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Fast and Mobile Cataract Detection by Applying Line Laser Eye Illumination

Nicole Fehler[1], Robin Haag[1], Andre Messias[2], and Martin Hessling[1]

[1] Institute of Medical Engineering and Mechatronics, Ulm University of Applied Sciences, Albert-Einstein-Allee 55, D-89081 Ulm, GERMANY
[2] Department of Ophthalmology, Otorhinolaryngology, and Head and Neck Surgery – Ribeirão Preto Medical School, University of São Paulo–Brazil, Campus Universitario, S/N, Ribeirão Preto - SP, 14048-900, BRAZIL
Corresponding author: Martin Hessling (email: martin.hessling@thu.de)

ABSTRACT Cataract is observed when the eye lens becomes opaque. This condition causes blurred vision and is the main cause of blindness worldwide. Cataract diagnosis is usually performed during ophthalmologist examination using a slit lamp, which requires expertise, is expensive and bulky. In this study, we present a small handheld illumination setup for cataract detection. Ex-vivo porcine eyes are investigated to determine whether colored line lasers, 450 nm (blue), 520 nm (green) and 650 nm (red), which shine obliquely into the eye, are principally suited for detection of the Y shaped suture cataract and of cold cataract, respecting exposure limits of EU guideline 2006/25/EC. Camera images of the cataract exhibited good results under illumination with all line lasers. Observations with the physician’s eye led to an even better diagnosis of cataract. Generally, green laser light illumination was the best choice for cataract detection. With red laser light illumination, it was also possible, but least suitable for this purpose. With this method, line lasers are a good choice for cataract identification, as cataract can be detected quickly and without much effort. This type of line laser illumination of the eye is safe and both types of cataracts are detectable with all wavelengths. For the human eye, a further development of this system is conceivable.

INDEX TERMS Cataract Diagnosis, Blindness, Porcine Eyes, Line Laser

I. INTRODUCTION

Cataract is the collective term for various lens opacities and the main cause of blindness worldwide [1–4]. 15 million people are newly affected annually [4]. The causes are multifactorial, with age being one of the most important factors [5–7]. Cataract diagnosis is usually performed using a slit lamp, which illuminates the eye with dilated pupil from the side while the ophthalmologist mostly examines it vertically. Technically, the slit lamp usually consists of a bright halogen lamp with some optical elements that generate one or more visible lines on and in the eye if the lamp is focused correctly and a small slit aperture is selected. The setup can be supplemented with a Scheimpflug camera to record opaque areas within the lens [8–14]. There are other techniques for cataract detection, e.g. using the clearness degree of retinal, retroilluminated images [15, 16], ultrasound approaches [17, 18] or optical coherence tomography [19–21] but the slit lamp is the most important instrument.

Cataracts can be distinguished by their location within the lens. Three of the most common cataract types are nuclear, cortical and posterior subcapsular cataract, whose names already describe their position in the lens. In addition, cataracts differ in size and degree of opacity [10, 14, 22]. The above-mentioned slit lamp allows a precise diagnosis of the cataract and the Scheimpflug camera its documentation, but such a system is expensive, unwieldy and not mobile and therefore not very suitable for field studies or examinations in remote areas.

For the latter, a small, preferably handheld illumination system with low power consumption and without the need for a power supply would be more suitable. Therefore, the present study will use porcine eyes to investigate whether colored line lasers used to shine obliquely into the eye would in principle be suitable for safe cataract detection and which wavelength provides the best results. The expected differences between different colors result from the wavelength dependence of absorption and scattering. Both effects increase to shorter wavelengths, so that in the blue spectral range the strongest scattering and thus the best detection could be expected. But at these shorter wavelengths, absorption also increases and the sensitivity of the human eye decreases. The results will be compared to

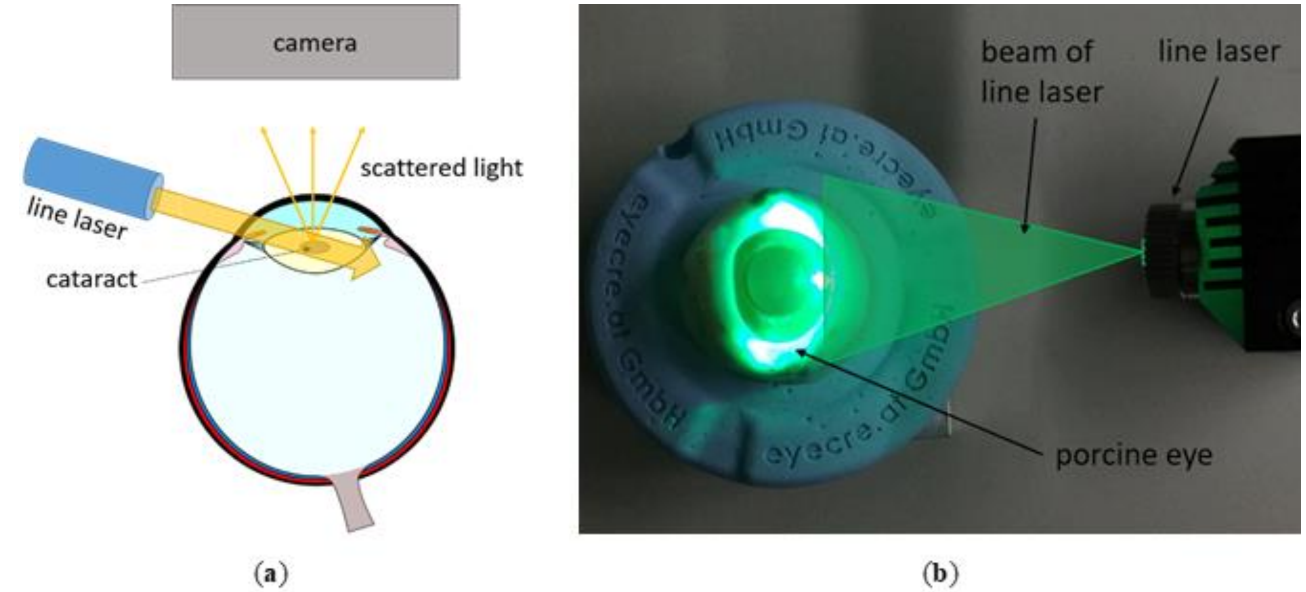


FIGURE 1. (a) Cross section of the illumination approach with a line laser. The irradiated cataract leads to visible stray light originating from the lens with a dilated pupil. (Modified according to [30]) (b) Schematic representation of the front view of the illumination of an eye with a green line laser.

observing cataract with ceiling light from above the eye or with white LED illumination.

In addition, it must be taken into account that the allowed exposure to the eye is also varying for different wavelengths and since a laser is to be applied to shine directly into the eye, special attention must be paid to eye safety. Here, it is positive that a so called "line laser" is employed. This does not mean that the laser beam is a line, but that the laser creates a line on an object, because the laser beam has the shape of a flat diverging triangle. This also means that there is no danger of the lens focusing the laser on a single point on the retina.

The experiments are performed on porcine eyes. They do not exhibit the typical nuclear, cortical and posterior subcapsular cataracts expected in human eyes, instead the Y shaped suture cataracts often observed in young pigs are examined, which are usually found directly in front or behind the nucleus [23, 24]. Also cold cataracts that are generated in the nucleus [25–27] and represent nuclear cataracts are investigated.

II. METHOD

Ex-vivo porcine eyes of typically 6 months old pigs, were obtained from a local butcher (Ulmer Fleisch in Ulm, Germany). From a previous study [28], we already knew that these eyes usually had a Y shaped suture cataract. To generate cold cataract, eyes were stored in a freezer at -20 °C overnight in BSS (Balanced Salt Solution). Similar cold cataract generation was reported by Sivak et al. [26] and Zhang et al. [25].

A LASER SAFETY

Three lasers with 35° beam angles from Medilas (Balingen, Germany) were tested. These emit light with wavelengths of 450 nm (blue), 520 nm (green) and 650 nm (red). According to EU (European) guideline 2006/25/EC [29] exposure limits for the irradiance $E_{photochem.}$ are given. These limits are valid for an area or aperture of 7 mm diameter, which represents the maximum diameter of the pupil as only light passing the pupil could be harmful for the retina. Photochemical hazard is possible between 400 and 600 nm. Exposure limits for the irradiance $E_{photochem.}$ for potential photochemical hazard can be calculated with equations (1), (2) and (3), for exposure durations above 10 s, according to [29].

$$E_{photochem.}(400 - 450\text{ nm}) = 1 \cdot C_B \left[\frac{\text{W}}{\text{m}^2}\right] \quad (1)$$

$$C_B = 1, \text{ for } \lambda \text{ between 400 and 450 nm} \quad (2)$$

$$C_B = 10^{0.02\cdot(\lambda - 450\text{ nm})}, \text{ for } \lambda \text{ between 450 and 700 nm} \quad (3)$$

Potential thermal hazard is possible between 400 and 700 nm and the limit for this hazard was calculated according to equation (4) and (5) for λ between 400 and 700 nm, where α_{min} = 1.5 mrad, $\alpha_{\max}$ = 100 mrad and T_2 = 100 s according to [29] and α = 610 mrad = 35° according to the data sheet of the line lasers.

$$E_{therm.} = 18 \cdot C_E \cdot T_2{}^{-0.25} \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] \quad (4)$$

$$C_E = \frac{\alpha^2}{\alpha_{min} \cdot \alpha_{max}} \quad (5)$$

The irradiances of the lasers were determined at 10 cm distance to an integrating sphere MSP REFLTRANS1 (Mountain Photonics GmbH, Landsberg am Lech, Germany) and a spectrometer AvaSpec-HSC 1024x58TEC-EVO (Avantes, Apeldoorn, The Netherlands) with an aperture of 7 mm, analogue to [29]. These irradiances should not exceed the values calculated with equations (1-5). Therefore, the current levels of the lasers were adjusted.

B CATARACT DETECTION

Images of cataract were taken one day after enucleation. The ex-vivo porcine eyes were illuminated from the side of the lens/cornea through the pupil at 10 mm distance between laser and eye, as illustrated in FIGURE 1. The distance in FIGURE 1 (b) was reduced for better illustration of the set-up as schematic representation. Light was scattered by the cataract and was detected in front of the pupil. For this, a camera from the mobile phone Poco X3 Pro (Xiaomi, China) was placed around 15 cm in front of the eyes´ pupil capturing pictures of the lens. To compare these wavelengths with white light illumination, images were also taken with white ceiling light from above the eye and with white LED light from a mobile phone from the side of the eye, analogue to FIGURE 1 (b).

III. RESULT

A. LASER SAFETY

The calculated allowed irradiances for the line lasers according to equation (1)-(3) for the photochemical hazard and according to equation (4) and (5) for the thermal hazard are given in table 1. In order to remain below these limits, the lasers were operated at different current levels. The 450 nm line laser was operated at 55 mA and the 520 nm line laser was operated at 200 mA to remain below the limits given in TABLE 1. With these currents the photochemical and thermal limit values from Table 1 calculated from [29] were not exceeded. The 650 nm line laser was operated at 70 mA, which did not create thermal hazard.

B CATARACT DETECTION

Photographs of porcine eyes with cataract illuminated with line lasers of different wavelengths are presented in FIGURES 2 and FIGURE 3. The images displayed here are examples of many shots that were taken. FIGURE 2 presents eyes with Y shaped suture cataract (“star cataract”) detected with blue line laser illumination (a), with green laser illumination (b) and with red illumination (c). During image acquisition it was observed that all wavelengths display cataract. Images with the smart phone camera presents best illustration of cataract with blue and red illumination. With red illumination the images are grainier. However, when looking at the lenses with the eye instead of using a cell phone camera, the cataract is most clearly visible through the green illumination, followed by blue and red illumination. In general, cataract is better seen with the human eye than with the camera.

FIGURE 3 presents eyes with cold cataract detected with blue line laser illumination (a), with green laser illumination (b) and with red illumination (c). Cold cataract is best observed with green laser light, followed by red laser illumination and blue line laser illumination. Observations with the eye of the observer (without the mobile phone camera) also exhibits the best results for green illumination and the worst results for blue illumination. Compared to the Y shaped suture cataract the line laser had to illuminate the eye slightly more from above, because the displayed cold cataract is located further posterior in the lens.

The results of the comparison of colored illumination of cataract with white light illumination is given in FIGURE 4. With ceiling lightning of the eye, no cataract could be observed in FIGURE (a). With ceiling lightning from above and additionally green laser light from the side cataract was made visible, see FIGURE 4 (b). The best detection of cataract was possible with green laser light FIGURE (c). With white LED illumination from the side cataract could be guessed at, but was very indistinct.

TABLE 1

Allowed irradiances according to EU guideline 2006/25/EC [29] for the potential photochemical and thermal hazard for different wavelengths passing an aperture of 7 mm diameter, which is defined by the size of the pupil.

$\mathrm{E_{photochem.}}$ (450 nm)	0.1 $\left[\frac{mW}{cm^2}\right]$
$\mathrm{E_{photochem.}}$ (520 nm)	2.51 $\left[\frac{mW}{cm^2}\right]$
$\mathrm{E_{therm.}}$ (450 nm)	1.41 $\left[\frac{W}{cm^2}\right]$
$\mathrm{E_{therm.}}$ (520 nm)	1.41 $\left[\frac{W}{cm^2}\right]$
$\mathrm{E_{therm.}}$ (650 nm)	1.41 $\left[\frac{W}{cm^2}\right]$

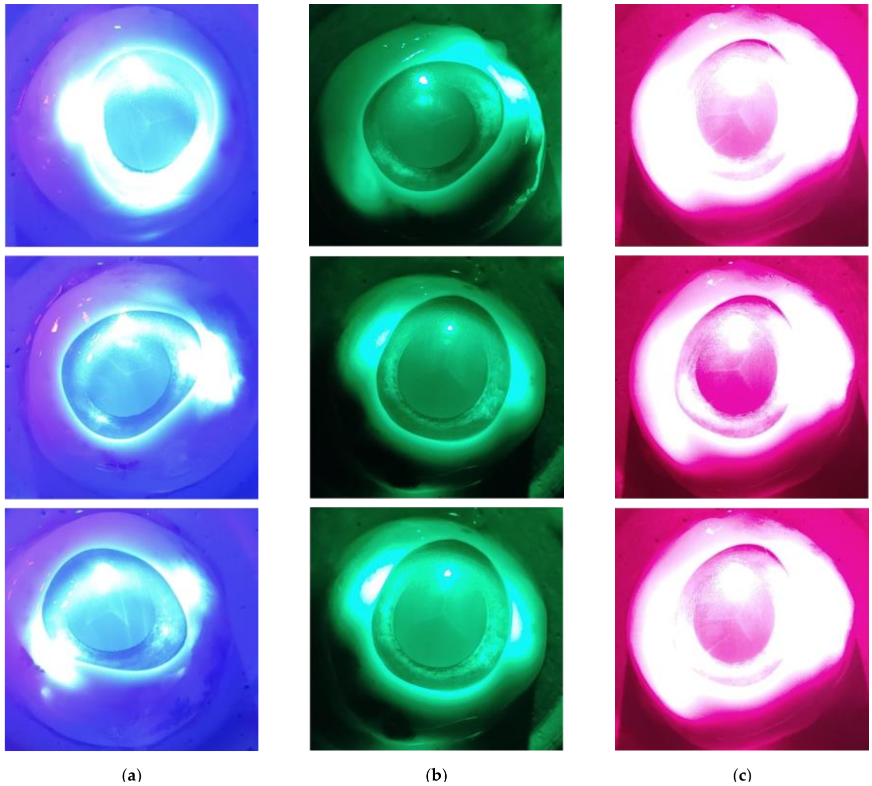


FIGURE 2. Detection of lens with star cataract with blue (a), green (b) and red (c) line laser illumination.

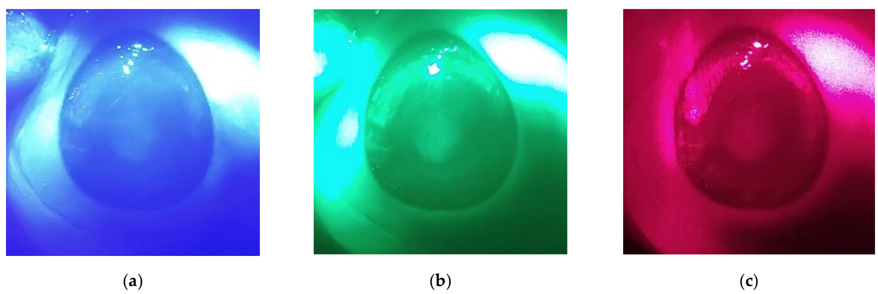
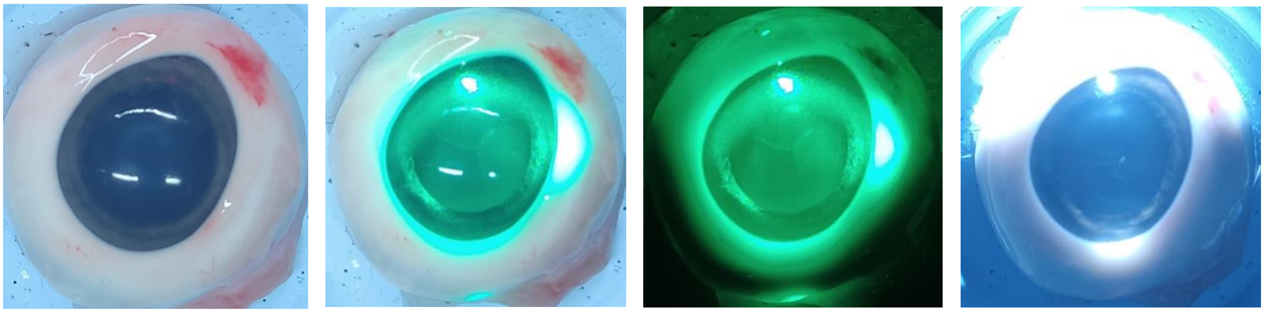


FIGURE 3. Detection of lens with cold cataract with blue (a), green (b) and red (c) line laser illumination.

IV. DISCUSSION

This feasibility study is not the first attempt to develop small, mobile devices for cataract disinfection. As early as 2011, Tkaczyk et al. developed a laser-based system [31]. A red laser shines vertically into the eye and a photodiode is supposed to detect the scattered light generated by the cataract. The technical components employed appear to be relatively sophisticated. The laser is modulated at 5.3 kHz and the photodiode is read out at this frequency. We assume that this was necessary to reduce extraneous light or electronic background. Nevertheless, the signals of the photodiode seem to scatter strongly. We have not found more new information on this approach.

A more recent approach comes from 2021 by Askarian et al. [32]. Here, a smartphone is supposed to take pictures of the eye with an LED flash and image processing performed on the smartphone is then supposed to evaluate the cataract. The idea is certainly very good, but has so far only been carried out on artificial, self-made eye models but no real eyes. The here suggested type of laser illumination of the eye has been tested on real porcine eyes. It is safe and both types of cataracts are detectable and easy to distinguish at all employed wavelengths. Blue and red line laser illumination seems to provide best results for cataract detection. With green laser light the Y shaped suture cataract appears to be a bit less recognizable than with other colored illumination. However, when the cataract is viewed directly by a physician without the camera, cataract detection with the green laser seems to work best followed by detection under blue light. Viewing the cataract without the camera seems to be most difficult with red light. However, these differences in the



(a) (b) (c) (d)

FIGURE 4. Ex-vivo porcine eye with Y shaped sutured cataract with ceiling light from above the eye (a), ceiling light from above the eye and green line laser from the side (b), green line laser from the side (c) and white LED illumination from the side.

quality of cataract detection are minimal. The results of this study reveals that all tested wavelengths can be used for the detection of Y shaped suture cataract and cold cataract.

The exposure limits in EU guideline 2006/25/EC [29] were respected, by choosing a distance of 10 cm between the laser and the pupil and with different currents for the line lasers. The EU guideline 2006/25/EC applies to lasers with spot light illumination. Since line lasers were involved in this study, the risk to the eye from laser radiation is even lower than suspected. Therefore, the distance could be reduced or the current of the lasers could be increased without causing damage to the eye. However, to be on the safe side, the values for a spot light laser were used as a limit. Thus, no damage to the eye is assumed at any time. Unfortunately, the photos in this paper do not reflect the recognizability of the cataracts as perceived by the living eye of the observer, although we have tried out several cameras. Another limitation of this study was, that young porcine eyes were examined under laboratory conditions and this approach could only be tested on Y shaped suture cataracts and cold cataracts, which are located in front or behind or inside the nucleus. However, cataract detection for human patients would usually happen in older eyes with typical human age-related cataracts like nuclear, cortical and posterior subcapsular cataract, which partly differ in structure and location from the examined porcine cataracts.

V. CONLUSION

The aim of this feasibility study was to use porcine eyes in the laboratory to investigate whether line laser illumination of the lens could be suitable for simple and reliable cataract detection and which wavelength or color is most suitable. In fact, cataract detection was possible at all wavelengths investigated, with green appearing to be the most promising. The next goals are to investigate this approach on the human eye, but also to develop a small device that is placed directly on the eye and in which the line lasers are replaced by small, fan-shaped, battery-powered green LEDs to allow application in the field.

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AUTHOR CONTRIBUTIONS

Conceptualization, N.F., R.H., A.M. and M.H; methodology, N.F., R.H., A.M. and M.H; validation, N.F., R.H., A.M. and M.H; formal analysis, N.F., R.H., A.M. and M.H; investigation, N.F. and R-H.; resources, M.H..; data curation, N.F., R.H., A.M. and M.H; writing—original draft preparation, N.F., R.H. and M.H.; writing—review and editing, N.F., R.H., A.M. and M.H; visualization, N.F. and R.H.; supervision, A.M. and M.H; project administration, M.H.; funding acquisition, M.H.. All authors have read and agreed to the published version of the manuscript.

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