Research of bright pupil effect based on Chinese human eye model

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An optical model of bright pupil effect based on Chinese human eye model is presented. The effects of the incident rays angle and the size of pupil on bright pupil effect are analyzed theoretically. For the incident rays with 5°–15° field of view, the spot diagram of emergent light is also presented. With the pupil diameters of 3–8 mm, the intensity distributions formed by emergent light are calculated. The optical model of bright pupil effect based on Chinese human eye provides a suitable model for the related further research studies and applications on bright pupil effect with Chinese eye.

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The bright pupil effect is the phenomenon of bright light spot in human eye pupil when taking flash photography. The main reason of bright pupil effect is the reflection of paraxial rays on the retina. At present, the research of the bright pupil effect as the red-eye effect has two main aspects. On the one hand, the bright pupil effect on photographs is not conducive to the appearance face, so some methods of image processing are used for manual correction of red-eye[1,2]. On the other hand, the bright pupil effect is of great importance in many applications, such as the facial fatigue detection[3–5], the human eye detection, and tracking[6,7].

However, there are few research studies on the detailed analysis of the optical causes and influencing factors of the bright pupil effect. Furthermore, there is significant variation in the magnitude of the bright pupil response across the population[8]. Therefore, based on our previous work result on Chinese human eye model[9], the theoretical research of bright pupil effect is presented in the work.

The optical model of bright pupil effect based on Chinese human eye model is built with Zemax optical design software. The structural parameters of Chinese generic eye model are from our previous work[9], which is not described again here.

Figure 1 shows the schematic plots of optical model of bright pupil effect at the pupil diameters of 3 and 6 mm. The eye optical system consists of six surfaces, from left to right in Fig. 1: the first and second surfaces represent the anterior and posterior of cornea; the third one represents the pupil; the fourth and fifth ones represent the anterior and posterior of lens; the sixth one represents retina. The pupil is not exactly centered with respect to the rest of the eye and is often displaced slightly nasally by ~0.5 mm[10]. Therefore, the displacement of the third surface is introduced (Fig. 1). In Fig. 1, the incident rays transmit the eye model and focus on retina, then reflected by retina. Parts of the reflected rays are blocked at the pupil (the third surface), and the other reflected rays, which pass through cornea and emit out, are captured by receiving device that cause bright pupil effect.

The effects of the incident rays angle and the size of pupil on bright pupil effect are analyzed with the optical model. The emergent light is captured by a receiving surface which is located before cornea in the model. The size of spot on the receiving surface is the size of bright light spot in bright pupil effect. Because the angle of eye visual axis and optical axis is about 5°, the incident rays with 5° field of view is the starting point. In the optical model of bright pupil effect at the pupil diameter of 3 mm, for the incident rays with 5°–15° field of view, the spot diagram of emergent light is as shown in Fig. 2.

In Fig. 2, when the fields of view of incident rays are 5°–8°, the spot diagrams of emergent light are shown in the first row; in the second row, the spot diagrams are obtained by the incident rays with 9°–11° field of view; in the third row, the spot diagrams are obtained by the incident rays with 12°–15° field of view. From the 11 spot diagrams in Fig. 2, we find that as the incident

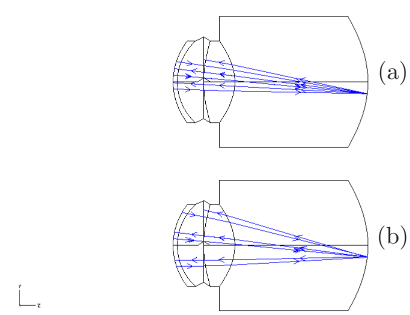

Fig. 1. Schematic plots of optical model of bright pupil effect at the pupil diameters of: (a) 3 and (b) 6 mm.

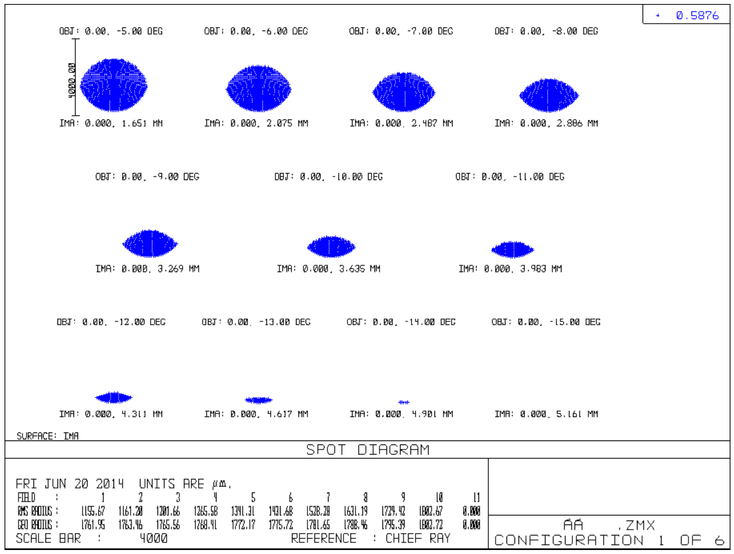

Fig. 2. Spot diagram of emergent light (incident rays with 5°–15° field of view).

angle increases, the spot size decreases. Moreover, the spot size corresponding to incident rays with 5° is maximum, whose coverage is about 3.404×2.632 (mm), and there is no spot, when the angle of incident rays is 15°.

In the visual axis direction, bright pupil effect can be observed significantly. Therefore, the effect of the size of pupil on the intensity of emergent light is analyzed with 5° field of view. The defaulted intensity of incident light source is supposed to be 1 W. Due to its double passage through the eye media, the emergent light intensity at any wavelength is proportional to the equivalent reflectance $T_{\mathrm{E}}(\lambda)^2 R_{\mathrm{R}}(\lambda)$, where $T_{\mathrm{E}}(\lambda)$ is the total transmittance of the eye media and $R_{\mathrm{R}}(\lambda)$ is the true retinal reflectance[11]. The equivalent reflectance is about 1%–10% in the visible spectrum[11]. For simplicity, we suppose the equivalent reflectance about 5% at the wavelength of 0.5876 μm.

With the pupil diameters of 3–8 mm, the intensity distributions formed by emergent light are as shown in Fig. 3 and the receiving total intensity values are listed in Table 1. All the intensities are calculated with the equivalent reflectance. From Table 1, we find that when the pupil diameter is less than 5 mm, the light intensity value is relatively small, less than 0.04 W; when the pupil diameter is greater than 5 mm, the light intensity value is relatively large, greater than 0.04 W, so the bright pupil effect is more obvious when the pupil diameter is greater than 5 mm.

Figures 3(a)–(f) represent the pupil diameters of 3–8 mm, respectively, the plane defined by the *xy*-axes represents the receiving surface and the vertical axis represents the light intensity distribution (unit: W/mm^2). It is shown that the light intensity density decreases with the increase in the pupil diameter, but the spot size on the receiving surface (Fig. 3) and the total intensity of emergent light (Table 1) increase. Equivalent reflectance rises with wavelength across the visible spectrum, to become quite high in the near-infrared[11]. The total intensity of emergent light will be greater at near-infrared wavelengths, so under the same conditions, for example, the pupil diameter and the reflection angle on the retina are the same, the bright pupil effect is more easily observed at near infrared wavelengths. Of course, when using near-infrared wavelength, the transmittance of the eye media of different wavelengths[12] is to be considered.

In conclusion, to the best of our knowledge, the building of optical model of bright pupil effect presented in this work is the first theoretical research of bright pupil effect based on Chinese generic eye model. Through the analysis results of effects of the incident rays angle and the size of pupil on bright pupil effect, we find that bright pupil effect is clearly observed: firstly, when the incident rays are in the visual axis direction or near the visual axis direction and secondly, when the pupil diameter is greater than 5 mm at least. Moreover, near-infrared wavelength is the better choice. The effects of wavelengths on bright pupil effect can

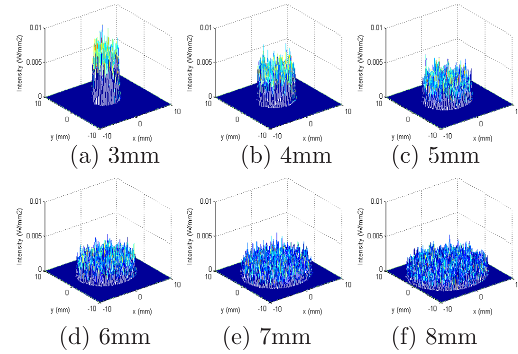

Fig. 3. Intensity distributions of emergent light (the incident rays with 5° field of view, the pupil diameters of: (a) 3, (b) 4, (c) 5, (d) 6, (e) 7, and (f) 8 mm).

Table 1. Total Intensity of Emergent Light Connected to Six Pupil Diameters

Pupil Diameter (mm)	3	4	5	6	7	8
Total Intensity of Emergent Light (W)	0.0352	0.0390	0.0408	0.0412	0.0426	0.0431

be further studied. These theoretical analysis results can be applied to provide a method for removing red-eye when taking photography without post-processing, which will be helpful in facial fatigue detection, the human eye detection and tracking, etc.

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