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Development and first assessment of a RGBW-LED Diaphanoscope

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ABSTRACT

BACKGROUND: Diaphanoscopy is an old but still useful technique in ophthalmic diagnostics. Its application suffers somewhat from the fact that the light is strongly attenuated and red-shifted in color when the eye wall is transilluminated.

MATERIAL AND METHODS: A color adjustable diaphanoscope prototype is developed based on a powerful red-green-blue-white light-emitting diode (RGBW-LED). Its optical and thermal properties are measured and tested on the porcine eyes of a local butcher. In addition, based on the technical data, the assumed retinal hazard to human eyes is assessed according to the standard DIN EN ISO 15004-2: 2007-6.

RESULTS: The investigated porcine eyes were brightly illuminated with all LED colors. The calculated values for judging the thermal and photochemical hazard were below the limits given in DIN EN ISO 15004-2: 2007-6.

CONCLUSION: Based on the standard mentioned above, there is no recognizable danger to the human retina when applied for a limited time, and at least in the porcine model, the presented RGBW-LED diaphanoscope allows an adjustable ophthalmological transillumination without the requirement of the more elaborated devices that are usually employed in operating rooms.

KEY WORDS: diaphanoscopy; RGBW illumination; photochemical hazard; thermal hazard

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INTRODUCTION

Diaphanoscopy is a 150-year-old technique attributed to the ophthalmology pioneer Albrecht von Graefe [1]. It involves transillumination of the apparently opaque eye wall, consisting of the retina, choroidea, and sclera, from the outside to the inside or in the opposite direction. The original application was primarily the detection of foreign bodies and tumors [2–9], whereas today's applications include the detection of retinal defects and detachments [10–12] and supportive imaging in vitreous surgery [13–15].

Historically, light sources were first the lens-focused light from the sun and gas flames [1]. Later, incandescent and halogen lamps came into use. Even then, the relatively low transmission of the eyewall led to the technical problem that bright transillumination of the eye is difficult to achieve without endangering the eye, e.g., thermally by the available light sources with their often strong infrared emissions.

Today's diaphanoscopic systems usually consist of filtered xenon light sources without strong infrared emissions. This light is transmitted to the sclera

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through a thin, light fiber with an applicator tip that increases the contact area with the eye. Because of the small diameter of the light guide, only a limited luminous flux reaches the eye, and even the spectral broadband xenon light is strongly attenuated as it passes through the eyewall. This is especially true for the blue spectral components, which makes the light intensity in the eye even weaker and at the same time more reddish.

For diaphanoscopic illumination of the eye's interior, therefore, a stronger illumination with a high blue component would be desirable so that higher luminous flux, particularly more blue light, reaches the eye. At the same time, it must be ensured that the patient's eye and especially the retina do not suffer thermal or photochemical damage.

Today, other diagnostic instruments like OCT (optical coherence tomography) devices exist that are very sophisticated and offer information that diaphanoscopy cannot provide. Nevertheless, diaphanoscopy has its advantages because it is relatively fast, inexpensive, and straightforward. Furthermore, it can be applied in less sterile environments as it does not require incisions in the eye like conventional fiber illuminators.

Therefore, this study aims to develop a prototype light-emitting diode (LED) diaphanoscopic system that is particularly bright and offers an adjustable emission spectrum that can be applied to achieve arbitrary illumination colors in the eye selectively. It is also capable of monochromatic illumination for special applications, such as blue excitation of the green fluorescent dye fluorescein for angiography. Despite this intended higher brightness, the patient's eye should not be endangered thermally or photochemically.

MATERIAL AND METHODS

Illumination experiments were performed in a laboratory with the porcine eyes of a local butcher. The investigations took place within about 8 hours after enucleation. The eyes were stored in a balanced salt solution (BBS) in the fridge at 4°C until the start of the experiments.

A central element of the illumination system was a red-green-blue-white light-emitting diode (RGBW-LED) type XM-L-Color LED (XM-LCTW-A0-0000-00C2AAAB1) of Cree (Durham, USA). According to the datasheet [16], it consists of four single LED chips in a shared LED housing with expected peak wavelengths at about 625 nm, 530 nm, and 460 nm for the color LED chips and a color temperature of about 4 000 K for the white LED chip.

Temperature measurements during preliminary tests with the temperature sensor UT320 of UNI-T (Dongguan City, China) revealed that the LED could become very hot at high currents. Therefore, the package was extended by about 20 mm (diameter 5 mm) with a transparent resin Crystal Clear 202 EU of KauPo (Spaichingen, Germany) as indicated in Figure 1, and the temperature at the tip was determined again. The extended LED was integrated into an aluminum housing to cool the LED chips and avoid glare.

The emission spectra of the extended LEDs were determined with a calibrated spectroradiometer CAS 140D of Instrument Systems (Munich, Germany). With these spectra, the photochemical and thermal hazard were calculated in accordance with the international standard DIN EN ISO 15004-2: 2007-6 *Ophthalmic instruments — Fundamental requirements and test methods — Part 2: Light hazard protection* [18].

The most important values regarding potential hazards to the retina are the "weighted retinal visible and infrared radiation thermal irradiance" $E_{VIR\text{-}R}$, the "weighted retinal irradiance" $E_{A\text{-}R}$, and the maximum exposure time T_{max}, which can be calculated by equation (1), (2) and (3):

$$E_{VIR-R} = \sum_{380}^{1400} E_\lambda \cdot R(\lambda) \cdot \Delta\lambda \qquad (1)$$

$$E_{A-R} = \sum_{305}^{700} E_\lambda \cdot A(\lambda) \cdot \Delta\lambda \qquad (2)$$

$$t_{max} = \frac{10\ \frac{J}{cm^2}}{\sum_{305}^{700} E_\lambda \cdot A(\lambda) \cdot \Delta\lambda} \qquad (3)$$

with the thermal hazard weighting function $R(\lambda)$ and the photochemical hazard weighting function $A(\lambda)$ as given in DIN EN ISO 15007-2: 2007-6. To calculate the irradiances E_λ at the tip of the LED extension, the measured emission spectra were divided by the cross-section area of the LED elongation of about 0.2 cm^2.

The control unit is based on a PI 3+ microcomputer of the Raspberry Foundation (Cambridge, Great Britain), which is connected to a touch screen

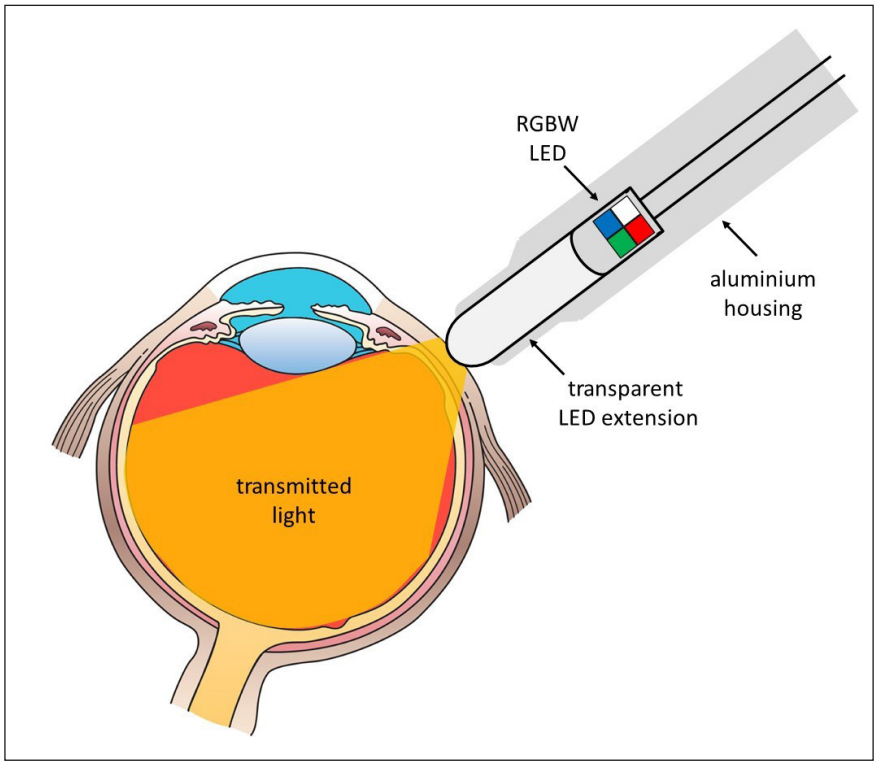

FIGURE 1. Scheme of the diaphanoscopic eye illumination with the extended red-green-blue-white light-emitting diode (RGBW-LED). Modified according to [17]

display type GEN4-4DPI-70CT-CLB of 4D Systems (Minchinbury, Australia). By this unit, an average current between 0 and 150 mA (0–100%) can be selected by pulse width modulation.

RESULTS

A photograph of the RGBW diaphanoscope prototype and its control unit is presented in Figure 2, and in Figure 3 the illumination of porcine eyes with different colors is depicted.

The emission spectra of the different LEDs for the maximum current are given in Figure 4. The maximum total power (for LEDs currents of 100 % or 150 mA), $E_{A\text{-}R}$, $E_{VIR\text{-}R}$, and the maximum exposure time — regarding a potential photochemical hazard — are compiled in Table 1. Due to the warming of the LEDs, the simultaneous emission of all LEDs (100 % RGBW) is lower than the sum of 100 % emissions of the single LEDs.

The "weighted retinal visible and infrared radiation thermal irradiance" $E_{VIR\text{-}R}$ — second row in Table 1 — is always below the limit of 0.7 W/cm2 given by the standard DIN EN ISO 15004-2: 2007-6, so the thermal effect of the radiation poses no threat to the retina.

The situation for the "weighted retinal irradiance" $E_{A\text{-}R}$ is more complex. Most of the maximum values in the third row of Table 1 exceed the limit of 0.22 mW/cm^2 given in DIN EN ISO 15004-2: 2007-6. In this case, a maximum exposure time can be calculated according to formula (3). These maximum exposure times assume a direct contact to the retina, which is not the case for diaphanoscopic illumination from the outside. In fact, the light has to pass the sclera and choroidea before it reaches the retina, and both are known for their low transmission, especially for blue light. This strongly reduces retinal irradiation and increases the allowed exposure time. According to Koelbl et al. [19], the human sclera transmission is about 13.6, 26.3, and 33.7% for 450, 530, and 630 nm and a pressure of about 60 kPa. A lower estimate for the minimal exposure time - that does not consider the absorption of the choroidea — is given in the fourth row of Table 1. Even the 7 min for 100 % blue LED emission exceeds the duration of usual diagnostic and therapeutic procedures at a single spot.

The measured maximum temperatures at the LED-tip are also given in Table 1. The temperatures for 100 % emission of the single LEDs were

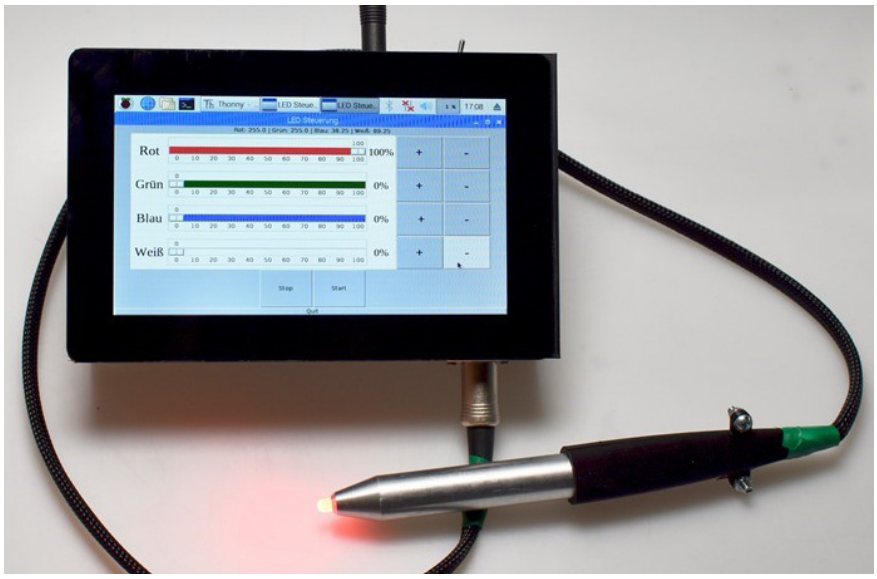

FIGURE 2. Photograph of the RGBW-LED diaphanoscope prototype

FIGURE 3. Photographs of a porcine eye transilluminated with the red, green, blue, and white light of the RGBW-LED diaphanoscope prototype

all about 32°C, and for the RGBW-LED with the maximum current of 4 × 150 mA (150 mA for each LED chip), the temperature reached 37 °C, which does not pose a threat to the patient.

DISCUSSION AND CONCLUSION

The developed RGBW-LED prototype provides a bright and adjustable illumination as demonstrated experimentally, at least in porcine eyes. This offers advantages compared to commercially available diaphanoscopes that usually consist of a xenon or halogen fiber light source with an applicator tip mounted to the end of the fiber. These systems offer a white illumination over a large spectral area. However, when this light passes the eyewall, a red-shift of the intraocular illumination is observed [4, 20–22] because blue light exhibits

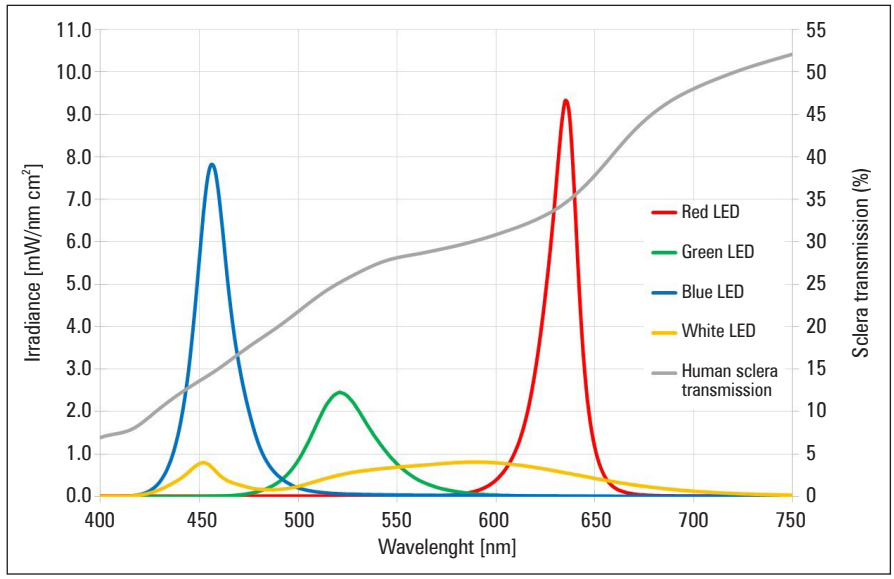

FIGURE 4. Measured irradiation spectra red (100%), green (100%), blue (100%), and white (100 %) for an assumed direct contact to the sclera and human sclera transmission spectrum of Koelbl et al. [19]

Table 1. Luminous flux and irradiance on the eye at maximum current (100%), and resulting E_{VIR-R} and E_{A-R} and resulting maximum exposure time in case of an assumed direct proximity to the retina (unrealistic), resulting maximum exposure time considering the sclera transmission spectrum of Koelbl et al. [19] (more realistic but still without choroidea absorption) and maximum temperature at the tip of the elongated LED

LED	Luminous flux [lm]	E_{VIR-R} [mW/nm cm²]	E_{A-R} [mW/nm cm²]	t_{max} [min]	t_{max} [min] with sclera transmission	LED tip temperature [°C]
100% red	7.1	201.5	0.47	358	2251.2	32
100% green	10.2	107.0	5.39	30.9	132.5	32
100% blue	2.2	202.1	156.6	1.1	7.3	32
100% white	9.1	138.7	21.6	7.7	53.0	32
100% RGBW	15.0	344.0	121.2	1.4	9.0	37

a stronger absorption in the different layers of the eyewall [19, 23] than red light.

The presented RGBW-LED diaphanoscope can at least partially compensate for this blue absorption by increasing the intensity of the blue LED chip. As can be concluded from Figure 3, even a totally blue intraocular illumination is possible. With the advantageous overlap between this blue LED emission and the absorption of fluorescein [24], this could be utilized, e.g., for fluorescein angiography [25]. Other LED settings might improve the visualization of other dyes and fluorophores.

An increased blue intensity also poses a higher burden to the retina. However, according to the standard DIN EN ISO 15004-2: 2007-6 no danger for a human patient is expected for time-limited employment. The blue LED poses the most significant hazard, and the time limit of about 7 min for 100% blue LED emission in Table 1 might sound short. However, these 7 min is the limit if the diaphanoscope stays in the same position for this period. If the physician moves the diaphanoscope, the 7 min clock starts again at the new spot. Additionally, the maximum exposure times given in Table 1 are only lower limits because the strong absorption of the choroidea, caused by hemoglobin with its high blue absorption [23], was neglected. Therefore, the intensity of the RGBW-LED diaphanoscope can probably still be increased considerably in potential future versions without posing a threat to the patients retina.

In this respect, this simple illumination system provides a wide range of ophthalmic applications in operation theatres or doctor´s practices. It might even be a useful tool in the field, e.g., after natural disasters like earthquakes, floods, and volcano erup-

tions, which might result in many injured patients and missing healthcare infrastructure for the examination or treatment of patients. The extensive application of light guide-based lighting devices with, e.g., xenon lamps seems rather unrealistic under such circumstances. Diaphanoscopic illumination at least places lower demands on the sterility of the environment and is nevertheless a useful tool for some expected cases, such as intraocular foreign bodies or retinal detachments, which were already diagnosed and treated by means of diaphanoscopy a hundred years ago [1, 4, 10].

Conflict of interest

The authors declare no conflict of interest.

Compliance with ethics guidelines

All institutional and national guidelines for the care and use of laboratory animals were followed.

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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.

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