far and near vision depends on the refractive power of the IOL for the far focus \( P_d \), on the addition \( \Delta P \) and on the lighted IOL diameter which contributes to the unfocused image \( (d_{pm} \) and \( d_{pd} \) respectively). When the IOL design produces \( d_{pd} = d_{pm} \), as in the case of non-apodized diffractive lenses (e.g. ZMA000), the halo diameter must be the same in near and far vision conditions, as published by Piek et al.\(^2\) On the contrary, with apodized lenses (e.g. ReSTOR), which have a diffractive design restricted to the central lens area while the periphery is purely refractive, the halo may have different sizes in far and near vision conditions.

**In vitro measurements**

When calculating a geometric parameter such as halo diameter with Eqs. (4) and (6), the possible apodization of the diffractive profile is not taken into account even though it will have an effect both on halo size and intensity. Similarly, the effects of high order system aberrations or scattering are not taken into account either. However, in vitro characterization allows for assessing the contribution of all these effects. This characterization can be performed with an eye model fulfilling international standards (ISO-11979). In the case reported herein, the eye model fulfills said requirements with the exception of the artificial cornea which, instead of being an aberration-free lens as suggested by said standard, it utilizes a lens which induces an amount of SA over the IOL similar to that of the average human cornea.\(^3\)\(^–\)\(^6\) Fig. 2 illustrates a lab configuration scheme of an optic bench.

For analyzing the diameter of the halo as well as its relative intensity in relation to the focused image in each IOL focus, a 200 μm pinhole was taken as objective under quasi-monochromatic green LED light (521 nm). Subsequently,
Fig. 2 – Scheme showing configuration of optic bench utilized for in vitro measurements.

captures were taken with a microscope connected to a CCD camera along the best focus planes of the eye model (artificial corneas and IOL), obtaining images as shown in Fig. 3a. After obtaining said images, their logarithmic and false color representation was used to facilitate halo display (Fig. 3b), representing 2 intensity profiles (vertical and horizontal) of each image also in logarithmic scale (Fig. 3c).

Results

The experimental method proposed for characterizing the halo was applied to different mono- and multifocal lenses for 2 pupil diameters (4.7 mm and 2.4 mm in the IOL plane). The main characteristics of the lenses included in this research are summarized in Table 1.

Monofocal lenses

The images formed by the model of eye in the optic bench for 3 IOL monofocal designs and the corresponding profiles are shown in Fig. 4. As can be observed, the largest halo diameter is exhibited by the spherical lens (SN60AT) for a large pupil diameter. In contrast, aspherical lenses (SN60WF and ZA9003) did not exhibit appreciable differences between them as regards halo diameter or intensity, regardless of their asphericity grade. For small pupils, the differences between spherical and aspherical lenses were significantly smaller.

Multifocal lenses

The logarithmic images corresponding to the best image planes in the far, intermediate (for the trifocal lens) and near vision, as well as their corresponding intensity profiles, are shown in Figs. 5 and 6 for pupil diameters in the IOL plane of 2.4 and 4.7 mm respectively. As can be deduced from Eqs. (4) and (6), halo size increases together with pupil diameter. As the differences are more meaningful for large pupil diameters, the results obtained are analyzed in great detail in Fig. 6 (largest pupil diameter).

Refractive lenses NXG1 and LS-313

In these lenses the influence of symmetric (NXG1) vs. asymmetric (LS-313) design can be observed. Whereas lens NXG1 (Fig. 6a) exhibits a circular halo, lens LS-313 (Fig. 6b) exhibits an asymmetric halo with an intensity pattern reminiscent of a coma-type aberration.

Aspheric diffractive lenses with addition 4.0D: ZMA00 and SN6AD3

The comparison of these lenses evidences the difference in size and intensity in lenses having a similar base design and

![Image](https://via.placeholder.com/150)

**Fig. 3** – (a) Actual image; (b) logarithmic image in false color; (c) vertical (red line) and horizontal (blue line) image intensity profiles.

<table>
<thead>
<tr>
<th>Reference (commercial name)</th>
<th>Type</th>
<th>SA correction</th>
<th>Base power (D)</th>
<th>Addition (D)</th>
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<tr>
<td>SN60AT</td>
<td>Monofocal</td>
<td>No</td>
<td>20</td>
<td>–</td>
</tr>
<tr>
<td>SN60WF (AcrySof IQ)</td>
<td>Partial</td>
<td>Partial</td>
<td>20</td>
<td>–</td>
</tr>
<tr>
<td>ZA9003 (Tecnis)</td>
<td>Total</td>
<td>Total</td>
<td>20</td>
<td>–</td>
</tr>
<tr>
<td>ZMA00 (Tecnis multifocal)</td>
<td>Diffractive (complete aperture) – bifocal</td>
<td>Total</td>
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<td>4</td>
</tr>
<tr>
<td>SN60D3 (AcrySof ReSTOR)</td>
<td>Diffractive apodized – bifocal</td>
<td>No</td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td>SN6AD3 (AcrySof ReSTOR)</td>
<td></td>
<td>Partial</td>
<td>20</td>
<td>4</td>
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<tr>
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<td></td>
<td>Partial</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>ATLisa 389 MP</td>
<td>Trifocal center – bifocal periphery</td>
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<td>3.33/1.66</td>
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<tr>
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<td>20</td>
<td>3.5</td>
</tr>
<tr>
<td>MPlus</td>
<td>Refractive – sectorial</td>
<td>?</td>
<td>20</td>
<td>3</td>
</tr>
</tbody>
</table>

?: Data not supplied by manufacturer.
addition (both are aspherical and exhibit the same addition) but with different diffractive design: one lens with diffractive profile throughout its surface (ZMA00) and the other with a diffractive profile apodized only in the central area (SN6AD3).

Fig. 6c illustrates the way in which the ZMA00 lens exhibits approximately the same halo diameter in near as well as far vision. However, Fig. 6e shows how the lens with apodized diffractive profile (SN6AD3) exhibits smaller halo diameter and intensity in far vision than near vision due to the asymmetric distribution of intensities between the far and near focal points for this pupil. In far vision, halo size of the SN6AD3 lens is smaller than that of the ZMA00 lens, while in near vision both exhibit approximately the same size, with greater intensity in the case of lens SN6AD3.

Apopized lenses: SN60D3, SN6AD3 and SN6AD1

As the diffractive area is apodized and occupies only the central part of the IOL (3.6 mm), these 3 lenses fulfill \( d_m \leq \delta_{pd} \) and therefore, in accordance with Eqs. (4) and (6), they exhibit smaller size and halo intensity in far than in near focus.

Comparing lenses with the same addition but with different base designs (spherical SN60D3 and aspherical SN6AD3, Fig. 6d and e) it can be seen how the spherical lens (SN60D3) exhibits larger halo diameter in the far focus than the aspherical lens due to the larger overall SA of the system. However, in the near focus it can be seen that the halo of the spherical lens (SN60D3) has smaller diameter than the aspherical lens (SN6AD3). For a better understanding of this result, reference can be made to Fig. 7 which shows a scheme of the energy allocated to the far focus of a lens with SA (Fig. 7a) and without it (Fig. 7b). The energy that goes to the near focus is not shown to make the figure easier to understand. As can be seen, in the case of the lens with positive SA (Fig. 7a), the energy coming from the periphery of the lens converges earlier (greater potential) and therefore in the near plane (C) said energy is distributed on a smaller surface, generating a smaller halo (red segment) and with greater relative intensity than in the case of the lens without SA (Fig. 7b).

When comparing aspherical lenses with different addition (SN6AD3, with addition of +4.0 D and SN6AD1, with addition of +3.0 D; Fig. 6e and f), it can be seen that in the near focus halo size and intensity are somewhat bigger with the lens having the largest addition in accordance with Eq. (4), even though the difference is not very large because both lenses exhibit the same diffractive surface (central 3.6 mm) which allocates little energy in relation to the near focus. In contrast, the halo generated in the near focus clearly exhibits a larger diameter in the case of the lens with the largest addition (SN6AD3) due to the bigger addition of this IOL which produces a longer distance between both focal points (Eq. (6)). On the other hand halo intensity in this situation (near focus) is larger in the lens having the lower addition (SN6AD1) because the overall energy allocated to the far focus is the same in both lenses, but in this (SN6AD1) it is distributed on a smaller surface.

Trifocal AT-LISA lens

The periphery of this lens is purely bifocal (which originates the far and near foci) and the central area is trifocal (which originates the far, intermediate and near foci). Fig. 6g illustrates the images corresponding to the far, intermediate and near foci as well as its intensity profiles. In the far focus, the halo diameter is similar to that of the diffractive lens with full aperture (ZMA00) with intensity being slightly higher. The intermediate focus shows the presence of 2 halos of different
Fig. 5 – Logarithmic images and intensity profiles in best image planes of each IOL for a pupil diameter of 2.4 mm.

Discussion

As predicted by the paraxial approach of geometrical optics, the halo diameter is dependent on the pupil diameter which contributes to the non-focused focus, on the base power.
of the lens (far power) and on the addition. With small pupil diameters the differences between lenses are considerably smaller. To obtain a better prediction than that given by this paraxial approach, exact beam tracing simulations should be performed. However, this is not generally possible because manufacturers do not provide the values of curvatures, asphericities, elevations, etc. of lens surfaces.

Aspherical monofocal lenses SN60WF and ZA9003 exhibit lower halo size and intensity than any other multifocal lens, without exhibiting significant differences between the 2 examined models (SN60WF and ZA9003). The halo produced by the SA of a spherical monofocal lens (SN60AT) for large pupils can be of the same size or bigger than the halos produced in some multifocal designs.

Fig. 6 – Logarithmic images and intensity profiles in best image planes of each IOL for a pupil diameter of 4.7 mm.
Multifocal lenses exhibit halos which can vary in size and shape in each one of the foci, depending on the design of each lens. Accordingly, asymmetric multifocal lenses also generate asymmetric halos (LS-313); complete aperture diffractive lenses (ZMA00) virtually exhibit the same halo size in near and far vision; apodized lenses exhibit smaller halo size and intensity in far vision but bigger in near vision, while the trifocal lens (AT-LISA) presents in each image plane 2 halos of different size and intensity, one for each power that is out of focus in each plane.

Numerous papers characterize the optic quality of in vivo IOL \cite{1,2,3,4,5,6,7,8,9} but in general do not include characterizations of the halos generated by the IOL and which form in the retina of patients. In addition, there are “halometers” \cite{5} which can be used for characterizing the perception of halo in these patients but to date no in vivo measurements have been taken on patients with IOL implants. The main difference between said halometers and the in vitro method proposed in this paper is that herein the only halo which is assessed is that induced by the optic system, whereas the use of a halometer includes halo perception evaluation by the patient (a subjective method) which includes optical quality and neuronal processing by the retina–brain.

It can be concluded that this paper has designed an experiment to in vitro method for objectively quantifying the characteristics of the halo that would form in the retina of patients implanted with different IOLs.

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**Conflict of interest**

The authors declare no conflict of interest.

**References**