Optical system design of portable non-mydriatic fundus camera

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Abstract: An optical system of a portable non-mydriatic fundus camera was designed. This design realized the highly clear imaging with three million pixels. Based on the physiological and optical characteristics of the human eye, the Gullstrand-Le Grand eye model was introduced to simulate the human eye with normal diopter. The Schematic eye model was used to examine the influence of the ametropia eye on imaging system. In the imaging system, the eye-piece objective lens were firstly used to converge the light emitted through the pupil reflected from the retina of the human eye, then it was imaged to the CCD receiver by the imaging objective lens. In case of the stray lights caused by the cornea, the illuminating system with an annular aperture and coaxial illumination was specially designed. The result shows that the field of view of this system is 30 degrees, the resolution is more than 120 lp/mm, the field curve value is less than 0.12 mm, the distortion value is only -1.2%, the chromatic aberration of all fields of view is within the Airy disk. It comes to a conclusion that this fundus camera has strong focusing abilities for accommodation, and adapts to different eyes from -10 D to +10 D. All the optical components of the optical systems are common spherical glasses, which are easy to manufacture and can reduce the production costs effectively.

Key words: optical design; fundus camera; eye model; high resolution

CLC number: TH744 Document code: A DOI: 10.3788/IRLA201847.0818001

便携式免散瞳眼底相机光学系统设计

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摘 要: 设计了一种便携式免散瞳眼底相机光学系统,达到了全视场 300 万像素的高清眼底成像。在考虑人眼生理特征和光学特性的基础上, 引入 Gullstrand-Le Grand 眼模型来模拟被测屈光度正常的人眼,用 Schematic 眼模型来检验屈光度异常人眼对成像光路的影响。在成像系统中,首先采用接目物镜会聚从人眼视网膜反射出瞳孔的光线,然后再由成像物镜将视网膜的像成像到 CCD 上。在照明系

收稿日期: 2018-03-05; **修订日期:** 2018-04-10

基金项目: 天津市科技重大专项与工程(17ZXSCSY00060,17ZXHLSY00040,17ZXSCSY00090);
天津市高等学校创新团队培养计划(TD13-5034)

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统中，为避免角膜中心区域产生杂散光，采用环形光阑和共轴照明相结合的照明方式给眼底照明。仿真结果表明：该系统视场角为 30°，成像分辨率高于 120 lp/mm，场曲值小于 0.12 mm，畸变仅为 -1.2%，全视场色差值均在艾里斑之内，且该光学系统具有较大的调焦能力，对 -10 D~+10 D 的人眼普遍适用。所用的光学元件均为普通的球面玻璃，便于加工制造且能有效降低实际的制作成本。

关键词：光学设计； 眼底相机； 眼模型； 高分辨率

0 Introduction

The fundus imaging is an important means to diagnose and identify the retinal diseases. Through the observation of the human eye, we can diagnose the patient's retinal lesions and systemic microcirculation changes of the whole body correctly[1]. The fundus imaging has the advantages of simple operation, low cost, real-time imaging, no trauma, repeatability, easy access and so on. It is the most economical and effective way to observe the human fundus. The fundus camera is a traditional medical device used to observe and record the human fundus image, which has become an important means of modern medical diagnosis. The first fundus camera of the world has been trial-produced by German CARL ZEISS company successfully in 1925. Subsequently, TOPCON, CANON, OLYMPUS, OPTON, VISUAL PATH, NIKON and other companies have a lot of improvements on fundus camera[2]. Taking into account the living retinal photography, and in order to improve the safety and comfort of the subjects, non-mydriatic fundus camera has become the first choice.

Due to the high cost and the strict using environment of the table-type fundus camera, it is only popular in large hospitals currently. However, in order to further popularize the fundus examination, especially in some underdeveloped areas where people are short of medical equipment, it is necessary to use a compact portable fundus camera as clinical diagnostic equipment which is convenient for doctor to carry. At the same time, the portable fundus camera can easily obtain a clear image of the fundus. It can be conveniently applied to the rapid fundus screening. And doctor can go out to diagnose diseases using the portable fundus camera, or provide diagnosis for those who are inconvenienced, or telemedicine and so on.

When we design the portable fundus camera optical system in this paper, the widely used Gullstrand -Le Grand eye model is introduced to simulate the actual human eye in order to take into account the impact of the human eye[3]. Although it does not consider the influence of higher-order aberrations of the human eye, it takes into account the chromatic aberration of the human eye. Therefore, it can adapt to the illumination of the dim light source in medical applications. The Schematic eye model is used to examine the effect on imaging system of the ametropia eye[4]. The results show that the proposed optical system has the advantages of compact volume, simple structure, high resolution, small distortion and large range of adjustment.

1 Design principle and system structure

1.1 Design principle

Fundus camera is generally composed of three parts: imaging system, illumination system and observation system. The imaging system images the fundus on the target surface of the CCD. The lighting system introduces enough light into fundus by an annular aperture. The observation system provides a platform for doctors to observe the fundus lesions and to focus for abnormal eyes.

In general, the photographic system can accomplish the basic function as long as it has two parts: the photographic objective lens and the imaging negative film. However, the imaging system of the fundus camera includes the following three parts: the eye-piece objective lens, the imaging objective lens, and the receiver. The reason why photographic objective lens is divided into two groups is that the human eye may have ametropia and this difference is usually very large. The light entering the fundus camera may be parallel light, convergent light or divergent light. On the one hand, it is difficult to adapt to different eyes when using only one set of objective lens. On the other hand, in order to improve the imaging quality, it needs to use the coaxial illumination. So we must leave a middle position. Usually the first group is called the eye-piece objective lens which is close to the human eye, and the second group is called the imaging objective lens which is close to the image plane.

The human eye is dark inside and does not give out light, so the fundus must be illuminated first before imaging. This requires the lighting system, it does not just only need to meet the condition of appropriate light intensity, uniform lighting, safety, but also needs to consider the ghost image and stray lights caused by illumination, which will have an impact on imaging. We adopt the coaxial annular illumination for comprehensive consideration in this paper[5].

1.2 System structure

The design process of the portable fundus camera optical system is under the condition of no-mydriatic. In order to make the human eye maintain the state of natural expansion, we select the dim light source which is often used in medical applications as the light source of the illumination system. And in the design process, we do not need special design for the observation system. The CCD is used to receive the real-time imaging of retina, so that the structure of the whole optical system is simplified.

The overall structure of the system is shown in Fig.1. The optical system includes two parts: imaging system and illumination system. The imaging system consists of eye, eye-piece objective lens, beamsplitter, imaging objective lens, and CCD. The illuminating system consists of light source, condenser, annular aperture, illuminating objective lens, beamsplitter, eye-piece objective lens and eye. The two parts use same eye-piece objective lens. In the optical system, the function of the illumination system is to make the light collimated and uniform emitted by the light source. After the light travels through beamsplitter and objective lens to the pupil, we can get the fundus image[6]. The function of the imaging system is to collect and integrate the light reflected from human retina through the pupil, and it can form a clear image on the CCD at last.

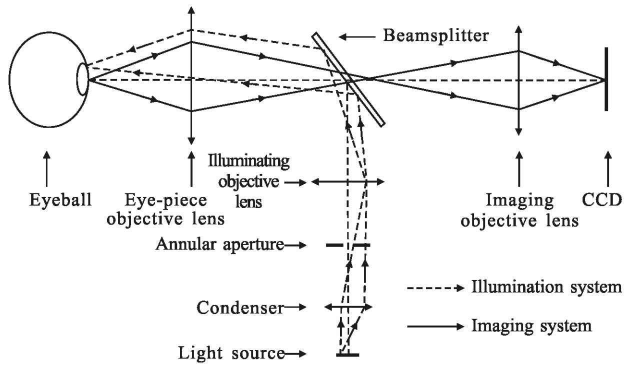


Fig.1 Schematic diagram of system design

2 Design process

2.1 Technical index

Pupil size: The normal regulating range of eye pupil is generally from 3 mm to 7 mm under the condition of non-mydriatic. We select 4 mm as the entrance pupil diameter.

Resolution: The object plane is 149 lp/mm. That means it can distinguish the 3.4 μm structural unit of the fundus (the smallest diameter of the retina cells is 2.6 μm, the largest is 9 μm). And the image plane is 120 lp/mm.

Size: To meet the portable conditions, the total length of the system is required to be less than 250 mm.

Field of view: Considering the manufacturing cost and medical requirements, the system field of view reaches 30 degrees.

Receiver: In order to reduce cost and complete imaging, 2/3 inch CCD of 3 million pixels is selected as imaging chip.

Lighting source: The dim light source is widely used in medicine, whose wavelength ranges from 420 nm to 580 nm.

2.2 Imaging system design

2.2.1 Initial structure selection

In the design process of imaging system structure, we choose the CCD with 3 million pixels and 2/3 inch size as the receiver. Its full field of view is 30 degrees. And the total length of the system is less than 250 mm. Since the pupil can not only limit the width of the beam entering the human eye, but also limit the width of the beam emitted from the human eye, it is appropriate to select the pupil position as the aperture stop of the imaging system [7]. Usually, the normal range of human eye pupil is from 3 mm to 7 mm, so we select 4 mm as the entrance pupil diameter. In addition, the working distance of the fundus camera cannot be too short to prevent the eye from contacting lens, and cannot be too long to avoid too large diameter of the eye-piece objective lens. Generally, the range of the working distance is from 30 mm to 40 mm. In the design process in this paper, we select 35 mm as the working distance of the fundus camera.

Because the design target is portable, the volume of the system should be as small as possible. The lenses of the imaging system are divided into two parts, i.e., the eye-piece objective lens and the imaging objective lens. Wherein, the eye-piece objective lens is shared by the imaging system and the illuminating system, which may increase the length of the system. Therefore, in the process of selecting the imaging objective lens, the light should be converged quickly, so that the whole length of the system can be as short as possible. In the design process, in order to make the system structure simple, we select four or five lens group as the initial models. Here, Petzval four lens group is selected as the initial structure of the imaging objective lens in the optical system, shown in Fig.2.

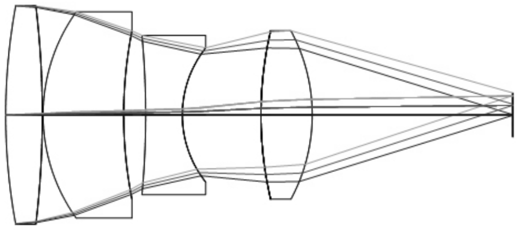


Fig.2 Initial structure of imaging objective lens of imaging system

Since the imaging system and the illumination system share the eye-piece objective lens, it is necessary to consider the selection of the initial structure of the lens comprehensively. The eye-piece objective lens should not only ensure the imaging quality of the imaging system, but also ensure that the energy loss of the light reflected by the beamsplitter is as low as possible in the lighting system. It is obvious to find the importance of the eye-piece objective lens; of course, it is also difficult to design it. Here, a lens group composed of three lenses is selected as the initial structure of the eye-piece objective lens in the optical system. The field of view is 30 degrees(Fig.3).

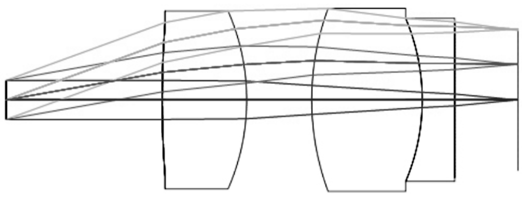


Fig.3 Initial structure of eye-piece lens of imaging system

2.2.2 System optimization design

Step 1: We choose the ZEMAX as optical design software. According to the requirements of system design, the selected Gullstrand-Le Grand eye model, the initial structure of the eye-piece objective lens and the initial structure of imaging objective lens are arranged in order to realize the target of designing initial structure of the imaging system.

Step 2: We set the structural parameters of each component in the ZEMAX optical design software, and then optimize the whole system. In this process, the image plane of the imaging system is close to 11 mm, and the total length of the system is limited to 250 mm.

Step 3: We optimize the parameters of the whole system, such as chromatic aberration, field curvature, and distortion. At the same time, the MTF (modulation transfer function) curve is needed to meet the requirements that the resolution of the image plane reaches 120 lp/mm.

Step 4: After finishing designing the illuminating system, we need to consider the eye-piece objective lens comprehensively. Then we need to optimize the whole system again. The configuration of imaging system is shown in Fig.4.

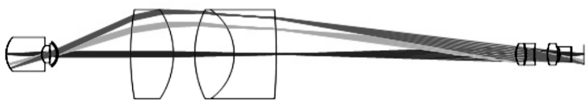


Fig.4 Configuration of imaging system

2.3 Illuminating system design

The main work of the illuminating system design is to find the suitable beamsplitter and annular aperture. The beamsplitter needs to reflect the illumination light through the annular aperture to the eye-piece objective lens and then image it on the pupil of the human eye to form an annular spot for the fundus illumination without interfering with the operation of the imaging system.

When non-mydriatic, the normal adjustment range of the eye pupil is about 3 mm to 7 mm. To reduce the requirement of lighting environment when taking images, the inner diameter of the annular illumination spot is chosen to be close to 4 mm which is the minimum adjustment value of the human pupil. At the same time, we select 8 mm as the outer diameter of the annular illumination spot to get enough lighting, which is slightly larger than the maximum adjustment of human eye pupil.

According to the principle of reversibility of light path, the human pupil is regarded as the object plane, and then we optimize the illuminating system. The results show that the inner diameter of the annular aperture is 5.4 mm and the outer diameter is 11 mm. The configuration of illuminating system is shown in Fig.5.

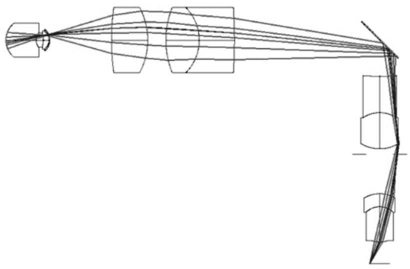
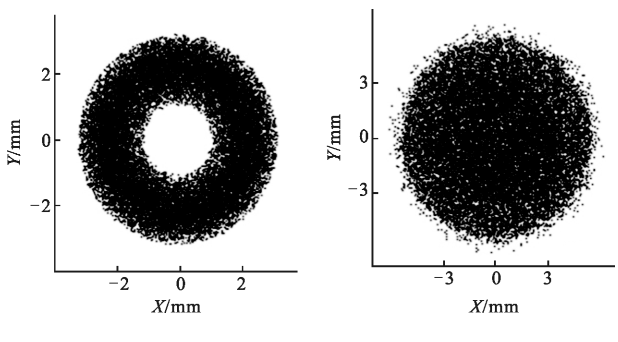


Fig.5 Configuration of illuminating system

In this paper, LightTools software is used to analyze the lighting effect of the illumination system, and the ray tracing is 1 million. The simulation results are shown in Fig.6. We can see that the effective lighting radius of annular illumination spot in the pupil ranges from 1.5 mm to 3 mm. Furthermore, the central illumination is slightly lower than the edge illumination. This is a good way to avoid the region where the corneal center curvature is large, thus avoiding the generation of corneal stray light. The illumination system selects a dim light source widely used in medicine, and the wavelength of the dim light ranges from 420 nm to 580 nm. The illumination system can match well with the CCD receiver.



(a) Annulus image of cornea (b) Illumination spot at fundus

Fig.6 Simulation of illumination uniformity in fundus

2.4 Focusing analysis

The above design is based on the normal human eye, that is, Gullstrand-Le Grand optical model eye.

But regarding to different eyes, diopter may be different, such as hyperopia and myopia. To get a clear image of the fundus with ametropia, it requires the imaging optical system to have the ability of diopter adjustment[8]. According to the existing adjustment methods of fundus camera, and taking into account the simple and convenient operation, the system uses a common way of regulation that we only move the CCD.

Modern medicine confirmed that changes of the diopter of human eye will cause multiple changes in the parameters of the eye, rather than a simple change in the axial length of the eye or curvature of lens. To simulate the effect of changing human eye diopter on the imaging quality, the Schematic eye model of Navarro is introduced and some improvements are made on the eye model. The curvature radius of anterior surface of lens plays an important role in the human eye diopter changing; curvature radius of rear surface and the thickness of the lens also have some effect.

According to the relational expression of the Schematic eye model, we calculated the lens parameters of eleven kinds of adjustment state (0, ±1, ±2, ±3, ±4, ±5 **D**). The corresponding values of the optical system can be obtained by the simulation in ZEMAX when changing the diopter of human eye. Figure 7 gives the numerical curves of MTF curves at 200 lp/mm and 120 lp/mm under the condition of different diopter in full field of view.

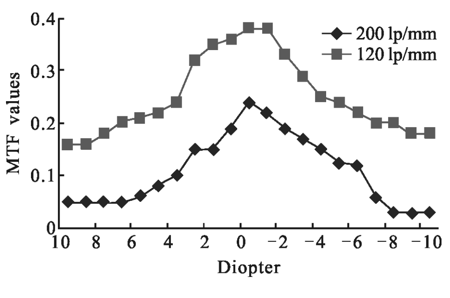


Fig.7 Curves of MTF values at 200 lp/mm and 120 lp/mm

It can be seen from Fig.7 that the MTF value of abnormal eye with ametropia decreases with the increase of the diopter value. For the curve of 120 lp/mm, the MTF value is higher than 0.1 in the range of -10 **D** to +10 **D**. For the curve of 200 lp/mm, the MTF value is not less than 0.1 in the range of -6 **D** to +4 **D**. The results show that the system has good imaging quality within the range of -10 **D** to +10 **D**, especially in the range of -6 **D** to +4 **D**, the imaging resolution can reach 200 lp/mm, which meets the design requirements.

3 Image quality evaluation and comparison of system design results

3.1 Image quality evaluation

As the fundus camera is used to image the retina, it requires a higher quality of imaging. In addition, the receiver of the fundus camera system selects a CCD with three million pixels and it requires the resolution to be higher than 120 lp/mm. That is, all the curves of field of view are located above 0.2 in the position where the abscissa is 120 lp/mm. From the MTF curves shown in Fig.8, we can see that all the curves of field of view are located above 0.4 in the position where abscissa is 120 lp/mm, which proves the good quality of the imaging. In the position where abscissa is 200 lp/mm, all the curves of field of view are located above 0.2, which also proves the image quality satisfying the design requirements.

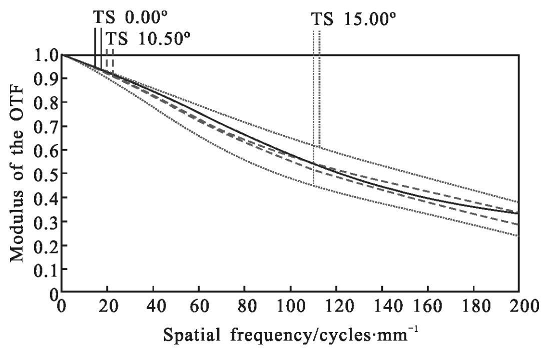


Fig.8 Curves of modulation transfer function (MTF)

The curves of field curvature and distortion of the system are shown in Fig.9. We find that the maximum field value is 0.12, and the distortion is only -1.2%. Compared with the common fundus camera, both the values are very small, thus the influence to the image quality is very little.

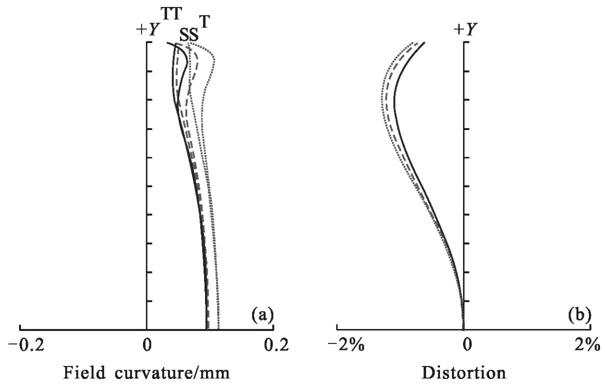


Fig.9 Curves of field curvature (a) and distortion (b)

Figure 10 is a graph showing curves of lateral color when the pupil diameter is 4 mm. It can be seen that the chromatic aberration of all fields of view is within the Airy disk. The pixel size of the selected CCD is 4.3 μm (**H**)×4.3 μm (**V**). Correction of chromatic aberration meets the design requirements. It can be concluded that the aberration quality of the fundus camera optical system is satisfying.

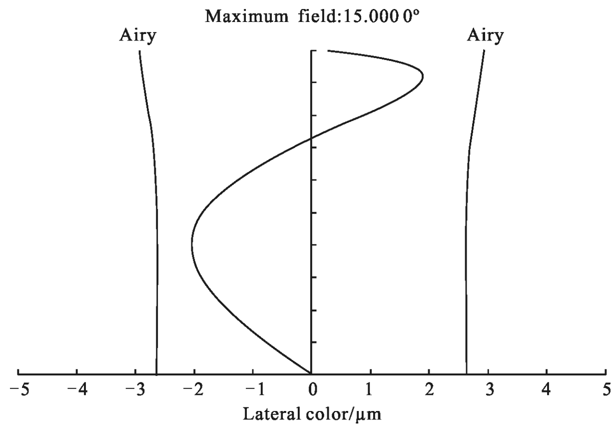


Fig.10 Curves of lateral color

3.2 Comparison of system design results

Table 1 shows the comparison of our optical system of the portable fundus camera with others. Compared with Ref. [5], our system has higher resolution, and the field curve and the distortion are much smaller. Compared with Ref. [9], a hybrid refractive/diffractive optical system, all design indexes of our system are better. What's more, using diffractive elements make it difficult to manufacture. Our design uses ordinary spherical mirror, which make it easy to manufacture and can reduce the actual cost substantially. The system of Ref. [10] is some compact, but the resolution is low. Using liquid lens to control the focal length, the system in Ref.[11] has a large field of view and small size, which will lead to the offset of the optical axis. In summary, our system has smaller field curve value, lower distortion and higher resolution.

Tab.1 Comparison of the proposed optical system with others

	Field of view/(°)	Resolution	Field curve/mm	Distortion
Wang Z Q et al.[5]	30	120 lp/mm,>0.1	0.86	-7.2%
Xu Y et al.[9]	28	120 lp/mm,>0.14	0.75	-5.3%
Li C et al.[10]	30	45 lp/mm,>0.2	0.2	-5%
Ma C et al.[11]	50	120 lp/mm,>0.2	-	-
Proposed design	30	120 lp/mm,>0.4	0.12	0.12

4 Conclusion

A portable non-mydriatic fundus camera optical system with a field of view of 30 degrees and a working distance of 35 mm is designed for the purpose of being light and portable. It realizes the high resolution imaging of the retina. Considering the physiological and optical characteristics of the human eye, the Gullstrand-Le Grand eye model is introduced to simulate the human eye with normal diopter and the Schematic eye model is used to examine the influence of the ametropia eye, which makes the optical system more close to the real situation. The size of the optical system is 150 mm(height)×40 mm (width)× 250 mm (length). The MTF values of all fields are higher than 0.2 at the resolution of 120 lp/mm. It comes to a conclusion that this fundus camera has strong focusing abilities for accommodation, and adapts to different eyes from -10 **D** to +10 **D**.

Moreover, the components of the proposed optical system are common spherical glass, which make it easy to manufacture, ensuring accuracy, and reducing costs.

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