



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

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ABSTRACT

Introduction: Posterior capsule opacification (PCO) is the most frequent late sequelae after successful cataract surgery. Neodymium:yttrium aluminum garnet (Nd:YAG) laser capsulotomy is considered the gold standard and a well-accepted, safe, and effective measure in treating PCO. However, iatrogenic damage of the intraocular lens (IOL) due to inappropriate focusing is a quite common side effect. These permanent defects (YAG pits) can critically affect overall optical quality.

Methods: In this laboratory study, we used the micro-computed tomography (μ CT) technique

to obtain high-resolution 3D images of the lens and the YAG pits.

Results: To the best of our knowledge, this is the first description of a detailed analysis of IOLs with μ CT technology. This non-destructive technique seems to be ideal for comparative studies, measuring dimensions of the damage, and visualizing shooting channels within the material.

Conclusion: μ CT is excellently suited to examine an IOL in detail, analyze optics and haptics in three dimensions, and to describe all kinds of changes within the IOL without damaging it.

Keywords: Micro-computed tomography (μ CT); YAG pits; Damage in intraocular lenses; Laboratory study to evaluate IOL quality; New technique

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Key Summary Points

To the best of our knowledge, this is the first laboratory study using micro-computed tomography (μ CT) technique to analyze intraocular lenses and describe YAG pits.

The μ CT technique and 3D reconstruction seems to be excellent for getting detailed information (dimensions and size ratios such as diameter and thickness) about all kinds of changes within the lens without damaging the material.

This laboratory study proved the feasibility of the technique and the effect of YAG pits (angle of penetration, defect size, penetration, course, and trajectory within the lens) was demonstrated impressively.

INTRODUCTION

Cataract is a leading cause of blindness and vision impairment globally and cataract surgery ranks as one of the most commonly done surgical procedures around the world: 34 million cataract procedures were performed worldwide in 2021 [1, 2]. There is no doubt that cataract surgery can be a highly efficacious intervention that restores vision. The technical equipment is state of the art and excellent outcomes and good postoperative vision are generally achieved in these settings nowadays [3, 4].

Nevertheless, as with any other surgery, there is still a possibility of complications and negative effects. Among them, especially important is the emergence of posterior capsule opacification (PCO) or secondary cataract. PCO remains the most common long-term postoperative complication of modern cataract surgery [5]. PCO can reduce visual acuity, decrease contrast sensitivity, and increase retinal stray light. Therefore, this condition must be treated. Neodymium:yttrium aluminum garnet

(Nd:YAG) laser capsulotomy is a well-accepted, safe, and effective measure in the treatment of PCO [6]. According to a real-world evidence study with more than 20,000 eyes, the incidence of PCO ranges between 4.7% and 18.6% at 3 years and 7.1–22.6% at 5 years, and the incidence of Nd:YAG capsulotomy ranges between 2.4% and 12.6% at 3 years and 5.8–19.3% at 5 years post cataract surgery [7]. The inconsistent data and large difference in the results regarding “PCO incidence” can be explained by the different study designs and different lens models used in the long-term studies. It is sufficiently described in the literature that there are differences in PCO development and expression depending on the intraocular lens (IOL) material and design. The interaction of various factors such as a sharp posterior optic edge and a smooth optic surface plays a key role in PCO development and can slow down and favorably influence the development of posterior capsule fibrosis [8, 9].

Another retrospective study of more than 3000 cases analyzed PCO formation and YAG capsulotomy rates in a 4-year follow-up of acrylic lenses. PCO that required capsulotomies occurred in patients who had received a hydrophobic acrylic IOL in 31.57% compared to the group with hydrophilic acrylic IOL implants (56.6%) [10].

Considering the high prevalence of cataract and the relatively high incidence of posterior capsule opacification, the economic burden associated with adverse effects of cataract extraction and PCO formation is of great relevance.

YAG capsulotomy is considered the gold standard for the treatment and elimination of posterior capsule fibrosis. This technique is described as a very safe and effective treatment to improve visual acuity. However, there are also reports on complications such as corneal injuries, pupil blockage, iritis, intraocular pressure rises, vitreous prolapse, retinal detachment, cystoid macular edema, IOL movement, and IOL dislocation or impairment [11–13]. An efficient technique with the lowest risk is not only determined by an adapted defocusing to prevent lens pit marks and a minimum possible individual pulse energy setting but also

characterized by the lowest possible total energy consumption if the necessary opening size is achieved by the smallest number of pulses [14].

IOL damage (lens pits) seem to be a relatively common side effect. In the past, studies investigating the incidence of laser defects in IOLs came up with a relatively high number of cases. Whereas one study found 11.7% of severe YAG damage, another group found up to 19.8% of YAG-associated damage in IOLs after capsulotomy [15]. The different rates of occurrence could be due to different lens models and optical properties, thus the insight during YAG capsulotomy is different [16]. In addition, various IOL models show different behavior in the capsule. There are differences of dimensions of contact to the posterior capsule due to the individual geometry or angulation of the haptic [17]. In addition, there are some lenses that make it difficult to see details of the posterior capsule, such as yellow lenses (blue blockers) or premium lenses with multifocal optical elements like diffractive ring segments. These IOLs can cause glare to the user during the procedure, but can also increase patients' sensitivity to light, leading to discomfort during the procedure—both resulting in a defocus of the laser beam and accidentally hitting the IOL.

Acrylic IOLs with different water content, hydrophilic and hydrophobic, seem to be affected differently by Nd:YAG treatment in terms of wavefront aberrations. The iatrogenic damage to IOLs during YAG laser capsulotomy is caused by acoustic shock waves and heat conduction [10]. These defects in the material of the IOL are called YAG pits or YAG shots.

The purpose of this experimental study was to verify if the micro-computed tomography technique is suitable to analyze and visualize laser-induced defects in hydrophilic and hydrophobic acrylic IOLs in order to obtain qualitative information on the characteristics and also analyze differences regarding IOL material and water content without damaging the lens. To the best of our knowledge, this is the first scientific report on this subject.

METHODS

Micro-computed tomography (μ CT) is increasingly used to study the internal structure of materials. The method uses X-rays to make radiographs of the sample at many different angles by rotating the sample. The contrast in the radiographs usually comes from the different absorption of the X-rays in different materials. Reconstruction software uses all the projections to compute the 3D structure of the sample. Thus the most important question is the resolution of the 3D structure. The resolution can be calculated using Eq. 1:

$$R = \frac{d}{M} + s \left(1 - \frac{1}{M} \right) \quad (1)$$

with R being the resolution, d the detector size and pixels, and M the geometrical magnification. M is calculated using Eq. 2:

$$M = \frac{SDD}{SOD} \quad (2)$$

with SDD being the source detector distance and SOD the source to object distance.

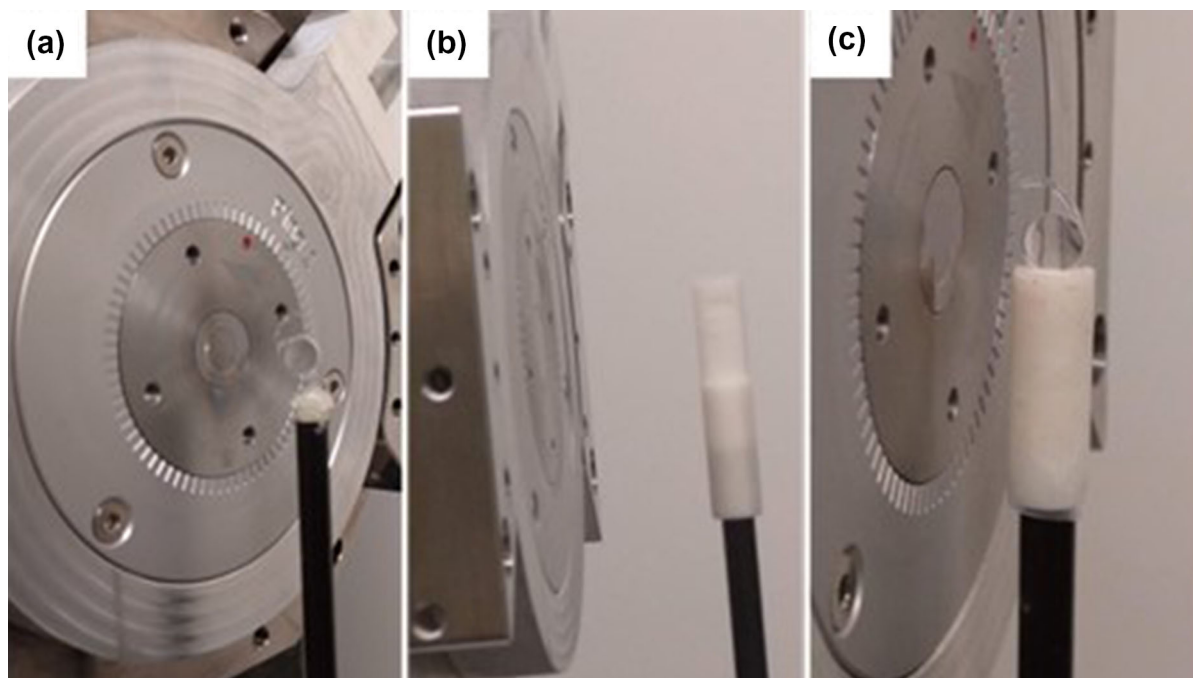
From these relations it is clear that for the best resolution one needs to move the object as close as possible to the source. This also means that small samples can be measured at better resolution than large samples. The best achievable resolution in many cases is in the single-digit micrometer range or in the high nanometer range. If one wants to see the whole sample the sample size dictates the reachable resolution.

The μ CT method usually does not damage the sample. However, with increasing X-ray energy and increasing measurement time it might lead to radiation damage in some samples. The method can be used as long as the X-ray absorption is not too low (no contrast in the radiographs) or too high (no X-rays reach the detector).

In μ CT one usually uses the X-ray absorption of the sample to get contrast in the individual radiographs. However, this means that it is more difficult to measure light elements as opposed to heavy elements. Therefore, it is sometimes helpful that there is a second effect

Table 1 μ CT parameters for different IOL lenses measured

Voltage (kV)	Power (W)	Voxel size (μm)	Exposure (ms)	Average	Projections	Scan time (h:min)
50	7	1.6	1100	2	2286	1:47
55	7	3.5	1350	3	2286	3:26
50	6	1.7	1250	4	2286	4:00

**Fig. 1** IOL lenses mounted in front of the X-ray source **a** directly glued on a carbon holder, **b** in a 3D printed cylinder, **c** inserted in polymeric foam

that changes the contrast. This is the so-called phase contrast. Phase contrast is often observed at surfaces and interfaces. In an absorption-based experiment phase contrast is considered an artifact. In samples where there is no or very little absorption contrast the phase contrast is the only source of contrast in the μ CT image.

This is the first description of a detailed analysis of IOLs with μ CT technology. The measuring parameters used in this study are given in Table 1.

From the discussions above it is clear that the way the sample is mounted in the μ CT has a strong impact on the quality of the measurement. Therefore, we tested several methods to

hold the sample. The sample holders are shown in Fig. 1a–c.

At first the lens was directly glued to the carbon sample holder (Fig. 1a) and positioned as close as possible to the X-ray source in order to gain a high resolution. In order to also see defects at the edge of the lens, the sample was positioned such that it was entirely inside the X-ray beam. In this first experiment the X-ray absorption of the lens was very low. This could make the later segmentation of the lenses very difficult. Actually, most of the contrast that we found under optimized parameters stems from phase contrast at the interfaces. Gluing the sample to the carbon rod has the disadvantage

that the sample is destroyed when it is taken off the carbon holder.

Second, we put the sample in an X-ray-transparent cylinder (Fig. 1b). This also had the advantage that hydrophilic lenses could be measured immersed in water. However, the lenses moved inside the tube during the measurements leading to too many artifacts. In addition, when we did the measurements in water, we lost all the contrast of the surfaces as the phase contrast was reduced by the water.

Third, we fixed the sample in a polymeric foam that is transparent in the X-ray range (Fig. 1c). This was the best method to mount the lens. There was no movement of the sample, the sample could be removed without damage, and the phase contrast was not reduced. With optimized measurement parameters (Table 1) this gave the sharpest images of the lenses.

Reconstruction was done using the reconstruction software provided by TESCAN. The analysis and rendering were done using the software Dragon Fly (ORS, Object Research Systems Montréal Canada, Member of the Comet Group) with an academic license.

We included hydrophobic and hydrophilic acrylic monofocal IOLs as well as multifocal IOLs in our laboratory study. All lenses were intentionally defected using a photodisruption laser (Visulas YAG III, Zeiss, Meditec) using the same energy level of 2.2 mJ in all cases. The disruption laser uses a wavelength of 1064 nm, a Super Gaussian mode, a pulse length of 2–3 ns, and a focus diameter of 10 μm . In our laboratory study the focal point of the target beam was aimed directly at the IOLs to create defects (YAG pits) intentionally.

The laboratory study was exempt from ethics committee approval as it was an *in vitro* study without humans involved.

RESULTS

The first task in this study was to check the suitability of the μCT method to detect damage of the lenses after intentional defect formation with the YAG laser. We put a lot of effort into finding the optimal μCT parameters (Table 1) in order to overcome the challenges posed by the

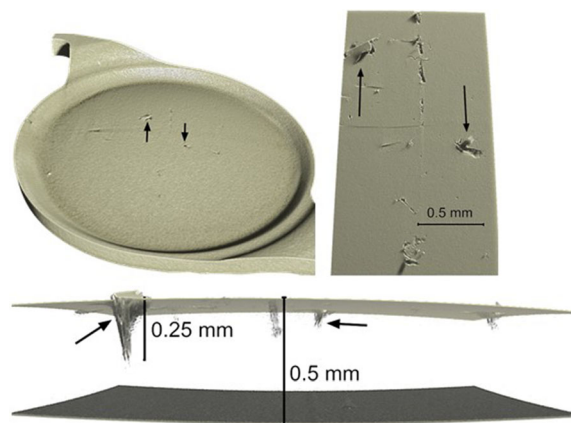


Fig. 2 Reconstruction of a monofocal IOL. Top left: full size of the lens (the arrows highlight large pits), Top right: zoom in on the surface (the arrows mark the same two pits). Note: parts of the material are torn out. Bottom: cross section through the lens (the arrows mark the same two pits. Note: different penetration depth and shot channel within the lens.

very low X-ray absorption of the acrylic lenses, which leads to very low contrast in the μCT image making potential segmentation of the data difficult. In this study the raw data was only rendered to make the YAG laser damage visible. The second problem was movement of the sample during the scans. This was only the case in the plastic cylinder sample holder. This leads to blurry images having a negative effect on the visibility of the YAG laser damage. The third common problem in μCT data is artifacts from the scans. These can usually be handled in the reconstruction stage and did not have a profound effect in this study.

We could show in this laboratory study that the μCT is excellently suited to examine an IOL in detail, to visualize it with optics and haptics in three dimensions, and in our case to analyze and describe defects within the IOL. Another advantage of μCT is that the lens material is not damaged because there is no emergence of heat.

Figure 2 top left shows an overview scan of a whole monofocal lens. Size ratios and dimensions of the IOL such as diameter and thickness can be determined excellently. The 3D reconstruction is excellent for getting an overview and numbering of defects for further detailed examination.

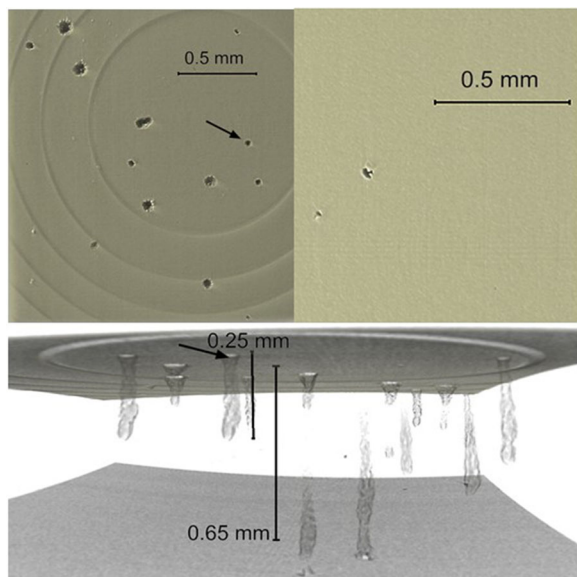


Fig. 3 Reconstruction of a multifocal, diffractive IOL with ring segments. Top left: front side surface (the arrow highlights one smaller pit), Top right: back side surface, Bottom: cross section through the lens (the arrows marks the same pit at front side surface). Note: using this technique, one can evaluate whether the YAG pit starts directly at the anterior surface or inside the lens and follow the shot channel and measure the dimensions. It can happen that the smaller, superficial defect is only slightly pronounced, but shows a clear and enormous penetration depth

The arrows in the figure show the positions of lens pits found on the sample using μ CT. In all three views the same pits are marked by the arrows. When comparing the three images of IOL01 it is clearly visible that the damage is not confined to the surface. In contrast the penetration of the pits into the material of the lens is considerably large (Fig. 2 bottom) with up to 0.25 mm at a lens thickness of about 0.5 mm.

In Fig. 3 a multifocal lens is shown with pits marked by arrows. Here one can clearly see that the pits penetrate the lens significantly (Fig. 3 bottom) and the shooting channel is clearly visible. The maximum length of the shooting channels is up to 0.5 mm at a lens thickness of about 0.65 mm (Fig. 3 bottom). In addition, pits are also seen on the back side of the lens (Fig. 3 top right).

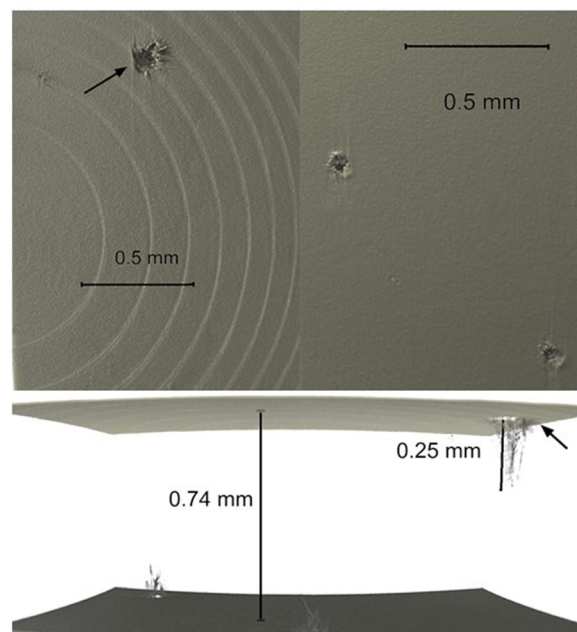


Fig. 4 Reconstruction of another multifocal IOL. Top left: front side surface (the arrow highlights a large pit with clear defect/crater on the surface). Top right: back side surface, Bottom: cross section through the lens (the arrow marks the same pit of front side surface)

In Fig. 4 another multifocal, diffractive lens with ring segments is shown. In this case the thickness is about 0.74 mm (Fig. 4 bottom). One can again clearly see the pits from the YAG laser damage on both sides of the lens (Fig. 4 top left and top right). In this case the penetration depth of the pits was about 0.24 mm (Fig. 4 bottom).

Considering that only a relatively low energy of 2.2 mJ was chosen for all experiments, the total penetration depth (more than half of the total lens thickness) is very impressive.

Another very useful feature of the μ CT technology is to make the lens transparent to examine the angle of penetration and the course and trajectory of defects within the IOL material.

When one makes the lens more transparent even defects can be seen that have a relatively small impact on the surface but lead to more pronounced defects within the lens material (see Figs. 2, 3, 4, 5).

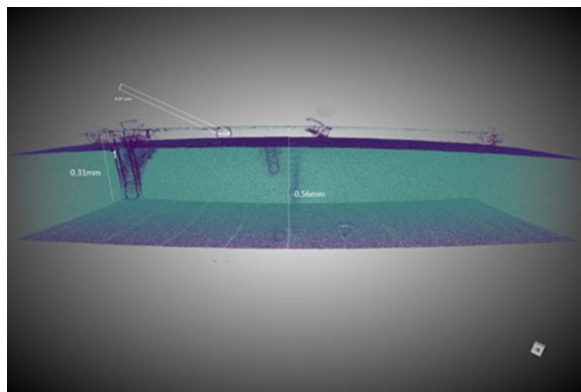


Fig. 5 Reconstruction and representation of the shot channel. The angle of entry can be measured, the volume can be calculated and displayed relative to the total thickness of the lens. Note: There are also changes on the surface of the lens directly next to the entry of the YAG pit. It appears as if parts of the material are blown out of the lens

DISCUSSION

A previous study conducted by the authors confirmed that there are differences in the defects depending on the material and water content in acrylic IOLs (hydrophilic vs hydrophobic) [18]. In that laboratory study microscopy and environmental scanning electron microscopic images were used to visually analyze the defects. Additionally, wavefront measurements were taken for power mapping and Raman spectroscopy was performed. Raman spectroscopy is a vibrational spectroscopy. This means that it analyzes a sample chemically, by using light to create molecular vibration, and interpreting this interaction afterwards. It is based on the inelastic scattering of light that occurs when matter is irradiated by light. Vertical and horizontal dimensions of the defects were analyzed and compared, and Raman line scans assessed the changes in the chemical structure in the defect area of the IOL. Results showed that Nd:YAG seems to have greater impact on hydrophobic IOL materials as that damage was greater and more frayed than that in hydrophilic materials. Moreover, it was shown that there is a larger and more distinctive damage area in IOLs (with chemical changes in the material) than is visually recognizable. The

effect of these defects in IOLs and the impact on visual acuity or negative impact on overall quality of vision including halo, glare, effects under mesopic conditions, and influence in daily life is still controversial. Many factors play a role, including the lens model and design, the material of the IOL, the number of defects, and the position of the defects within the optic. However, it seems obvious that defects cannot be an improvement in overall quality and must have some effects of varying degrees. Experimental studies evaluated the effects of damage on IOLs regarding different materials and concluded that defects are more severe in rigid materials and less pronounced in soft materials and that shape and form vary greatly depending on the material [16, 18].

Other direct effects of YAG laser capsulotomy on IOL position have also been studied. It has been shown that decentration and tilt can occur and a hyperopic axial displacement (shift) was observed in some cases [19].

In the present laboratory study the effects of YAG pits on the lens were again impressively demonstrated and it was shown that the μ CT technology is a useful tool for getting detailed images of the lens and 3D impressions to analyze, measure, and compare lenses and defects, both on the surface and the interior of the material without destroying the lens.

The World Report on Vision placed a strong emphasis on the need for integrated people-centered eye care [20] and subsequent work by the World Health Organization (WHO) and the Lancet Global Health Commission on Global Eye Health provided a platform for a framework regarding quality of cataract services [21, 22]. To improve patients' experience and quality of cataract services in future, we also need to better understand what "quality cataract services" means to patients.

Efficiency was the most assessed quality element among included studies. A broad range of interventions have been assessed, and with almost three-quarters of authors reporting a desired effect in relation to quality, there appear to be many promising strategies to improve the quality of cataract services and ultimately reduce vision loss from cataract. In the past, however, the main research and clinical focus

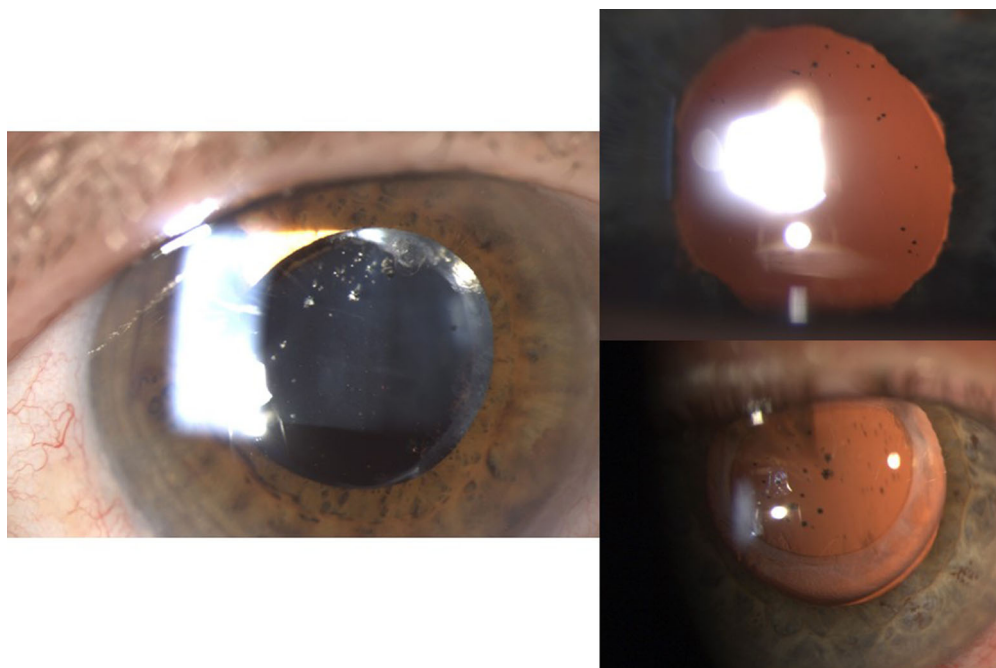


Fig. 6 Impressive slit lamp images showing clinical cases of IOLs with multiple lens pits after capsulotomy. In these cases, patients still achieved good uncorrected visual acuity

but experienced dysphotopsia (glare, halo, starburst) when driving at night. One can imagine that the number, location, and extent of the defects play a decisive role

was on the procedure itself or the implants used. Therefore, it seems very important not only to establish the optimal technique of lens removal in cataract surgery but also to try to achieve sustained, long-lasting good results. Although enormous progress has been made in recent years owing to advances in preoperative diagnostics, in the technique of the surgery procedure itself, and also in the choice of available implants, the postoperative course should not be undervalued. PCO is still a very common condition and therefore YAG capsulotomy as a very effective treatment has to be performed to enhance quality of life in these cases. During this supposedly easy procedure, the overall quality can be negatively affected by the iatrogenic emergence of YAG pits and therefore also negatively affect quality of life. An example can be seen in Fig. 6 where patients developed dysphotopsia and problems at night although visual acuity remained stable.

The problem should be taken seriously, even if only a certain proportion of those affected show clinical symptoms. Case reports indicate

that patients with clinical symptoms caused by YAG pits are distressed and dissatisfied over a long period of time, and therefore increasingly visit other physicians for a second opinion.

In addition to the positive direct impact on the individual, avoidance of YAG pits would reduce overall costs for the insurance system, reduce the number of additional ophthalmological examinations, and thus also be more efficient and contribute to the very important issue of reducing greenhouse gases. Furthermore, it seems to be important to analyze the defects with a scientific technique in order to develop methods for the future to reduce the possibility of creating these defects, such as safety features in the laser systems to avoid defocusing on the IOL.

CONCLUSION

The μ CT technique seems to be excellent to analyze the iatrogenic defects and to find out differences in materials and water content.

Capturing high-resolution images without damaging or altering the material is possible. Other advantages are additional options such as measuring dimensions and determinations of angles of entry and extent of penetration in the material.

The first laboratory results provide objective evidence that YAG pits lead to a defect on the lens surface but also inside the lens. These defects depend on the laser energy used and vary in severity depending on the material properties of the lens. Depending on the angle of entry, the shot channels are quite deep and can penetrate more than half of the entire lens even at standard energy levels. Therefore, it can be understood that the extent of the negative influence on the overall performance of the lens depends on the size of the defects, the number of defects in the lens, and the position of the defects within the optics.

More studies have to be done and clinical cases and their effects should be compared with results found in laboratory studies.

The μ CT technique is excellent for detecting and analyzing the defects as well as measuring them. In addition, it is imaginable that scratches, glistening, or calcifications could be visualized by μ CT.

An incorrectly performed capsulotomy can produce permanent and irreversible damage, impressively shown in clinical cases (Fig. 5). Depending on the position, the energy used and the size of the defect, the number of defects, and the optical design of the IOL, this can lead to severe negative effects. The authors are working in parallel to establish the correlation between purely objective defects (laboratory studies) and clinical effects (case series and optical property measurements).

Feasibility and Proof of the Methodology

It was shown that the new μ CT technology is an effective tool for high-resolution 3D imaging of IOLs. Defects and damage within the IOL can be easily detected without the risk of damaging the lens by temperature, as can be seen with scanning electron microscopy, or mechanically by repeated touching with instruments.

Depending on the evaluation mode, a variety of recording and imaging options exist: overview images for 3D reconstruction, cut along the z-direction showing, e.g., the shooting channel of a defect within the material, zooming into the lens and cut at the position of the lens pit to evaluate the penetration depth, transparent modes to show the exact course of the laser shot (shooting channel), analyzing length and width. Highlighted traces of lens pits in high magnification for better comparison and detailed analysis of the measurements are possible.

LIMITATIONS OF THE STUDY

We would like to point out that this is an initial description of a new technique to detect and evaluate YAG pits in IOLs. The background of the laboratory study was to prove the feasibility of the methodology and confirm that the samples are not damaged by the μ CT technique. Follow-up studies to perform exact analysis of YAG pits due to different lens material properties (water content, refractive index) and evaluating the impact of different energy levels are in progress. It is planned to compare hydrophilic and hydrophobic materials regarding the extent of laser shots.

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Compliance with Ethics Guidelines. The laboratory study is exempt from ethics committee approval as it is an in vitro study without humans involved.

Data Availability. The data used to support the findings of this study are available from the corresponding author upon request.

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