Multifocal IOLs with apodized diffractive central zone and refractive periphery: optical performance and clinical outcomes

Javier Tomás-Juan, OD, MSc

ABSTRACT: The apodized diffractive multifocal intraocular lens is one of the intraocular lens types currently available for the correction of presbyopia. The design of apodized diffractive multifocal intraocular lenses improves on the visual outcomes obtained with the full optic diffractive and refractive intraocular lenses. In addition to the visual improvements, apodized diffractive multifocal intraocular lenses, using a combination of diffractive and refractive technologies and gradually decreasing diffractive steps from the center to the periphery of the intraocular lens, reduce or eliminate the visual phenomena produced mainly in night conditions when the pupil size increases.

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Nowadays, diffractive multifocal intraocular lenses (IOLs) are considered a good alternative for the correction of presbyopia. The working principle of the full optic diffractive multifocal IOLs is based on the creation of two focal points, by using diffraction orders (order 0 and order 1). The power corresponding to the 0-order diffraction is used to image distant objects, whereas the power corresponding to the 1-order is used for near vision. In diffractive multifocal IOLs, the image is divided into two focal points, one for distant vision and the other one for near vision, so one of the images will always be sharp whereas the other one will be barely perceived or blurred. The blurred image is usually said to be located in the blur circle. Nevertheless, full optic diffractive multifocal IOLs have the disadvantage that the image formed by one of the foci in the retina will have the defocused image from the other focus superimposed along the optical axis. This can cause side effects, such as glares and halos, mainly in mesopic and scotopic conditions when the pupil diameter is increased. Furthermore, due to the design of the diffractive multifocal IOLs, patients who have been implanted may have lower contrast sensitivity (CS) values, mainly due to forward dispersion and the higher-order aberrations (HOA). It is very important to consider the visual effects of the multifocal diffractive IOLs, such as night vision disturbances, and dissuade people with nighttime visual needs, for example, professional drivers, from undergoing this surgery. To reduce the visual effects mainly produced in night vision with full optic diffractive multifocal IOLs, IOLs combining refractive technology with diffractive technology have been introduced.

OPTICAL PERFORMANCE

The apodized diffractive IOLs consist of a peripheral refractive zone and a central apodized diffractive zone for achieving appropriate power in distant vision and in near vision. One of the main characteristics of this type of IOL is the apodization of the central diffractive zone, which, by gradually reducing the number of diffractive steps in width and height, produces a gradual transition from the center to the periphery of the lens, in order to create a smooth transition between the far, intermediate and near focal points. With apodization, the percentage of light...
reaching the near focus and the distant focus depending on the patient's pupil size can be modified, so in bright light conditions, when the patient's pupil size is small, the IOL distributes the energy similarly between the distant focus and the near focus. Nevertheless, in limited light conditions, when the patient's pupil size increases, less light will be directed to the near focus and the refractive area will direct the light to the distant focus. This design prevents the light from reaching both focal points with the same fixed percentage, and the distribution of light will depend on the patient's pupil size, as occurs with the full-optic diffractive IOLs. Visual results will differ, depending on the type of apodized diffractive multifocal IOLs implanted and the refraction and diffraction surface, benefitting or deteriorating intermediate vision.

**CLINICAL OUTCOMES**

**Degree of satisfaction**

The degree of satisfaction among patients receiving an apodized diffractive multifocal IOL is high. Knorz et al., in a study performed after implanting the AcrySof® ReSTOR® 3.0 D multifocal toric IOL (Models SND1T3, SND1T4 or SND1T5; Alcon Laboratories, Inc., Fort Worth, TX, USA) in 49 patients, evaluated the degree of satisfaction 6 months after the intervention. They used a subjective questionnaire with a scale ranging from 1 (the worst) to 10 (the best). The average score reported by the patients regarding their uncorrected vision was 7.9 ± 1.9, six months after implantation of the AcrySof® ReSTOR® 3.0 D multifocal toric IOL (n = 37).

<table>
<thead>
<tr>
<th>Study</th>
<th>IOL</th>
<th>EYES</th>
<th>MONTHS</th>
<th>UDVA</th>
<th>CDVA</th>
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<tr>
<td>Cillino et al. (2014)</td>
<td>AcrySof® SN6AD3</td>
<td>40</td>
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<td>0.010 ± 0.08</td>
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<td>6 months</td>
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<td>0.05 ± 0.08d</td>
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1. In photopic conditions; 2. At 80 cm; 3. At 70 cm; 4. LogRAD scale.
compared to preoperative values of 3.6 ± 2.0 (n = 38)\textsuperscript{25}. Van der Linden et al. assessed the degree of satisfaction between the LENTIS\textsuperscript{a} Mplus LS-312 (Oculentis GmbH, Berlin, Germany) sectorial addition multifocal IOL and the AcrySof\textsuperscript{a} ReSTOR\textsuperscript{a} SN6AD1 apodized diffractive multifocal IOL. At three months, patients who received the AcrySof\textsuperscript{a} ReSTOR\textsuperscript{a} SN6AD1 apodized diffractive multifocal IOL were more satisfied with their vision (p < 0.001)\textsuperscript{11}. Apodized diffractive multifocal IOLs provide independence from the use of spectacles after the intervention\textsuperscript{10,14,16,22,24,26-31}. Peng et al. found that the vast majority of patients who were implanted with the AcrySof\textsuperscript{a} ReSTOR\textsuperscript{a} IOL did not require spectacles after the intervention, increasing the independence from spectacles in near vision tasks by approximately 78%\textsuperscript{17}. These authors also found that the results obtained with the AcrySof\textsuperscript{a} ReSTOR\textsuperscript{a} 3.0 D IOLs are better with bilateral implantation\textsuperscript{17}. However, Kohnen et al. found 88% independence from spectacles after the intervention, when the AcrySof\textsuperscript{a} ReSTOR\textsuperscript{a} SN6AD1 3.0 D was implanted bilaterally\textsuperscript{10}. Ferreira et al. found that independence from spectacles with the new AcrySof\textsuperscript{a} ReSTOR\textsuperscript{a} 3.0 D was 100% at the three-month follow-up\textsuperscript{32}.

### Visual acuity

Apodized diffractive multifocal IOL implantation is a safe and effective procedure for the correction of presbyopia that provides good visual outcomes in distance and near vision\textsuperscript{13,20,33-40}. In recent years, randomized studies that demonstrate the visual performance of apodized diffractive multifocal IOLs have been conducted (Table 1). Furthermore, good outcomes have been observed in other non-randomized studies. Apodized diffractive multifocal IOLs provide better results in near vision than monofocal IOLs\textsuperscript{9,14,41,42}. Zhao et al., in a study performed in 161 eyes, implanted the AcrySof\textsuperscript{a} ReSTOR\textsuperscript{a} multifocal IOL in 72 eyes, and the AcrySof\textsuperscript{a} SA60AT monofocal IOL in 89 eyes. Six months after the intervention, they found that patients who had received the AcrySof\textsuperscript{a} ReSTOR\textsuperscript{a} multifocal IOL had better Uncorrected Near Visual Acuity (UNVA) than patients who had received the AcrySof\textsuperscript{a} SA60AT IOL (p < 0.05)\textsuperscript{14}. Furthermore, 6 months after the intervention, multifocal IOL group showed better Corrected Near Visual Acuity (CNVA) than the monofocal IOL group (p < 0.05)\textsuperscript{14}. As a result, the apodized diffractive multifocal IOL is considered a safe and effective procedure for the correction of refractive errors after clear lens extraction\textsuperscript{23,43}. Sun et al. performed a non-randomized prospective study comparing the results of the SN6AD1 apodized diffractive multifocal IOL with the SN60WF monofocal IOL. Three months after the intervention, they found that the SN6AD1 provided better visual outcomes for UNVA, Corrected Distance Visual Acuity (CDVA) and Uncorrected Intermediate Visual Acuity (UIVA) in conditions of high contrast (p < 0.05)\textsuperscript{23}. However, they found that UNVA, CDVA and the low contrast UIVA did not differ between both groups for the distances of 63 cm and 100 cm (p > 0.05), with better UIVA in mild emmetropic and myopic patients than in hyperopic patients\textsuperscript{23}. In addition, Distance Visual Acuity (DVA) and Near Visual Acuity (NVA) depend significantly on the patient’s pupil size. Alfonso et al. found that large pupil diameters were correlated with better DVA, and poorer NVA\textsuperscript{9}.

The addition of apodized diffractive multifocal IOLs may vary according to the patient’s need, proving that, although these have a similar performance in CS, quality of life, distant vision and near vision, they may differ in intermediate vision\textsuperscript{8,44}. The AcrySof\textsuperscript{a} ReSTOR\textsuperscript{a} 4.0 D

<table>
<thead>
<tr>
<th>UIVA</th>
<th>DCIVA</th>
<th>UNVA</th>
<th>CNVA</th>
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<td>0.16 ± 0.12\textsuperscript{a,b}</td>
<td>0.15 ± 0.07\textsuperscript{a,b}</td>
<td>0.05 ± 0.08\textsuperscript{a}</td>
<td>0.04 ± 0.05\textsuperscript{a}</td>
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<td>0.09 ± 0.12\textsuperscript{a,b}</td>
<td>0.07 ± 0.05\textsuperscript{a,b}</td>
<td>0.02 ± 0.04\textsuperscript{a}</td>
<td>0.01 ± 0.05\textsuperscript{a}</td>
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<td>0.11 ± 0.04\textsuperscript{a,b}</td>
<td>0.10 ± 0.04\textsuperscript{a,b}</td>
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<td>0.035 ±0.05\textsuperscript{a}</td>
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<td>0.18 ± 0.10\textsuperscript{c}</td>
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<td>0.17 ± 0.11\textsuperscript{c}</td>
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(Model SN60AD3) apodized diffractive multifocal IOL provides good visual outcomes in distant vision and in near vision14,15, especially the lower the power of the IOL13. Moreno et al. found that the Uncorrected Distance Visual Acuity (UDVA) and Distance Corrected Near Visual Acuity (DCNVA) deteriorated with increasing lens powers15. Increased HOA undermine the flawed visual outcomes of higher power lenses13. The Alcon Company has improved the AcrySof® ReSTOR® 4.0 D with the aim of improving intermediate vision, reducing the number of diffractive steps from 12 to 9, but maintaining the same diffractive zone size to provide a lower addition with the AcrySof® ReSTOR® 3.0 D (Figure 1)16,17,36.

The apodized diffractive multifocal IOL, besides providing excellent outcomes in UNVA, provides good results in UDVA in photopic conditions8,31,47. Alió et al. compared the visual outcomes of the rotationally asymmetric multifocal LENTIS® Mplus LS-312 IOL, and the apodized diffractive multifocal IOL (AcrySof® ReSTOR® SN6AD3) in 74 eyes of 40 cataract patients. They found that UNVA and DCNVA were better in the apodized diffractive multifocal IOL group than in the rotationally asymmetric multifocal IOL group (p = 0.01)48. Nevertheless, they found that intermediate visual acuity was better in the rotationally asymmetric IOL group (p = 0.01) than in the apodized diffractive multifocal IOL group48. These outcomes agree with those obtained by Van der Linden et al. who showed that the rotationally asymmetric multifocal IOL (LENTIS® Mplus LS-312 IOL) provided worse visual outcomes than the apodized diffractive multifocal IOL (AcrySof® ReSTOR® SN6AD3) at reading distances between 30 cm (0.15 ± 0.08 logMAR versus 0.05 ± 0.14 logMAR) and 40 cm (0.16 ± 0.21 logMAR versus 0.05 ± 0.14 logMAR; p < 0.01 and p < 0.03, respectively)11. Subsequently, Van der Linden et al. performed a study to compare the visual outcomes obtained with the SeeLens MF IOL (Hanita Lenses, Hanita, Israel) in 48 eyes and the SN60AD1 in 37 eyes. Three months after the intervention, the UNVA between the SeeLens MF group (0.02 ± 0.07 logMAR) and the SN60AD1 group (0.04 ± 0.09 logMAR) was not statistically significant. Better CDVA results were obtained with the SeeLens MF (−0.04 ± 0.05 logMAR) than with the SN60AD1 IOL (−0.01 ± 0.04 logMAR, p < 0.019), although the difference was not statistically significant2. At visual distances between 30 cm and 40 cm no statistically significant differences were obtained in UNVA for both implanted lenses (0.09 ± 0.12 logMAR vs 0.08 ± 0.09 logMAR). However, at distances between 50 cm and 60 cm (p < 0.03, p < 0.07 respectively), the UNVA differed, with better visual outcomes being obtained with the SeeLens MF2.

Besides studying the outcomes of monofocal and multifocal apodized diffractive IOLs, single-optic accommodating IOLs have also been analyzed49. Ang et al. found that the AcrySof® ReSTOR® 3.0 D multifocal IOL (Model SN6AD1) provides similar UDVA and UNVA outcomes as the CrystaLens® (Bausch & Lomb Inc., North Bridgewater, NJ, USA). Nevertheless, they found that the CrystaLens® IOL provides better intermediate vision outcomes49.

Apodized diffractive multifocal toric IOLs can also be implanted in patients who have previously undergone Laser In Situ Keratomileusis (LASIK). Good visual results are obtained if the apodized diffractive multifocal IOL is implanted before or after

Figure 1. AcrySof® ReSTOR® 3.0 D (Model SN6AD1) consisting of 9 diffractive apodized rings in the central zone, with apodized diffractive zone of 3.6 mm and refractive periphery zone. A gradual transition in the number of diffractive steps from the center to the periphery is observed (with permission from Alcon).
LASIK. Muftuoglu et al. implanted apodized diffractive multifocal IOLs after myopic LASIK in 49 eyes. They found that, in the postoperative visit at six months, 36 of the 49 eyes had a UDVA of 20/25 or better. In addition, they found that UNVA was Jaeger 1 or better in the last follow-up visit. Alfonso et al. found that the Acrysof ReSTOR* SN60D3 implanted in eyes which had previously undergone hyperopic LASIK, provides good visual outcomes at all distances, similar to those obtained in phakic eyes under photopic conditions. Nevertheless, they found that the visual quality was especially limited under mesopic conditions. However, Muftuoglu et al. showed that in the presence of residual astigmatism after implantation of the apodized diffractive multifocal IOL, with or without subsequent LASIK, limbal relaxing incisions were effective in reducing corneal astigmatism and improving visual outcomes.

Recently, the toric diffractive multifocal IOL 3.0 D, based on a modification of the apodized diffractive multifocal IOL, has been introduced. The Acrysof ReSTOR* 3.0 D allows correction of up to 2.5 D of corneal astigmatism. It consists of a diffractive central optic of 3.6 mm, and it is comprised of 9 concentric steps, with refractive periphery, and a toric component on the posterior surface of the IOL. The aspheric apodized diffractive multifocal toric IOLs, in addition to providing good visual acuity at all distances, reduces corneal astigmatism greatly, showing good performance in terms of rotation.

Alfonso et al., in a study performed in 49 patients implanted with Acrysof ReSTOR* 3.0 D multifocal toric IOL, found that the cylinder average decreased from 1.07 ± 0.71 D to 0.33 ± 0.44 D and reported an IOL rotation average of 2.20 ± 4.34 degrees.

**Contrast sensitivity**

Apodized diffractive multifocal IOLs do not produce significant variations in long-term CS. Cioni et al. found that CS is similar when an apodized diffractive multifocal IOL (Acrysof ReSTOR*) is implanted binocularly and monocularly. Yoshino et al. implanted an apodized diffractive multifocal IOL in 21 patients (42 eyes). They found that, after a follow-up period of five years, the value of the CS was normal for all the spatial frequencies. No significant long-term variations were produced in CS. However, changes in light levels can reduce CS, mainly at high frequencies.

CS has been compared between multifocal IOLs implantations. Alfonso et al. evaluated CS between apodized diffractive central zone and refractive periphery lenses (Acrysof ReSTOR* SN6AD3), and IOLs that intercalate the refractive and diffractive technology from the center to the periphery (Acri.LISA*, Carl Zeiss Meditec, Dublin, CA, USA; aspheric). They found that both lenses produce a normal CS range under photopic conditions and reduced CS under mesopic conditions. Alíó et al. compared the outcomes of CS after the implantation of the Acrysof ReSTOR* SN6AD3 apodized diffractive multifocal IOL and the LENTIS Mplus LS-312 rotationally asymmetric multifocal IOL. They found that, three months after the intervention, CS was significantly higher in patients with the LENTIS Mplus LS-312 rotationally asymmetric multifocal IOL than in patients with the Acrysof ReSTOR* SN6AD3 apodized diffractive multifocal IOL (p = 0.04). Later, Rosa et al. assessed CS between the LENTIS Mplus LS-312 IOL and the Acrysof ReSTOR* SN6AD1 IOL, finding that CS under photopic and mesopic conditions was better in the Acrysof ReSTOR* SN6AD1 group. Rosa et al. found that the CS was higher for the high spatial frequencies (7.1 cycles per degree [cpd] vs 23.6 cpd, respectively), and for the intermediate spatial frequencies (2.2 cpd versus 3.4 cpd, respectively) which is important for intermediate vision.

In addition to investigating CS between multifocal IOLs, comparisons have also been performed between multifocal IOLs and monofocal IOLs. Zhao et al. found that patients who had been implanted with the single-piece Acrysof SA60AT IOL had significantly better CS than patients who had been implanted with the Acrysof ReSTOR* SA60D3 apodized diffractive multifocal IOL (both p < 0.05). Vingolo et al. studied CS between the Acrysof ReSTOR* apodized diffractive multifocal IOL and the Acrysof SA60AT monofoveal, obtaining lower CS values for the Acrysof SA60AT IOL. Nevertheless, Bissen-Miyajima et al. compared the Acrysof ReSTOR* SA60D3 apodized diffractive multifocal IOL and the Acrysof SA60AT monofocal IOL finding that CS was similar between both groups for all spatial frequencies.

CS has also been compared with the single-optic accommodating IOL. Ang et al. compared CS between the Crystalen*, the TECNIS* (Abbott Medical Optics, Illinois, USA) and the Acrysof ReSTOR*. They found that the Crystalen* IOL provides better CS than the Acrysof ReSTOR* under mesopic conditions without glare at 3.0 cpd (p = 0.046). However, they found that the Acrysof ReSTOR* provides better visual outcomes than the TECNIS* at 1.5 cpd (p = 0.010).

**Depth of focus**

Although apodized diffractive IOLs increase depth-of-focus, Zheleznyak et al. found that, when an astigmatism of 0.75 D or more is maintained without correction, the depth-of-focus decreases considerably.
Anterior Chamber Depth (ACD)

It is well known that the contraction of the ciliary muscle can produce an IOL shift. Monofocal IOL movement has been documented in a variety of studies. However, there are few studies evaluating shift in apodized diffractive multifocal IOLs. Tsorbatzoglou et al. analyzed apodized diffractive multifocal IOL shift (AcrySof® ReSTOR® SA60D3) with partial coherence interferometry after pharmacologically induced ciliary muscle relaxation and confirmed that apodized diffractive multifocal IOL shift was similar to monofocal IOL shift.

Visual fields

Apodized diffractive IOLs can alter the results obtained with the FDT Perimetry, so the influence of the apodized diffractive IOLs on the results obtained with the FDT Perimetry must be carefully analyzed. Bojikian et al. performed a study with 37 eyes of 22 patients aged between 41 and 79 years (70.78 ± 9.83 years). The AcrySof® ReSTOR® Natural was implanted in 17 eyes and the yellow counterpart (Natural IQ), in 20 eyes. Three months after the intervention, FDT Matrix Perimetry was performed in all cases. The mean deviation obtained in the Natural IQ group was −1.83 ± 3.46 dB, whereas in the AcrySof® ReSTOR® Natural group it was −1.77 ± 3.94 dB (p = 0.28). The standard deviation in the Natural IQ group was 3.49 ± 0.79 dB, whereas in the AcrySof® ReSTOR® Natural group it was 3.20 ± 0.86 dB (p = 0.27). The authors concluded that there were no differences between eyes implanted with the AcrySof® ReSTOR® Natural and the Natural IQ.

Reading speed

The effectiveness of apodized multifocal IOLs in patients’ visual quality is very important. Visual acuity tests are not considered a good indicator of the patient’s visual quality because it measures the visual quality in static conditions. In the clinical practice, reading speed tests assessing visual capacity in dynamic conditions are increasingly common. Reading speed tests, in addition to assessing the ability to read sentences, rather than isolated letters as in the static visual acuity tests, provide quantitative and qualitative measurements about various components of reading ability. Reading speed studies performed in apodized diffractive multifocal IOLs show that this type of IOL increases reading speed. Some reading speed parameters have been studied by various groups (Table 2). Alió et al. compared reading speed parameters after apodized diffractive multifocal IOL (AcrySof® ReSTOR® SN6AD3 and Acri.LISA® 366D; Carl Zeiss Meditec, Dublin, CA, USA) implantation with monofocal (Acri.

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<th>Study</th>
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<th>EYES</th>
<th>MONTHS</th>
<th>URS (wpm)</th>
<th>CRS (wpm)</th>
<th>URD (cm)</th>
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<td>152 ± 40</td>
<td>156 ± 40</td>
<td>37.1 ± 7.3</td>
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<td>AcrySof® SN6AD3</td>
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<td>6 months</td>
<td>110 ± 30</td>
<td>114 ± 30</td>
<td>29.2 ± 4.1</td>
</tr>
<tr>
<td></td>
<td>Acri.LISA® 366D</td>
<td>84</td>
<td></td>
<td>114 ± 28</td>
<td>119 ± 23</td>
<td>30.1 ± 3.7</td>
</tr>
<tr>
<td></td>
<td>ReZoom®</td>
<td>70</td>
<td></td>
<td>107 ± 25</td>
<td>120 ± 24</td>
<td>35.3 ± 7.1</td>
</tr>
</tbody>
</table>

wpm: words per minute; cm: centimeters; mm: millimeters; URS: Uncorrected Reading Speed; CRS: Corrected Reading Speed; URD: Uncorrected Reading Distance; CRD: Corrected Reading Distance; USPZ: Uncorrected Smallest Print Size; CSPZ: Corrected Smallest Print Size. *In photopic conditions.
Smart 48S; Carl Zeiss Meditec, Dublin, CA, USA) and refractive (ReZoom®; Abbott Medical Optics, Illinois, USA) multifocal IOLs. They found that the apodized diffractive multifocal IOL group had better reading acuity than the rest of the groups at one and six months after surgery (p < 0.01)\(^5\). Subsequently, in another study, Rasp et al. compared reading speed parameters after Acri.Smart, AT LISA® (Carl Zeiss Meditec, Dublin, CA, USA), AcrySof® ReSTOR®, ReZoom® and TECNIS® MF implantation. They found that apodized diffractive IOLs provided better reading speed outcomes than multifocal refractive IOLs and monofocal IOLs\(^4\). Furthermore, reading speed parameters with the apodized multifocal diffractive toric IOL have also been evaluated, showing good results. Alfonso et al. evaluated visual outcomes after bilateral implantation in 49 patients with AcrySof® ReSTOR® 3.0 D diffractive multifocal toric IOL\(^5\). Six months after the intervention, mean corrected reading speed increased from 125.4 ± 33.6 words per minute (wpm) to 132.7 ± 23.7 wpm\(^5\).

### Visual effects

Apodized diffractive IOLs have been specifically designed with the aim of minimizing the presence of halos and glares in low light conditions\(^1\). Since the apodized diffractive multifocal IOL is diffractive at the center and refractive at the periphery, it tends to reduce visual alterations such as halos and glares where the pupil diameter increases, especially in night conditions\(^17\). Cristóbal et al. implanted apodized diffractive multifocal IOLs (AcrySof® ReSTOR® SN60D3) in five children between four and six years of age with unilateral cataract. Disturbances like glare and halos were absent in the 21-month follow-up\(^6\). More recently, Ram et al. implanted the apodized diffractive multifocal IOL in children above the age of 5. They determined that two patients complained of mild glare\(^6\). However, it is worth pointing out the added difficulty of making accurate measurements and carrying out subjective questionnaires properly in children.

Nevertheless, patients who have received an apodized diffractive multifocal IOL, despite reporting better quality vision, sometimes tend to have visual alterations, such as halos and glares, which are related to the IOL design\(^23,31\). The incidence of halos varies depending on if the IOLs are implanted monocularly or binocularly. Cioni et al. found that the incidence of halos in patients with monocular implantation of the AcrySof® ReSTOR® diffractive multifocal IOL (57%) was lower than in patients who had received the same lens binocularly (77%), although no statistically significant differences were found\(^16\).

Kohnen et al. found that after bilateral implantation of the AcrySof® ReSTOR® SN60D1 3.0 D, patients reported few visual disturbances\(^30\). De Vries et al. found that patients implanted with the AcrySof® ReSTOR® SA60D3 diffractive multifocal IOL had less glare and halo than patients who had been implanted with AcrySof® SA60AT monofocal IOL\(^6\). Nevertheless, Van der Linden et al. found that approximately 18% of patients who received the AcrySof® ReSTOR® SN60AD1 apodized diffractive multifocal IOL had dysphotopsia\(^12\). Yoshino et al. implanted the apodized diffractive multifocal IOL in 21 patients (42 eyes). Five years after the intervention, no patient complained of glare or halo\(^35\).

The new material (Benz26) and the design of the SeeLens MF apodized diffractive multifocal IOL (Figure 2), allow a greater amount of light to reach the

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**Table 2.** Comparison of reading speed parameters among the different randomized studies

<table>
<thead>
<tr>
<th>IOL</th>
<th>AcrySof® SN6AD3</th>
<th>AcrySof® SN6AD1</th>
<th>TECNIS® ZMA00</th>
<th>AcrySof® AT LISA® 366D</th>
<th>AT LISA® 366D</th>
<th>TECNIS® ZMA00</th>
<th>Acri.LISA® 366D</th>
<th>Acri.Smart 48S</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRD (cm)</td>
<td>0.35 ± 0.2*</td>
<td>0.35 ± 0.2*</td>
<td>0.34 ± 0.1*</td>
<td>0.36 ± 0.1*</td>
<td>0.35 ± 0.2</td>
<td>0.34 ± 0.1</td>
<td>0.35 ± 0.1</td>
<td>0.34 ± 0.1</td>
</tr>
<tr>
<td>USPZ</td>
<td>1.76 ± 0.61</td>
<td>0.87 ± 0.34</td>
<td>0.74 ± 0.19</td>
<td>0.87 ± 0.39</td>
<td>0.87 ± 0.39</td>
<td>0.87 ± 0.39</td>
<td>1.38 ± 0.53</td>
<td>1.38 ± 0.53</td>
</tr>
<tr>
<td>CSPZ (mm)</td>
<td>0.72 ± 0.16</td>
<td>0.84 ± 0.24</td>
<td>0.67 ± 0.17</td>
<td>0.72 ± 0.19</td>
<td>0.74 ± 0.26</td>
<td>0.74 ± 0.26</td>
<td>0.74 ± 0.26</td>
<td>0.74 ± 0.26</td>
</tr>
</tbody>
</table>

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**Figure 2.** SeeLens MF Intraocular Lens consisting of 12 diffractive apodized rings in the central zone, with apodized diffractive zone of 4 mm. A gradual transition in the number of diffractive steps from the center to the periphery is observed (with permission from Hanita Lenses).
retina, decreasing forward scattering and eliminating reflections. Van der Linden et al. implanted the SeeLens MF in 48 eyes and the AcrySof® ReSTOR® SN60AD1 in 37 eyes. They found that three months after the intervention, the patients implanted with the SeeLens MF presented a significant decrease in light diffusion ($p < 0.0001$) and less glare ($p < 0.002$), compared to those who had received the SN60AD1 IOL.

However, although multifocal apodized diffractive IOLs show a lower incidence of halos, Ang et al. found a lower incidence of halo and starbursts both monocularly and binocularly with the accommodative IOL Crystalens® than with the AcrySof® ReSTOR® 3.0 D (Model SN6AD1).

**Intraocular straylight**

Laboratory studies have shown that spherical multifocal IOLs and monofocal IOLs are associated with light scattering. Although the increase of straylight levels in the monofocal IOLs does not affect the patient’s quality of vision, it may affect CS. In pseudophakic eyes with the apodized diffractive multifocal IOL, intraocular straylight increases with pupil diameter, mainly if the capsulorhexis is small. Besides the increase in forward scattering with diffractive multifocal IOLs, patient age, pupil diameter and corneal surface quality are also thought to be important. Some studies have been conducted to determine how the levels of straylight affect visual function. Peng et al. conducted a randomized prospective study of 204 eyes (102 patients) with bilateral AcrySof® ReSTOR® SN6AD1 3.0 D diffractive multifocal aspheric IOL implantation to determine the adverse effects produced in comparison to the AcrySof® SN60WF monofocal aspheric IOL. Medium levels of straylight were analyzed through the C-Quant, and no statistically significant differences were found in the AcrySof® ReSTOR® SN6AD1 compared to the AcrySof® SN60WF monofocal IOL group. These outcomes coincide with those obtained by Bissen-Miyajima et al. who found that six years after the intervention, previous surface light scattering increased similarly in the apodized diffractive multifocal AcrySof® ReSTOR® SA60D3 and in the monofocal IOL AcrySof® SA60AT. Nevertheless, de Vries et al. observed that, six months after the intervention, the average intraocular straylight level was higher in patients with the AcrySof® ReSTOR® SA60D3 multifocal IOL than in patients who received the AcrySof® SA60AT monofocal IOL ($p = 0.026$). Yoshino et al. found after a period of five years that the CS and visual acuity of the apodized diffractive multifocal IOL were not affected by straylight increases.

**Ocular aberrations**

It is well known that IOLs with spherical profile increase spherical aberration. In order to reduce that HOA, IOLs with aspheric profiles have been designed. At present, there is a great interest in determining the benefits that could be offered by an aspherical multifocal IOL, because some studies have demonstrated that the IOLs with aspheric profile provide no benefits in patients with small pupils. However, other studies have showed that diffractive multifocal IOLs with aspheric profiles produce fewer ocular aberrations than diffractive multifocal IOLs with spherical profiles. Diffractive multifocal IOLs with an aspherical profile induce less spherical aberration than diffractive multifocal IOLs with a spherical profile. Toto et al., in a six-month prospective study, found that AcrySof® ReSTOR® SN6AD3 4.0 D and AcrySof® ReSTOR® SN6AD1 3.0 D aspheric IOLs induce less spherical aberration than the AcrySof® ReSTOR® SN60D3 4.0 D spherical IOL. Furthermore, Ferreira et al. found that HOA with AcrySof® ReSTOR® 3.0 D, measured with OPD-III scanning system, were similar to those obtained with AcrySof® ReSTOR® monofocal toric.

Gradually decreasing the apodization of multifocal IOLs from the center to the periphery allows a decrease in ocular aberrations, mainly of a spherical nature. In addition, the refractive zone of the IOL minimizes disturbances, such as halos and glare. Zelichowska et al. evaluated ocular aberrations after the implantation of the AcrySof® ReSTOR® SN60D3 diffractive multifocal IOL compared to the ReZoom® refractive multifocal IOL, finding more HOAs (coma and spherical aberration) with the ReZoom® IOL ($p < 0.001$). Peng et al. found that in 204 eyes (102 patients) with bilateral implantation with the AcrySof® ReSTOR® SN60D3 aspheric diffractive multifocal IOL, the spherical aberration was 0.05 ± 0.06 μm. There were no statistically significant differences in coma aberration six months after the intervention. These outcomes also coincide with those obtained by de Vries et al., in which the spherical aberration was 0.03 ± 0.06. Alió et al. also found a decrease in ocular aberrations in patients who had received an apodized diffractive multifocal IOL (AcrySof® ReSTOR® SN6AD3) in comparison with patients who had received a rotationally asymmetric multifocal IOL (LENTIS® Mplus LS-312 IOL, $p = 0.02$).

**Optical quality**

Point Spread Function (PSF) in apodized diffractive multifocal IOLs has been studied. Moreno et al. measured the PSF of the AcrySof® ReSTOR® SN6AD3 multifocal IOL in 38 eyes of 19 patients with the double-pass system. They found that there was a correlation between
the power of the apodized diffractive multifocal IOL and the PSF width at 50% (p = 0.017). Furthermore, these authors also found a correlation between the power of the apodized diffractive multifocal IOL and the PSF width at 10% (p = 0.017)\textsuperscript{13}. This demonstrates that optical quality is worse in eyes with high power apodized diffractive multifocal IOLs\textsuperscript{13}.

The Modulation Transfer Function (MTF) describes how all spatial frequencies are transmitted by an optical system\textsuperscript{66}. Compared to CS, MTF is considered an objective average, barely affected by the nerve pathways of the retina that provides more precise data on the quality of vision\textsuperscript{17}. The image quality of the apodized diffractive IOL provided by the manufacturer is based on ex vivo models (in water or in air)\textsuperscript{3}. However, more studies are required to investigate the optical quality of the apodized diffractive multifocal IOL, in order to determine its performance. Ortiz et al. compared in vivo optical quality of apodized diffractive multifocal AcrySof\textsuperscript{®} ReSTOR\textsuperscript{®} and refractive ReZoom\textsuperscript{®}, in terms of the MTF of the monofocal AcrySof\textsuperscript{®} MA60 IOL. They found that in vivo MTF was better in the AcrySof\textsuperscript{®} ReSTOR\textsuperscript{®} group\textsuperscript{3}. Artigas et al. analyzed the performance of apodized multifocal IOLs in vitro, with the aim of determining quality of vision. They found that monofocal IOLs provided better image quality than apodized diffractive multifocal IOLs for distance focal points with small pupils\textsuperscript{66}. However, they concurrently found that apodized diffractive multifocal IOLs had better image quality in near focus with all pupil sizes\textsuperscript{66}. Subsequently, MTF with different power lenses was studied. Moreno et al. measured the MTF of the AcrySof\textsuperscript{®} ReSTOR\textsuperscript{®} SN6AD3 multifocal IOL in 38 eyes of 19 patients with the double-pass system. They found a correlation between the power of the apodized diffractive multifocal IOL and the MTF (p = 0.05)\textsuperscript{13}. It is well known that a tilt in the IOL can affect the optical quality of the patient. More recently, Soda and Yaguchi evaluated the validity of the MTF with decentration. They found that near MTF of the apodized diffractive multifocal IOL (AcrySof\textsuperscript{®} ReSTOR\textsuperscript{®} SA60D3) decreased with increasing decentrations, while MTF improved in distance vision with same changes in decentration\textsuperscript{67}. They concluded that decentration above 0.75 mm was associated with visual effects\textsuperscript{67}.

In order to improve intermediate vision, apodized diffractive multifocal IOLs with three focal points have been introduced. Some studies have verified how the distribution of the light in trifocal apodized diffractive multifocal IOLs affects optical quality, particularly in intermediate focusing\textsuperscript{21}. Apodized diffractive IOLs with two main focal points provide a better MTF for the near focal points than IOLs with three focal points. Nevertheless, trifocal IOLs provide better resolution at intermediate visual distances than bifocal lenses\textsuperscript{21,68}. Montés-Micó et al. found that apodized diffractive multifocal IOLs with two main focal points (AcrySof\textsuperscript{®} ReSTOR\textsuperscript{®} 3.0 D) provides a wider range of vision from far to near than the diffractive multifocal IOLs with three main focal points (Finevision multifocal IOL)\textsuperscript{21}. They found that for the 0.0 D and −2.5 D focal points, the AcrySof\textsuperscript{®} ReSTOR\textsuperscript{®} 3.0 D provides better MTF values than Finevision multifocal IOL. Nevertheless, for the intermediate focal point (−1.5 D and −3.5 D), diffractive multifocal IOLs with three main focuses (trifocal IOL) are thought to provide a better optical quality\textsuperscript{21}. These outcomes agree with those obtained by Madrid-Costa et al. who found that IOL with three focal points (AT LISA\textsuperscript{®} 839MP) provide better optical quality in the −1.5 D focal point than the AcrySof\textsuperscript{®} ReSTOR\textsuperscript{®} SN6AD1\textsuperscript{69}. Madrid-Costa et al. found that the optical quality of the AT LISA\textsuperscript{®} trifocal lens for focal points of −2.5 D was significantly lower than in the bifocal lenses\textsuperscript{69}. Peng et al. found some statistically significant differences between patients implanted with the AcrySof\textsuperscript{®} ReSTOR\textsuperscript{®} SN6AD1 aspheric diffractive multifocal IOL at 5 and 10 cpd with pupil diameters of 3 mm\textsuperscript{17}. Nevertheless, they found that the MTF was lower in the AcrySof\textsuperscript{®} ReSTOR\textsuperscript{®} SN6AD1 aspheric diffractive multifocal IOL group than in the AcrySof\textsuperscript{®} SN60WF IOL group in pupil diameters from 3 mm to 5 and 10 cpd\textsuperscript{17}.

Furthermore, MTF outcomes between apodized diffractive IOLs and IOLs with the nonrotational symmetric IOL have been studied\textsuperscript{70}. Montés-Micó et al. found that the AcrySof\textsuperscript{®} SN6AD1 provides better values for all frequencies than the LENTIS\textsuperscript{®} Mplus LS-312. They found that the MTF of the apodized diffractive IOL decreased considerably when the IOL was decentered or tilted. However, they found that the PSF was worse for the apodized diffractive IOL\textsuperscript{70}.

**POSTERIOR CAPSULAR OPAICATION**

Posterior capsule opacification (PCO) is one of the main complications which often occurs after cataract surgery, greatly affecting the visual quality of the patient. Due to the design and the biocompatibility of the material, the implantation of the diffractive multifocal IOLs often produces lower levels of PCO\textsuperscript{22,24}. Yoshino et al. implanted an apodized diffractive multifocal IOL in 21 patients (42 eyes). Five years after the intervention, they found that only 14.3% of operated eyes (6 eyes) required of Nd:YAG laser capsulotomy for the elimination of PCO\textsuperscript{37}.

Patients who receive an apodized diffractive multifocal IOL requiring Nd:YAG laser capsulotomy usually achieve good visual outcomes. Vrijman et al. performed a retrospective study in 75 pseudophakic eyes (50 patients) which had been implanted with an
apodized diffractive multifocal IOL that subsequently needed of Nd:YAG laser capsulotomy for the elimination of PCO. After Nd:YAG laser capsulotomy, there was a statistically significant improvement in CDVA and in UDVA (p < 0.001), with no changes in astigmatic power vectors J(0) and J(45). These authors found that in the vast majority of the patients who underwent Nd:YAG laser capsulotomy, there was no variation in refraction, while only 7% of patients experienced a significant variation in subjective refraction, resulting in a variation of approximately 0.5 D in the spherical equivalent for subjective refraction.

**CONCLUSIONS**

The new designs of apodized diffractive multifocal IOLs provide good visual outcomes in distant vision, intermediate vision and near vision, regardless of the use of spectacles in the majority of cases. The gradual transition which is produced in the number of diffractive steps from the center to the periphery avoids variations in CS and produces fewer aberrations and fewer glares and halos, mainly in night conditions, when the pupil size increases.

**REFERENCES**


