



Incorrectly Focused Neodymium:Yttrium–Aluminum-Garnet (Nd:YAG) Laser Beam Leads to Massive Destructive Effects in Small-Aperture (Pinhole) Intraocular Lenses

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ABSTRACT

Introduction: Pinhole intraocular lenses (IOLs) were developed to improve reading by compensating for loss of accommodative function. The IC-8[®] Aphthera[™] is a small-aperture presbyopia-correcting IOL that combines the proven principle of small-aperture optics with an aspheric monofocal lens to deliver a continuous range of vision for patients with cataracts from distance to near vision. Posterior capsule opacification

is the most common sequela after cataract surgery. It is effectively treated by laser capsulotomy. However, if the laser beam is incorrectly focused, the IOL can be permanently damaged (pits/shots).

Methods: In this experimental study, yttrium–aluminum-garnet (YAG) pits were purposefully created. Defects were analyzed and compared between the periphery of the ring in the clear area of the hydrophobic acrylic lens and at the carbon black (CB)-polyvinylidene fluoride (PVDF) filtering component (FilterRing[™]) of the pinhole lens. All defects were made using identical settings/energy levels (2.6 mJ). The damage induced to the IC-8[®] Aphthera[™] IOL was examined by low-magnification images, light microscopy, scanning electron microscopy, and micro-computed tomography (micro-CT).

Results: YAG defects in the carbon black filter ring were much more severe than those in the clear zone due to the high absorption of the carbon black. Massive defects and destruction of the lens with tearing out of fragments and particles were observed. The missing volume calculated from the micro-CT reconstruction was 0.266 mm³, which is 1.6% of the entire IOL volume, or more than 1000 times the volume damaged in the largest shot in the periphery.

Conclusion: Based on the results, we highly recommend using the lowest possible energy levels, posterior offset setting, and circular pattern for maximum safety when performing

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laser capsulotomy with pinhole implants. Care should be taken to avoid creating irreversible iatrogenic defects that may affect overall quality. The safest area for performing capsulotomy seems to be the periphery of the ring segment. Video available for this article.

Keywords: Small aperture; Pinhole intraocular lens; Presbyopia correcting lens; Damage in intraocular lens; YAG pits; Hydrophobic acrylic; Nd:YAG laser; Capsulotomy

Key Summary Points

This laboratory experiment shows that laser-associated defects are much more severe in the carbon black filter ring of pinhole intraocular lenses (IOLs) due to the high absorption.

Incorrect focusing of the laser with standard energy levels leads to massive defects and destruction of the lens.

The safest area for performing laser capsulotomy in pinhole IOLs seems to be the clear area in the periphery of the ring segment.

DIGITAL FEATURES

This article is published with digital features, including a video, to facilitate understanding of the article. To view digital features for this article, go to <https://doi.org/10.6084/m9.figshare.26312122>.

INTRODUCTION

A pinhole is a small circular hole, as could be made with the point of a pin. In optics, pinholes with various diameters are used as apertures in optical systems and can focus light or act as a kind of lens. This effect is used in solarigraphy and in pinhole cameras and the so-called camera

obscura [1, 2]. The same effect is used in pinhole occluders, which are used by ophthalmologists to test visual acuity. The pinhole effect has also been successfully used in spectacles, contact lenses, and corneal inlays to improve reading. In recent years, presbyopia-correcting intraocular lenses (IOLs) have become increasingly popular and more frequently used in cataract surgery to treat presbyopia after removal of the cloudy lens [3, 4]. Pinhole IOLs were developed to use the pinhole effect to improve reading by compensating for loss of accommodative function [5]. The effect of paraxial rays is minimized by the small aperture, reducing the circle of blur and minimizing the effect of higher-order aberrations (HOAs), enhancing depth of focus, and reducing the effect of refractive errors.

The IC-8® Aphthera™ (Bausch & Lomb) is a small-aperture presbyopia-correcting IOL that combines the proven principle of small-aperture optics with an aspheric monofocal lens to deliver a continuous range of vision from distance to near vision for patients with cataracts. The hydrophobic acrylic, ultraviolet-blocking one-piece lens has a 6.0 mm optic diameter and an overall diameter of 12.5 mm. The biconvex IOL with an anterior aspheric surface is built on a classic c-loop IOL platform with 360° posterior square edge design and 5° angulation to prevent posterior capsule opacification (PCO). The spherical aberration is −0.22 mm. The refractive index of the material is 1.48 at 35 °C and 589 nm. The lens has a filtering component (FilterRing™) made of polyvinylidene fluoride (PVDF) and carbon black (CB) with an outer diameter of 3.23 mm and an aperture diameter size of 1.36 mm. The FilterRing component thickness is 5.00 mm, and the number of micro-perforations is 3200.

PCO is still the most common late consequence of cataract surgery [6–8]. The data differ greatly on the frequency and timing. This is due to different study designs and many different existing IOL models. Various factors have been identified which may have an influence. In addition to the material and design of the lens, these include factors relating to the surgical technique as well as secondary diagnoses of the eye [9–13]. Experts currently agree that secondary cataracts (PCO) can develop with all IOLs after a certain

period of time. PCO incidence has been reduced by various measures and advancements in IOLs but is still an important issue [14, 15]. PCO can lead to deterioration of visual performance, decrease in contrast, increase in glare and stray light, and decrease in overall visual quality with blurred vision. This condition is currently treated with a neodymium:yttrium–aluminum–garnet (Nd:YAG) laser to create a posterior capsulotomy (gold standard). This procedure is considered safe, simple, and effective. Nevertheless, complications can still occur. These include permanent damage to the implant if laser-associated defects occur within the IOL.

The main purpose of this experimental study was to compare the YAG-associated defects at the clear zone of the hydrophobic acrylic lens with the YAG-associated defects at the carbon black filter ring of the IC-8® Aphthera™. We demonstrate that, due to the high absorption of the carbon black, the YAG defects in the carbon black filter ring are much more severe than those in the clear zone and should be avoided.

METHODS

In this laboratory experiment, a Q-switched Nd:YAG laser system (Visulas YAG III, Carl Zeiss, Germany) with a wavelength of 1064 nm and pulse length of <4 ns was used. IOL samples were placed within a self-constructed transparent glass cuvette, which was fixed to the head and chin-rest of the device. The laser beam was focused directly on the surface of the IOL and within the IOL material body in order to intentionally create defects. In all cases, the same energy level of 2.6 mJ was used. The defects were made in the periphery of the ring in the clear area of the hydrophobic acrylic lens and at the carbon black (PVDF) filtering component (Filter-Ring™) of the pinhole lens. In total, 17 Nd:YAG pits (defects) were created, out of which 13 were focused in the clear part of the lens (10 anterior surface, three posterior surface) and four were focused in the ring layer.

The following measurements and tests were carried out to investigate the effects of the laser on the test samples.

Low-Magnification Images

Low-magnification images of the entire IOL and large defects were acquired using an Olympus SZ Series stereomicroscope (Olympus, Tokyo, Japan) equipped with a camera and a Nikon D7500 photo camera (Nikon, Tokyo, Japan) with an RS1 stand (Kaiser Fototechnik, Buchen, Germany). The images were taken directly in the IOL fixation device.

Light Microscopy

Light microscopy images were acquired using an Alicona Infinite Focus microscope (IFM; Bruker Alicona, Graz, Austria) in order to ensure a sufficient depth of focus, even for high-resolution images on the sloped surface of the IOL. The images were taken using a Nikon LU Plan ×50/NA0.55 objective (Nikon, Tokyo, Japan) and directly in the IOL fixation device.

Environmental Scanning Electron Microscopy (ESEM)

Secondary electron (SE) images were acquired using an FEI Quanta 600 FEG (Thermo Fisher Scientific, Waltham, MA, USA) ESEM. To compensate for surface charges and to minimize alterations of the sample surface, the measurements were taken in the low-vacuum (LV) mode, using water vapor as the imaging gas. An accelerating voltage of 10 kV was used for all measurements, and the IOL was placed in the microscope directly in the IOL fixation device.

Micro-Computed Tomography (micro-CT)

The volume study of Nd:YAG pits was conducted with a TESCAN UniTOM HR instrument (Tescan, Brno, Czech Republic) operating in microfocus regime. The sample in its native protective casing (as supplied from the manufacturer) was

pre-dried with CO₂ gas flow and fixed with a custom-made polylactic acid (PLA) holder and Parafilm. Accelerating voltage of 50 kV at 5 W target power was used. Tilt series were acquired at 7.5 μ m voxel size over 2286 projections in 360° range, each constituting 1500 ms exposure and four averages. Tilt series were reconstructed with TESCAN Panthera software (Tescan, Brno, Czech Republic). Visualization and analysis were carried out with Object Research Systems (ORS) Dragonfly software (Comet Technologies, Montreal, Canada). Ethics approval was not required for this experimental, laboratory study type, as no human or animal subjects or materials were involved.

RESULTS

The damage induced to the IC-8® Apthera™ IOL by the Nd:YAG laser was examined by light microscopy, scanning electron microscopy, and micro-CT. Figure 1 demonstrates the IOL position in its native protective casing/fixation device, where the IOL was kept throughout all the measurements. It was adapted for the micro-CT setup using a slot-in holder.

The micro-CT reconstruction in Fig. 2 classifies defects based on their depth relative to the position of the CB-PVDF ring (anterior/posterior, ring layer) and their lateral position (periphery or on the ring). The numbered shots (1–4)

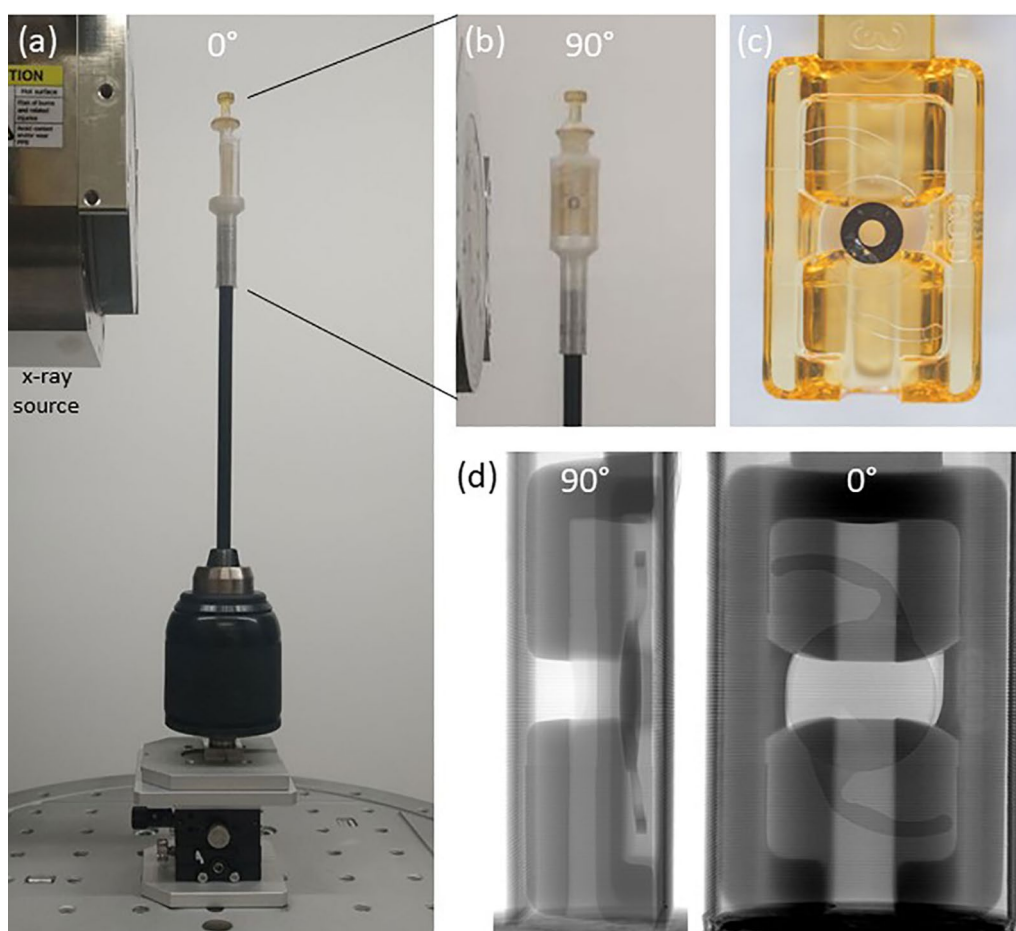


Fig. 1 Overview of the micro-computed tomography (micro-CT) experiment: **a–b** sample positioning using the custom-made polylactic acid holder; **c** orientation of the

intraocular lens (IOL) in the fixation device viewed with a photograph; **d** X-ray transmission images (radiographs) of the IOL in the fixation device in the front and side views

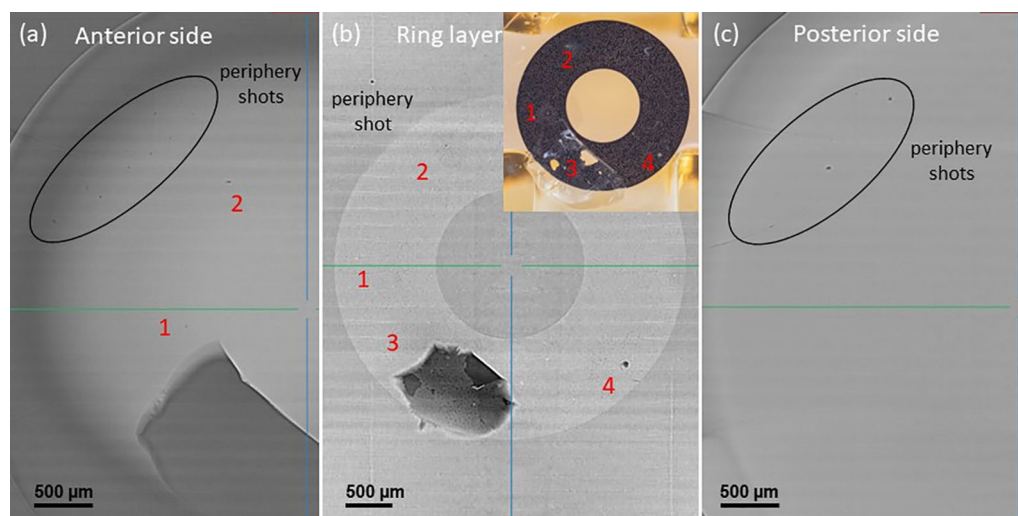


Fig. 2 Classification of the defects based on the lateral position (periphery/ring) and depth: **a** anterior, **b** ring layer, **c** posterior. Laser shots radially matching the filter ring are shown in red and numbered. The numbering order has no relation to the order the shots were induced. The crosshair marks the center of the lens. The inset in **b** shows

a photo of the critical shots. Note that the horizontal stripes are absorption shadows of the polylactic acid holder and that micro-computed tomography (micro-CT) views are averaged over a depth of 80 µm to make all the features visible simultaneously

marked in red are the shots on the ring. Damage to the lens is already discernible with the naked eye, as is evident from the photo in the inset of Fig. 2b, where at position 3, part of the acrylic material is missing, accompanied by two missing patches of the CB-PVDF ring layer. This shot led to severe and most obvious damage. The damage caused by the other three shots in the ring (1, 2, 4), while not as clearly visible here, is still significant. Finally, the damage from the shots in the periphery (both anterior and posterior) is smaller.

Figure 3 presents typical examples of shots in the periphery (the clear part of the IOL), including two shallow surface shots < 50 µm in depth (Fig. 3a, b) and a deep-penetrating shot (Fig. 3c, d). Characteristic diameters of the shot pits are 10–50 µm, resulting in damage volumes of up to 200,000 µm³ (0.0002 mm³) for the largest shot measured. The sizes and shapes of the pits on the surface, as seen in the IFM/SEM images, from laser shots to the periphery of the lens have characteristics similar to those observed in previous research for other IOL types [16]. Narrow but deep penetration shots like the one seen in Fig. 3c, d were also observed in a micro-CT

feasibility study for the 3D imaging of Nd:YAG shots for other IOL types [17].

The defects resulting from the Nd:YAG shot of the CB-PVDF ring layer are much more dramatic. At the largest damage site (position 3 in Fig. 2), a macroscopically recognized portion of acrylic lens material is missing, as shown in Fig. 4. This missing piece is about 1.95 mm in diameter and extends as deep as the CB-PVDF ring layer (~0.29 mm). The missing volume, calculated from the micro-CT reconstruction, is 0.266 mm³, which is about 1.6% of the entire IOL volume, or more than 1000 times the volume damaged in the largest shot in the periphery.

The dimensions can be clearly observed in a 3D rendering (Video 1). Note: See Video 1 in the online/HTML version of the manuscript or follow the digital features link under the abstract.

An additional long crack is present in the acrylic material propagating from the right wall of the missing piece to a total distance of 2 mm that could potentially result in a second comparable piece being broken.

Furthermore, a region of the CB-PVDF ring itself (1.15 mm in diameter) is exposed and a

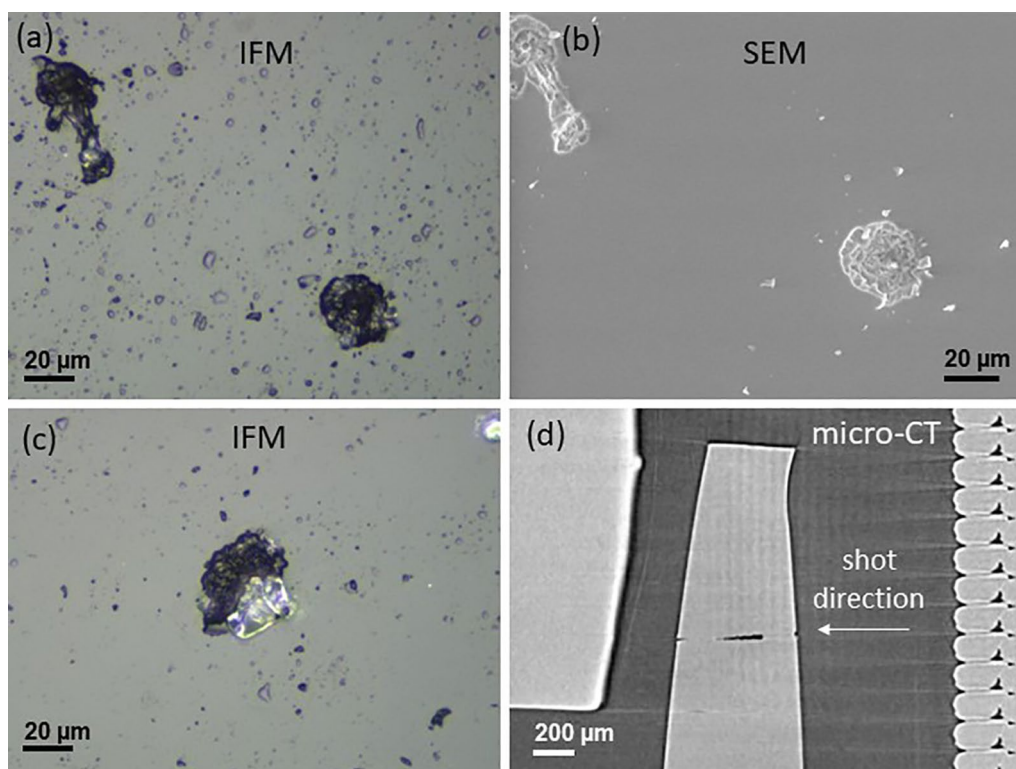


Fig. 3 Periphery shots: **a–b** shallow shots $< 50\ \mu\text{m}$ as seen with infinite focus microscope (IFM) and scanning electron microscope (SEM), respectively; **c** deep-penetrating

shot seen in IFM and **d** its depth profile in micro-computed tomography (micro-CT) side-view cross section

large degree of damage to the ring layer is clearly visible (Fig. 5). The perforated CB-PVDF ring appears to be both bending and torn, with missing patches as large as 0.38 mm in diameter and curling edges ready to fall off.

While the other three shots on the CB-PVDF ring did not blow off a large piece of acrylic material, there is nevertheless substantial damage visible on the CB-PVDF ring itself. At all positions, damaged areas of the CB-PVDF ring are visible by light microscopy (Fig. 6).

In summary, for the Nd:YAG shots that hit the carbon black filter ring directly, substantial damage to the ring and the IOL was observed, as compared to Nd:YAG shots that hit the peripheral clear zone of the acrylic lens and missed the filter ring. This makes sense, as the high absorption of the carbon black in the filter ring for the laser wavelength means that significantly more laser energy is absorbed by the CB-PVDF filter. Consequently, this leads to more heating, higher

temperatures, and thus more damage. However, shots that also hit the carbon black filter ring but were focused anteriorly or posteriorly caused comparatively minor damage. This can be explained by the lower energy density of the defocused laser at the ring.

DISCUSSION

Many investigations of laser-associated defects in clear acrylic IOLs have been carried out using various methods and have delivered consistent results [16–18]. These results showed that, depending on the water content of the material and the manufacturing process of the lens, there may be differences in laser-associated and mechanically induced defects/scratches. These differences relate to the depth, shape, and extent of the craters. It has also been shown that these

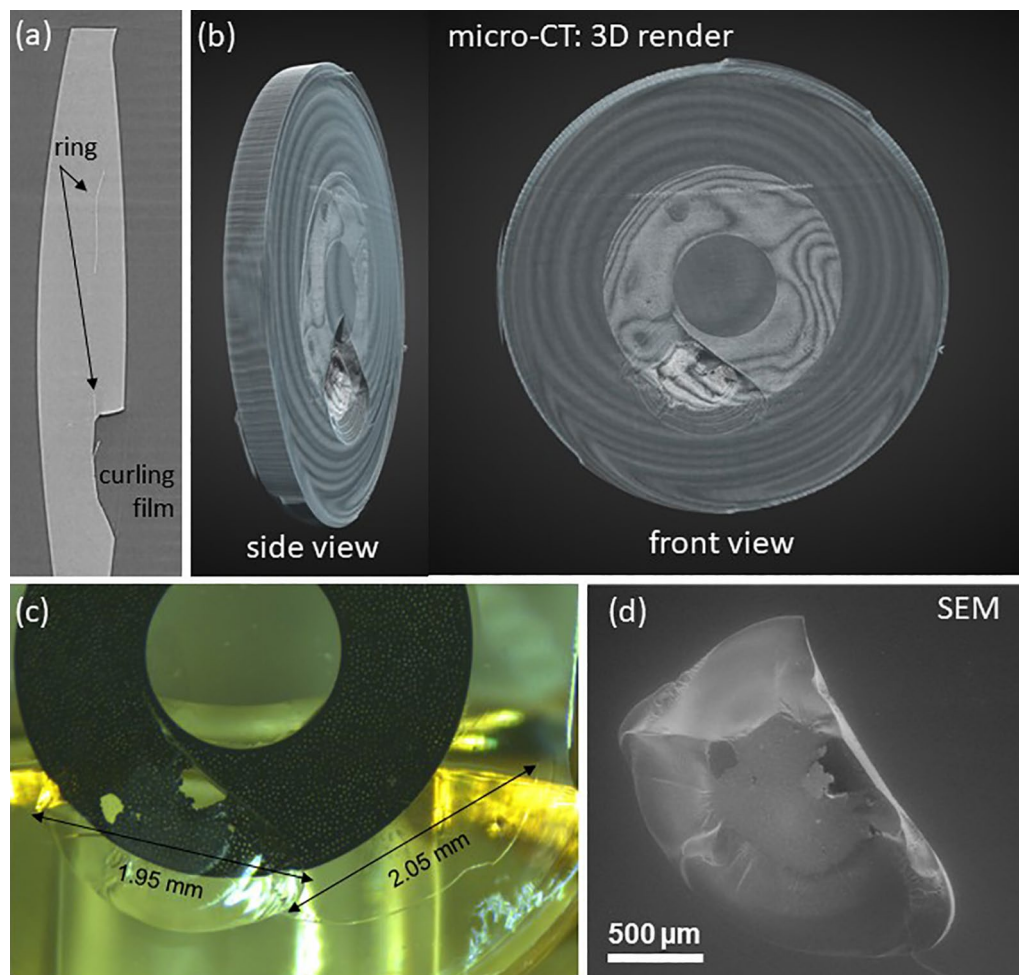


Fig. 4 Largest area of damage to the intraocular lens (IOL) by a Nd:YAG-shot: **a** micro-computed tomography (micro-CT) side-view slice, showing the missing piece of acrylic and curling carbon black–polyvinylidene fluoride

(CB-PVDF) film, **b** 3D rendering of the damage, **c** optical appearance of the lens featuring the missing piece and additional crack, **d** surface of the damage accentuated with scanning electron microscopy (SEM)

damage-induced tiny defects within the IOL can have a negative impact on the quality of the lens optics, with a reduction in contrast sensitivity, stray light effects, and increased glare [19, 20].

In this study, the Nd:YAG pits that were introduced in the clear acrylic part of the IOL appear comparable in size and shape to Nd:YAG pits introduced into a variety of other IOL types in the literature [16], when observed using light microscopy and ESEM on the surface (2D structure). Note that a comparison of the 3D structure and extent of these defects for different IOL types is part of ongoing research. However, this work clearly shows that significantly larger

defects occur at the same laser energy when the laser beam is focused directly on the carbon black ring compared to the clear zone. Whilst a detailed account of the damage mechanism is well beyond the scope of this work and is likely highly complicated in a composite material like this, we can obtain some indications from the literature on laser ablation of polymers.

Laser ablation, i.e. the removal of material from a solid by a laser, occurs above a critical fluence, called the ablation threshold, which is dependent on (among other things) the absorption coefficient of the material [21]. For polymethyl methacrylate (PMMA) and a 1064 nm

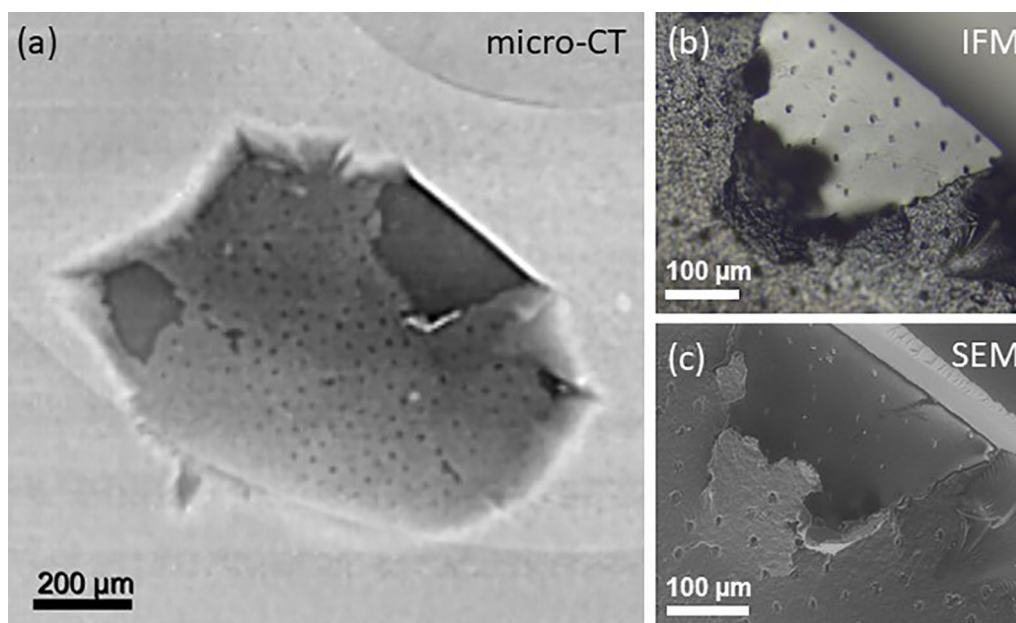


Fig. 5 Largest area of damage to the carbon black–polyvinylidene fluoride (CB-PVDF) filter ring by a Nd:YAG-shot: **a** micro-computed tomography (micro-CT) view of exposed CB-PVDF film averaged over a depth of 50 μm ,

b infinite focus microscope (IFM) and **c** scanning electron microscope (SEM) close-up view of the torn curling CB-PVDF film

Nd:YAG laser, it has been shown that the ablation process is mostly photothermal [22]. A study on the ablation of various polymers using a 1064 nm Nd:YAG laser also showed that exceeding the degradation temperature of the polymer is critical for the onset of ablation in this case [23]. Finally, Zelenska et al. specifically mixed carbon black with a transparent polymer matrix (polystyrene; PS) to achieve local photothermal decomposition of the PS at lower laser fluence [24]. Based on these insights from the literature on laser ablation of polymers, we propose that there is a risk of crossing critical temperature thresholds when the laser directly hits the highly absorbent carbon black in the filter ring, leading to the large degree of damage observed for the Nd:YAG shots. Once again, it should be emphasized that all defects in this experiment were made with the same device and identical energy and settings. This explanation also means that it is more likely to observe significant anterior damage, as seen in this study, because it is the anterior side of the carbon ring that is heated the most by the laser. However,

this does not mean that it is not possible to induce posterior damage as well.

The positive effects of the pinhole concept have been confirmed several times in the past. Studies showed that the pinhole effect improved visual acuity in patients with irregular corneas and higher-order aberrations that cannot be treated with customized refractive surgery. Results of clinical studies demonstrated that the monocular IC-8[®] intraocular lens provides a continuous, broad range of vision and excellent visual acuity across all focal distances [25]. The small-aperture IOL has also shown a high safety index and a high satisfaction rate [26, 27]. According to authors, the pinhole sulcus implant not only helped eliminate the fluctuation in residual refraction after cataract surgery, but also provided an elongated depth of focus without greatly affecting the visual field [28, 29]. Studies showed that the pinhole effect helped to substantially decrease irregular astigmatism and improve visual acuity. With a partial aniridia implant, a reduction in glare symptoms was achieved, while allowing sufficient fundus assessment. The combined implantation of

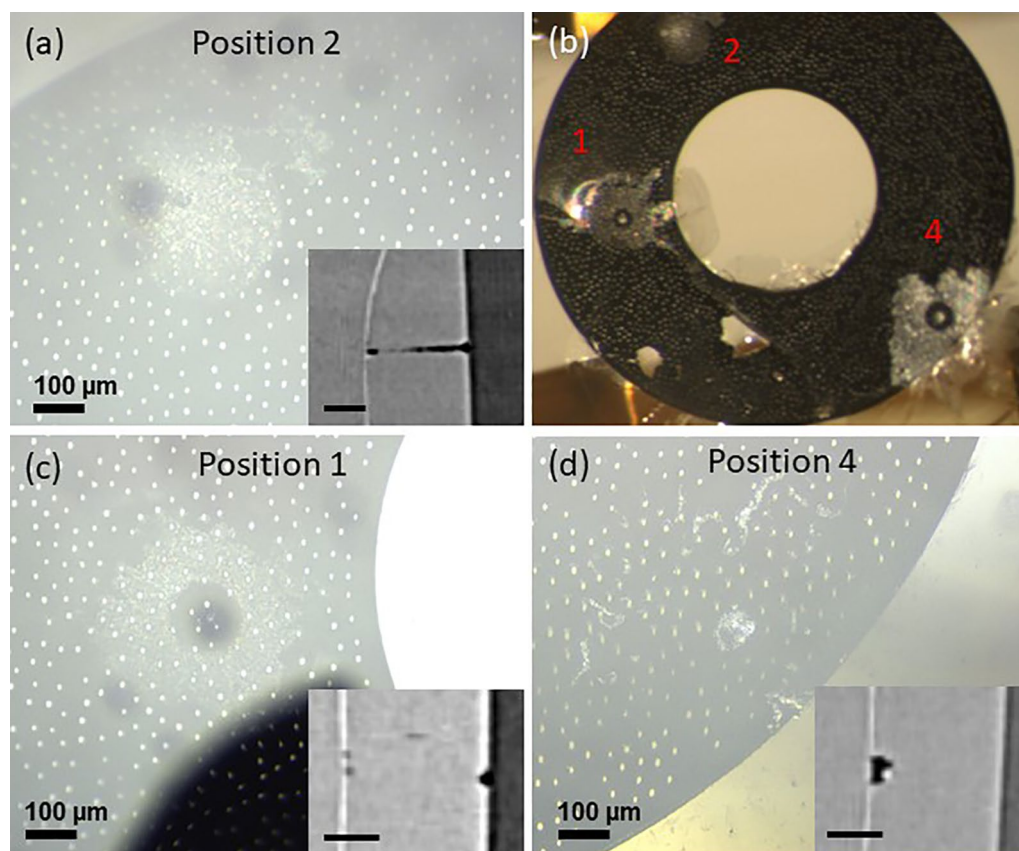


Fig. 6 Damage to the carbon black–polyvinylidene fluoride (CB-PVDF) filter ring by the other three shots; **a**, **c**, **d** infinite focus microscope (IFM) images showing distorted interface of acrylic/CB-PVDF film in positions 1 (**c**), 2 (**a**),

and 4 (**d**). Inset in each panel is a micro-computed tomography (micro-CT) cross section of the respective shot profile. **b** Frame from a slit-lamp image showing the extent of damage

the small-aperture IOL and the partial aniridia device, therefore, presents an effective option for improving the visual symptoms in patients with traumatic iris defects [30]. Laboratory tests with eye models confirmed that pinhole implants have the potential for increasing the depth of focus compared to conventional intraocular lenses [31]. Small-aperture optics seem to be a good option in treating presbyopia-related problems. They are effective throughout the range of accommodation loss and in pseudophakia. Small-aperture optics offer an opportunity to improve vision in presbyopes. They may also be able to reduce the impact of aberrations or improve vision in eyes with corneal irregularities, scars, or iris damage [32].

The IC-8[®] Aphthera[™] IOL has demonstrated high quality in various clinical studies and

has led to good postoperative results. The lens appears to be an important component in the adequate treatment of special patient groups. The IC-8[®] Aphthera[™] IOL is US Food and Drug Administration (FDA)-approved as presbyopia-correcting or extended-depth-of-focus intraocular lens. It filters out peripheral light entering the eye, delivering only central light rays to the retina and thus providing extended depth of focus, free from “blurry zones.” This pinhole effect provides a continuous clear range of vision from near to far.

According to the manufacturer, the IC-8[®] Aphthera[™] IOL is indicated for unilateral implantation to create monovision. Indications include patients with bilateral cataracts and astigmatism up to 1.5 D. There must be no pronounced retinal diseases and no signs of early stages of

retinal diseases at the time of surgery. According to the manufacturer, the pinhole lens should only be implanted after successful surgery has been performed on the contralateral eye. This eye should be adjusted to emmetropia with a monofocal or monofocal toric lens. The IC-8[®] is intended for implantation in the capsular bag of the non-dominant eye. The refractive target for the IC-8[®] Aphera™ should be slight myopia (−0.75 D). The lens provides an extended depth of focus by improving intermediate and near visual acuity, while maintaining comparable distance visual acuity, compared to an aspheric monofocal or monofocal toric IOL [32].

Disadvantages of using the pinhole effect can include high susceptibility to decentration and decreased retinal luminance levels. Difficulties in performing fundus examinations or posterior segment surgery in eyes with implanted devices have been described. There are also concerns regarding issues of perception with different retinal illuminance in the two eyes [5]. The so-called Pulfrich effect is caused by the brightness-dependent delay in the perception of visual stimuli [33].

In the FDA registration studies, the rate of clinically significant PCO needing treatment was 32.4% in IC-8[®] eyes compared with 14.0% in fellow eyes and 16.4–17.3% in the eyes of the control group subjects [34]. During the FDA study, 31.2% of the IC-8[®] eyes received posterior capsulotomy (Nd:YAG) as treatment for PCO affecting vision. In 12.1% of these capsulotomy procedures, the investigators reported some difficulty in performing the procedure in an IC-8[®] IOL-treated eye. Moreover, a correlation was noted between difficulty performing a capsulotomy procedure and resulting issues or laser damage (pits) to the IOL [34]. It should be noted here that the final publication of the FDA-approved study was not available at the time of our laboratory tests. The summary of safety and effectiveness data (SSED) available online at fda.gov is provided herein [34].

Our laboratory experiments support and confirm these data and show that an appropriate capsulotomy technique in pinhole IOLs is particularly important. Therefore, it is recommended by the manufacturer that in the event of secondary cataracts (PCO), a hinged circular

YAG capsulotomy should be performed around the FilterRing component (i.e. “a capsule opening of approximately 10 clock hours around the outside of the FilterRing component from 5 to 7 o’clock leaving an inferior hinge”). This should ensure that the capsulotomy flap retracts inferiorly and does not interfere with visual quality later on. It is recommended that the capsulotomy be performed in the periphery of the FilterRing component [34]. Therefore, in cases with pinhole implants, particular attention should be paid to sufficient pupil dilation.

Limitations of the Study

For our laboratory tests, we used Nd:YAG energy levels that are used by many colleagues as standard settings in clinical routine. However, the energy levels of Nd:YAG capsulotomy still warrant further investigation to determine critical limits. The defects were not evenly distributed in each group, and the small sample size of the study is a limitation. Given that this was an experimental study, further clinical studies are needed to evaluate patients’ subjective perception, including visual acuity, contrast sensitivity, and visual symptoms. The topic should be given much more attention in order to avoid negative effects and increase safety. At the time of submission of our revised manuscript, there were only case reports presented by colleagues at conferences discussing the challenges of Nd:YAG laser in eyes with pinhole IOLs and the possibility of damaging the lens. No published articles were available at that time.

CONCLUSION

In summary, it can be concluded that the capsulotomy for presbyopia-correcting lenses should be performed with the utmost precision and accuracy, taking care in all cases to avoid causing iatrogenic defects in IOLs. This applies in particular to pinhole implants like the IC-8[®] Aphera™. It seems most important that the clear central area is not compromised, as this area is essential for the quality of vision and should therefore not be damaged. It is also

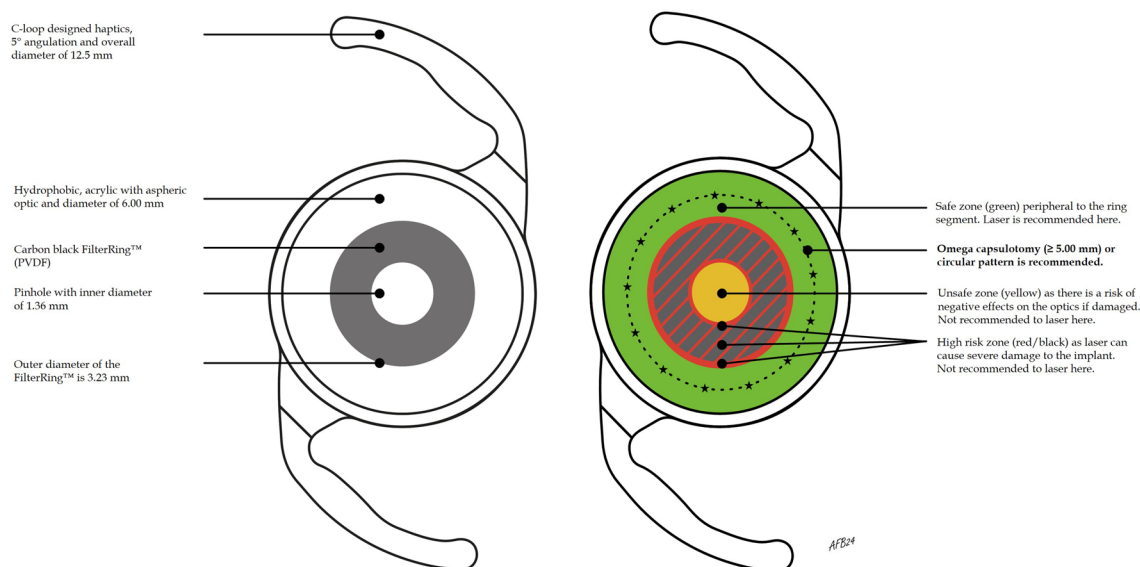


Fig. 7 Schematic overview of the pinhole lens. Left: Total diameter of the hydrophobic, acrylic intraocular lens (IOL) with design of the haptics and optics as well as the ring segment. Right: The zones are indicated which are important to ensure that the carbon black filter ring is not damaged by the Nd:YAG laser, as relatively severe effects and damage are to be expected there, and particles/fragments of the material could even detach from the implant.

The lab experiment again showed that direct focusing of the Nd:YAG laser beam on the hydrophobic acrylic IOL leads to tiny defects (YAG pits) in the material, as has been shown for other IOL types. The size and shape of these tiny defects on the surface (2D structure) is comparable to what has been observed for other IOL types [16]; a detailed comparison of the size and shape of the 3D structure of these defects in different IOL types is part of ongoing research. However, it has been shown that hitting the carbon black filter segment with the same energy levels leads to dramatically more severe defects, resulting in partial destruction of the ring segment and the destruction of the lens material. Consequently, parts of the material detach from the lens, creating a crater or hole.

Therefore, special care should be taken when PCO occurs in an eye with an implanted pinhole IOL. Nevertheless, Nd:YAG laser capsulotomy can be performed effectively and safely in these cases with the necessary caution.

considered dangerous in the event of damage by the laser and the zone which can be described as safe when performing Nd:YAG capsulotomy to treat posterior capsule opacification

The safest zone of the IC-8® IOL seems to be the clear area of the acrylic lens outside the carbon black ring segment, as this is where the risk is lowest, comparable to other acrylic IOLs (Fig. 7). Therefore, with pinhole implants, we can recommend using the lowest possible energy levels, the posterior offset setting, and a circular pattern for maximum safety. As with all other implants, care should be taken to avoid creating irreversible iatrogenic defects that may affect the overall quality. Further laboratory and clinical studies are needed to determine what effects fragments or particles of broken material can have in the eye.

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Authorship. All named authors meet the International Committee of Medical Journal Editors (ICMJE) criteria for authorship for this article, take responsibility for the integrity of the work as a whole and have given their approval for this version to be published.

Author Contributions. The authors confirm responsibility for the following: Study concept and design by Andreas F. Borkenstein; data collection by Andreas F. Borkenstein, Tatiana K. Kormilina, Harald Fitzek, Johannes Rattenberger, Fabio E. Machado Charry; analysis and interpretation of data by Andreas F. Borkenstein, Tatiana K. Kormilina, Harald Fitzek, Johannes Rattenberger, Gerald Kothleitner, Fabio E. Machado Charry, Eva-Maria Borkenstein; final approval of the manuscript by Andreas F. Borkenstein, Tatiana K. Kormilina, Harald Fitzek, Johannes Rattenberger, Gerald Kothleitner, Fabio E. Machado Charry, Eva-Maria Borkenstein.

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Data Availability. The authors confirm that the data supporting the findings of this study are available within the article.

Declarations

Conflict of Interest. Andreas F. Borkenstein, Tatiana K. Kormilina, Harald Fitzek, Johannes Rattenberger, Gerald Kothleitner, Fabio E. Machado Charry and Eva-Maria Borkenstein have nothing to disclose. All named authors declare that they have no personal, financial, commercial, or academic conflicts of interest and agree with the contents of the manuscript.

Ethical Approval. Ethics approval was not required for this laboratory study type, as no human or animal subjects or materials were used.

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REFERENCES

1. Rego JD, Chen H, Li S, Gu J, Jayasuriya S. Deep camera obscura: an image restoration pipeline for pinhole photography. *Opt Express*. 2022;30(15):27214–35. <https://doi.org/10.1364/OE.460636>.
2. Wade NJ, Finger S. The eye as an optical instrument: from camera obscura to Helmholtz's perspective. *Perception*. 2001;30(10):1157–77. <https://doi.org/10.1068/p3210>.
3. Wolffsohn JS, Davies LN. Presbyopia: effectiveness of correction strategies. *Prog Retin Eye Res*. 2019;68:124–43. <https://doi.org/10.1016/j.preteyres.2018.09.004>.
4. Zhu Y, Zhong Y, Fu Y. The effects of premium intraocular lenses on presbyopia treatments. *Adv Ophthalmol Pract Res*. 2022;2(1): 100042. <https://doi.org/10.1016/j.aopr.2022.100042>.
5. Kanclerz P, Khoramnia R, Atchison D. Applications of the pinhole effect in clinical vision science. *J Cataract Refract Surg*. 2024;50(1):84–94. <https://doi.org/10.1097/j.jcrs.0000000000001318>.
6. Dewey S. Posterior capsule opacification. *Curr Opin Ophthalmol*. 2006;17(1):45–53. <https://doi.org/10.1097/01.icu.0000193074.24746.e6>.
7. Wormstone IM, Wang L, Liu CS. Posterior capsule opacification. *Exp Eye Res*. 2009;88(2):257–69. <https://doi.org/10.1016/j.exer.2008.10.016>.
8. Lee Y, Kim JS, Kim BG, Hwang JH, Kang MJ, Lee JH. Comparison of the incidence of Nd:YAG laser capsulotomy based on the type of intraocular lens.

- Medicina (Kaunas). 2023;59(12):2173. <https://doi.org/10.3390/medicina59122173>.
9. Maedel S, Evans JR, Harrer-Seely A, Findl O. Intraocular lens optic edge design for the prevention of posterior capsule opacification after cataract surgery. *Cochrane Database Syst Rev*. 2021;8(8):CD012516. <https://doi.org/10.1002/14651858.CD012516.pub2>
 10. Vock L, Menapace R, Stifter E, Georgopoulos M, Sacu S, Bühl W. Posterior capsule opacification and neodymium:YAG laser capsulotomy rates with a round-edged silicone and a sharp-edged hydrophobic acrylic intraocular lens 10 years after surgery. *J Cataract Refract Surg*. 2009;35(3):459–65. <https://doi.org/10.1016/j.jcrs.2008.11.044>.
 11. Sacu S, Menapace R, Buehl W, Rainer G, Findl O. Effect of intraocular lens optic edge design and material on fibrotic capsule opacification and capsulorhexis contraction. *J Cataract Refract Surg*. 2004;30(9):1875–82. <https://doi.org/10.1016/j.jcrs.2004.01.042>.
 12. Nishi Y, Rabsilber TM, Limberger IJ, Reuland AJ, Auffarth GU. Influence of 360-degree enhanced optic edge design of a hydrophilic acrylic intraocular lens on posterior capsule opacification. *J Cataract Refract Surg*. 2007;33(2):227–31. <https://doi.org/10.1016/j.jcrs.2006.10.020>.
 13. Auffarth GU, Golescu A, Becker KA, Völcker HE. Quantification of posterior capsule opacification with round and sharp edge intraocular lenses. *Ophthalmology*. 2003;110(4):772–80. [https://doi.org/10.1016/S0161-6420\(02\)01980-2](https://doi.org/10.1016/S0161-6420(02)01980-2).
 14. Nibourg LM, Gelens E, Kuijter R, Hooymans JM, van Kooten TG, Koopmans SA. Prevention of posterior capsular opacification. *Exp Eye Res*. 2015;136:100–15. <https://doi.org/10.1016/j.exer.2015.03.011>.
 15. Spalton D. Posterior capsule opacification: have we made a difference? *Br J Ophthalmol*. 2013;97(1):1–2. <https://doi.org/10.1136/bjophthalmol-2012-302570>.
 16. Borkenstein AF, Borkenstein EM. Analysis of YAG Laser-induced damage in intraocular lenses: characterization of optical and surface properties of YAG shots. *Ophthalmic Res*. 2021;64(3):417–431. <https://doi.org/10.1159/000513203>.
 17. Borkenstein AF, Borkenstein EM, Machado E, Fitzek H, Rattenberger J, Schennach R, Kothleitner G. Micro-computed tomography (μ CT) as a tool for high-resolution 3D imaging and analysis of intraocular lenses: feasibility and proof of the methodology to evaluate YAG pits. *Ophthalmol Ther*. 2023;12(1):447–457. <https://doi.org/10.1007/s40123-022-00622-8>.
 18. Borkenstein AF, Mikitisin A, Schwedt A, Borkenstein EM, Mayer J. A novel 3D high resolution imaging method using correlative X-Ray and electron microscopy to study Nd:YAG laser induced defects in intraocular lenses. *Ophthalmic Res*. 2024; <https://doi.org/10.1159/000539243>.
 19. Borkenstein AF, Borkenstein EM, Omidi P, Langenbucher A. Evaluating impact of Nd: YAG laser associated defects on optical quality of hydrophilic and hydrophobic intraocular lenses using visualization of light propagation and USAF test targets. *BMC Ophthalmol*. 2022;22(1):494. <https://doi.org/10.1186/s12886-022-02738-8>.
 20. Borkenstein AF, Borkenstein EM, Omidi P, Langenbucher A. Image contrast and spectral transmission in intraocular lenses with Nd:YAG pits. *Curr Eye Res*. 2023;48(10):911–8. <https://doi.org/10.1080/02713683.2023.2229540>.
 21. Ravi-Kumar S, Lies B, Zhang X, Lyu H, Qin H. Laser ablation of polymers: a review. *Polym Int*. 2019;68(8):1391–401. <https://doi.org/10.1002/pi.5834>.
 22. Torrisi L, Borrielli A, Margarone D. Study on the ablation threshold induced by pulsed lasers at different wavelengths. *Nucl Instrum Methods Phys Res, Sect B*. 2007;255(2):373–9. <https://doi.org/10.1016/j.nimb.2006.12.144>.
 23. Augustyn P, Rytlewski P, Moraczewski K, Skibicki A, Mazurkiewicz A. Ablation of selected thermoplastic polymers using an Nd: YAG laser. *J Mater Sci*. 2023;58(21):9073–86. <https://doi.org/10.1007/s10853-023-08566-5>.
 24. Zelenska KS, Zelensky SE, Poperenko LV, Kanev K, Mizeikis V, Gnatyuk VA. Thermal mechanisms of laser marking in transparent polymers with light-absorbing microparticles. *Opt Laser Technol*. 2016;1(76):96–100. <https://doi.org/10.1016/j.optla.2015.07.011>.
 25. Grabner G, Ang RE, Vilupuru S. The small-aperture IC-8 intraocular lens: a new concept for added depth of focus in cataract patients. *Am J Ophthalmol*. 2015;160(6):1176–1184.e1. <https://doi.org/10.1016/j.ajo.2015.08.017>.
 26. Franco F, Branchetti M, Vicchio L, Serino F, Piergentili M, Spagnuolo V, Santoro F, Virgili G, Giansanti F. Implantation of a small aperture intraocular lens in eyes with irregular corneas and higher order aberrations. *J Ophthalmic Vis Res*. 2022;17(3):317–23. <https://doi.org/10.18502/jovr.v17i3.11568>.

27. Shajari M, Mackert MJ, Langer J, Kreutzer T, Wolf A, Kohnen T, Priglinger S, Mayer WJ. Safety and efficacy of a small-aperture capsular bag-fixated intraocular lens in eyes with severe corneal irregularities. *J Cataract Refract Surg*. 2020;46(2):188–92. <https://doi.org/10.1097/j.jcrs.0000000000000045>.
28. Son HS, Khoramnia R, Mayer C, Labuz G, Yildirim TM, Auffarth GU. A pinhole implant to correct postoperative residual refractive error in an RK cataract patient. *Am J Ophthalmol Case Rep*. 2020;20: 100890. <https://doi.org/10.1016/j.ajoc.2020.100890>.
29. Barnett V, Barsam A, Than J, Srinivasan S. Small-aperture intraocular lens combined with secondary piggyback intraocular lens during cataract surgery after previous radial keratotomy. *J Cataract Refract Surg*. 2018;44(8):1042–5. <https://doi.org/10.1016/j.jcrs.2018.06.005>.
30. Son HS, Yildirim T, Khoramnia R, Labuz G, Mayer C, Auffarth GU. Implantation of a small-aperture intraocular lens and a partial aniridia implant in eyes with traumatic iris defects. *Am J Ophthalmol Case Rep*. 2020;18: 100673. <https://doi.org/10.1016/j.ajoc.2020.100673>.
31. Eppig T, Spira C, Seitz B, Szentmáry N, Langenbacher A. A comparison of small aperture implants providing increased depth of focus in pseudophakic eyes. *Z Med Phys*. 2016;26(2):159–67. <https://doi.org/10.1016/j.zemedi.2016.03.003>.
32. Dick HB. Small-aperture strategies for the correction of presbyopia. *Curr Opin Ophthalmol*. 2019;30(4):236–42. <https://doi.org/10.1097/ICU.0000000000000576>.
33. Rodriguez-Lopez V, Dorronsoro C. Case report of the evidence of a spontaneous reverse Pulfrich effect in monovision after cataract surgery. *BMC Ophthalmol*. 2023;23(1):289. <https://doi.org/10.1186/s12886-023-03041-w>.
34. https://www.accessdata.fda.gov/cdrh_docs/pdf21/P210005B.pdf