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Geometric approach to the design of an imaging probe to evaluate the iridocorneal angle structures

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ABSTRACT

Photographic imaging methods allow the tracking of anatomical changes in the iridocorneal angle structures and the monitoring of treatment responses overtime. In this work, we aim to design an imaging probe to evaluate the iridocorneal angle structures using geometrical optics. We first perform an analytical analysis on light propagation from the anterior chamber of the eye to the exterior medium using Snell's law. This is followed by adopting a strategy to achieve uniform near field irradiance, by simplifying the complex non-rotational symmetric irradiance distribution of LEDs tilted at an angle. The optimization is based on the geometric design considerations of an angled circular ring array of 4 LEDs (or a 2×2 square LED array). The design equation give insights on variable parameters such as the illumination angle of the LEDs, ring array radius, viewing angle of the LEDs, and the working distance. A micro color CCD video camera that has sufficient resolution to resolve the iridocorneal angle structures at the required working distance is then chosen. The proposed design aspects fulfil the safety requirements recommended by the International Commission on Non-ionizing Radiation Protection.

Keywords: Geometric optics, glaucoma, iridocorneal angle imaging, circular ring LED array

INTRODUCTION

The phenomenon of total internal reflection has to be taken into account when considering light transmission from the iridocorneal angle region, through the cornea, to the outside medium. Figure 1(a) shows an illustration of light transmission from the anterior chamber to air. Under normal condition at the tear-air interface, light is totally reflected back into the cornea because the critical angle for total internal reflection is reached. Direct visualization of iridocorneal angle structures is therefore not possible. Since the cornea is relatively thin, the refracted angle at the posterior cornea θ_2 , is almost equal to the incident angle at the anterior cornea θ_3 . Using Snell's law, we can express θ_4 as a function of the refractive index of the aqueous humour n_1 , refractive index of the immediate medium outside the eye n_3 , and the incident angle at the posterior cornea θ_1 as shown. The real and imaginary values of θ_4 are plotted as a function of θ_1 , while varying n_3 , as shown in Figure 1(c).

$$\begin{aligned}n_1 \sin \theta_1 &= n_2 \sin \theta_2; \\n_2 \sin \theta_3 &= n_3 \sin \theta_4; \\ \theta_4 &= \sin^{-1} \left(\left(\frac{n_2}{n_3} \right) \sin \left(\sin^{-1} \left(\left(\frac{n_1}{n_2} \right) \sin \theta_1 \right) \right) \right); \\ \theta_4 &= \sin^{-1} \left(\left(\frac{n_1}{n_3} \right) \sin \theta_1 \right).\end{aligned}$$

Gonioscopy^[1] is the current gold standard in clinical ophthalmology for viewing of iridocorneal angle structures. Total internal reflection is eliminated at the tear-air interface by placing a glass or plastic lens adjacent to the front surface of the eye. The air spaces between the cornea and lens is then filled with an optical coupler. Our group has recently published a review paper on the progress in anterior chamber angle imaging techniques^[2], highlighting the advantages and limitations of existing imaging methods. Some of these limitations include patient discomfort,

physician compliance, time-consuming image acquisition, and the need for trained and experienced operator to avoid epithelial injury. The lack of an all-round, foolproof concept and methodology motivates researchers to work on new instrumentations and devices for imaging the iridocorneal angle region^[3]. Instrumentations and optical configurations that were conceptualized from fiber optics and bulk optics have been applied widely in bio-imaging and metrology^[4-14].

In this context, we propose a geometric approach to the design of a photographic imaging probe to evaluate the iridocorneal angle region. The proposed strategy to design and optimize the photographic imaging probe is shown in Figure 2. Here, we use hydrogel contact lens as an index matching medium to overcome total internal reflection at the tear-air interface.

Figure 1. (a) Illustration of light transmission from the anterior chamber to air. (b) Real and (c) imaginary values of θ_4 plotted as a function of θ_1 at varying n_3 .

Figure 2. Procedure to design and optimize the photographic imaging probe.

METHODOLOGY

2.1 Optical model of a LED source

The irradiance distribution of a LED source in watts per meters squared ($W m^{-2}$) can be approximated as an imperfect Lambertian distribution function given by^[15]

$$E(r, \theta) = E_0(r) \cos^m \theta. \quad (1)$$

Here, $E_0(r)$ is the on axis irradiance at distance r from the source, and θ is the viewing angle of the LED. An ideal LED source is a perfect Lambertian emitter where $m = 1$. In this case, $E(r, \theta)$ is simply a cosine function of θ . For an imperfect Lambertian emitter, the value m is dependent on the semiconductor region shapes and the encapsulant. m can be expressed in terms of the half viewing angle of the LED, $\theta_{1/2}$, which is the view angle when irradiance is half of the value at 0°

$$m = \frac{-\ln 2}{\ln(\cos \theta_{1/2})}. \quad (2)$$

In Cartesian coordinates, the irradiance distribution over every point on a xy planar surface at distance z from the LED array is written as^[16]

$$E(x, y, z) = \frac{z^m L_{LED} A_{LED}}{[(x - x_1)^2 + (y - y_1)^2 + z^2]^{(m+2)/2}}, \quad (3)$$

where, L_{LED} is the radiance in watts per meters squared per steradian ($W m^{-2} sr^{-1}$), and A_{LED} is the LED emitting area in meters squared (m^2). The dimensions and optical characteristics of the LEDs used for this study are shown in Figure 3.

Figure 3. (a) Physical dimensions of the high luminous white LED, LM520A (Seoul Semiconductor Co., Ltd); optical characteristics showing (b) the radiation diagram at 20° viewing angle, and (c) its spectral characteristics.

2.2 Circular ring array of four LEDs at the desired angle

From equation 3, the irradiance of a circular ring array of four LEDs at 0° illumination angle and radius r_0 can be written as^[15]

$$E(x, y, z) = z^m L_{LED} A_{LED} \sum_{n=1}^4 \left\{ \left[x - r_0 \cos\left(\frac{2\pi n}{4}\right) \right]^2 + \left[y - r_0 \sin\left(\frac{2\pi n}{4}\right) \right]^2 + z^2 \right\}^{-(m+2)/2} \quad (4)$$

The variable r_0 can be optimized in order to achieve uniform irradiance distribution over the central region. We aim to separate the irradiance patterns of the four LEDs, such that the irradiance slope variation is minimal over the central region (i.e. eliminating the implicit second-order term of Equation 4). The concept is same as the Sparrow's criterion in imaging resolution^[15, 17]. In order to achieve the maximally flat condition^[18] for r_0 , we differentiate E twice and set $\frac{\partial^2 E}{\partial x^2} = 0$ at $x = 0$ and $y = 0$. Therefore,

$$r_0 = \sqrt{\frac{2}{m+2}} l. \quad (5)$$

The distance l is also the working distance of the imaging probe. It is noted that the maximally flat condition for r_0 is not dependent on the number of LEDs. The complex non-rotational symmetric irradiance pattern of individual LEDs should be considered for a circular ring array of LEDs at desired illumination angle. This can be simplified using a geometrical model shown in Figure 4 where l is the working distance, r_0 is the maximally flat condition, r is the ring array radius, and α is the illumination angle,

$$\tan \alpha = \frac{(r - r_0)}{l}. \quad (6)$$

And by substituting r_0 from Equation 5,

$$r = l \left(\tan \alpha + \sqrt{\frac{2}{m+2}} \right). \quad (7)$$

Therefore, given m , the parameters α , r , and l have to be carefully considered in order to achieve uniform irradiance. Figure 5 shows a plot of r as a function of α and l , where θ_{LED} is 20° .

Figure 4. Geometry of a circular ring array of 4 LEDs at the desired angles.

Figure 5. Plot of r as a function of α and l , where θ_{LED} is 20° .

2.3 Selecting a suitable camera

This section of the paper aims to discuss the factors that were put into considerations for the camera selection process. In addition to its ability to provide a direct visualization of the iridocorneal angle region with good quality images, the selected camera should be compact, and be able to readily integrate into the proposed imaging probe. Since water-based ophthalmic gels or saline solutions may be used as coupling medium to overcome the phenomenon of total internal reflection at the tear-air interface, the camera should be completely waterproof. Also, to be cost effective, the camera system should be durable and suitable for reusable medical applications after high level disinfection.

2.4 Safety exposure limit and risk of epithelial injury

The types of optical hazards to the eye include ultraviolet photochemical injury, thermal injury to the retina, blue-light photochemical injury, near-infrared thermal hazard to the lens, and thermal injury to the cornea. Since we are using white light LED sources, the potential hazard that should be considered is blue-light photochemical injury. These are addressed properly in the following section.

Like all contact procedures in ophthalmology, imaging with the proposed imaging probe creates discomfort to the patient and exposes them to risks of corneal abrasions and infections. A skilled and experienced operator is often needed and the procedure can be time-consuming.

3 DISCUSSION

There are a wide range of LEDs with varying radiation patterns. For this study, we chose spherically encapsulated white light LEDs with Lambertian radiation pattern. This is because Lambertian radiation pattern emits more radiation along the optical axis. In Equations 1-7, the LEDs were approximated as imperfect Lambertian emitters since their chip size are small compared to the radius of the encapsulating lenses^[15]. Similar to all other optical instruments, alignment of the components is very critical. The LED chips in the ring array (or 2×2 square LED array) should be coplanar. Since the direct view of the iridocorneal angle is obstructed by the scleral overlap, the imaging probe has to be positioned at the limbal region to image the opposite iridocorneal angle. It should be noted that the LED plane array is not parallel to the target plane.

The design equation for circular ring array of LEDs at an angle is bounded by four parameters α , r , l , and m . Because the viewing angle and hence m , cannot be continuously adjusted, it is more convenient to consider only three variables for optimization. From Equation 7, we see that the ring array radius is proportional to the working distance. Since the distance from the limbal region to the opposite iridocorneal angle is approximately 10 mm, we set l to 10 mm. Equation 7 also shows that the array radius increases with increasing illumination angle, and that the increase in array radius is more dramatic when illumination angle is large.

We chose micro ScoutCam™ 3.0 charged-coupled device (CCD) camera (Medigus Ltd., Israel) as our image sensor. It is a 3.0 mm $\times$ 3.0 mm, advanced, high-end color camera that operates with a video processor. It has system functions such as automatic gain control, brightness control, color correction, and white balance etc.. Image acquisition is possible in either single frame mode or fast kinetic series. The CCD camera has a pixel size of 2.95 μm (horizontal) $\times$ 1.90 μm (vertical), and 291,000 effective numbers of pixels (582 lateral $\times$ 500 longitudinal). It has a frame rate of 30 frames per second (fps), and a field of view (FOV) of 140° which is sufficient to capture an entire quadrant of the eye at any one time. The micro ScoutCam™ has variable resolution at different working distances. At a working distance of approximately 10 mm at the iridocorneal angle region, it has a spatial resolution of 10.08 line pairs per mm ($\sim 49.61 \mu\text{m}$), which is sufficient to delineate the iris root, ciliary body band, trabecular meshwork and the scleral spur.

LEDs are grouped under incoherent optical sources because of their larger spectral bandwidth. Ophthalmic diagnosis with the proposed imaging probe exposes the eye to incoherent optical radiation. Spectral details such as spectral irradiance, spectral radiance, and the angular subtense of the LED sources perceived by patients need to be considered for the correct application of exposure limits if luminance is greater than 10,000 candela per meter squared (cd m^{-2})^[19]. Since we are using LM520A (Seoul Semiconductor Co., Ltd) with a luminous intensity of 7,000 millicandela (mcd), evaluation of retina hazard is not required. The optical characteristics of the LED are shown in Figure 3. It should however be fairly noted that there will be patient discomfort because the natural defense mechanisms of eyes' such as blinking, eye movements, glare avoidance and squinting are compromised during image acquisition. Also, target fixation limits the movement of retina relative to the white light LED sources, and increases the concentration of radiant energy at the retina. Pupillary constriction to bright light is not inhibited since cycloplegics and mydriatics drugs are not used.

In order to reduce epithelial trauma, we propose the use of hydrogel contact lens as an index matching medium and better protective barrier, as an alternative to conventional ophthalmic gels. Hydrogel contact lens also serves as a better mechanical protective barrier against epithelial injury during indentation examination. It does not introduce any imaging artefacts, and can give good quality digital images.

4 CONCLUSION

Ophthalmic instruments based on medical photographic methods enable clinicians and vision researchers to evaluate the internal drainage system of the eye, and are essential for the accurate diagnosis, prognosis, and management of glaucoma. These methods capture images of the iridocorneal angle region, and store them in the patients' database. They allow the clinical documentation of anatomical changes and treatment responses with disease progression, and are also the preferred patient education tools.

In summary, we present a strategy to design and theoretically analyze an ocular photographic imaging probe consisting of four LED light sources at the desired angle and an image capturing device. The parameters for modelling a circular ring array of LED include the illumination angle, ring array radius, viewing angle and working

distance. The design equation for ring array at an angle illustrates the relationship between these parameters, and is derived geometrically from the design equation for ring array at 0° illumination. This design strategy can also be extended to fiber laser sources. For simplicity, we fix the viewing angle and working distance, and optimized other variables to suit our intended purpose. This method, when coupled with software simulation, can be useful for a quick estimation to optimize LED arrays for uniform near field irradiance. The image capturing device was chosen based on its compactness, durability, and imaging capability. Lastly, it is important to ensure that the imaging probe fulfils the safety directions adopted in routine clinical use as per international standards. We have recently successfully applied the results of this research to design and assemble a LED ring array for ocular imaging^[20]. The images acquired are similar to direct gonioscopy. Unlike direct gonioscopy however, anesthesia is not required and patients can be in an upright seated position. Indentation examination is also possible. One of the future work directions is to integrate the photographic imaging probe with a slit lamp.

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