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用于儿童斜视矫正的压贴三棱镜设计与制作

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摘　要:为了填补我国学术界和产业界在压贴三棱镜的国产化设计、制作以及测试等方面工作的空白,研究了压贴三棱镜镜片结构设计理论,并推导了压贴三棱镜镜片透过率以及畸变的计算公式,数值模拟了不同材料、不同棱镜度数的压贴三棱镜的透过率以及压贴三棱镜的畸变情况.数值模拟结果表明:与现有 PVC 材料相比,PMMA 材料具有更大的阿贝系数和更小的材料吸收率,是一种制作低成本压贴三棱镜的理想材料.利用金刚石切割工艺制作出精密的压贴三棱镜模版,模版的表面光洁度达到 14 级,并采用热压工艺,在温度为 180 ℃压力为 130 kg/cm^2 的工艺参数下制作出不同棱镜度数的压贴三棱镜样片,验证了以 PMMA 材料为基材、采用热压工艺制作压贴三棱镜的可行性.为了测试压贴三棱镜样片的实际棱镜度(Δ),自主设计并搭建了压贴三棱镜棱镜度测量系统.实验结果表明:对低(10Δ)、中(20Δ)、高(30Δ)三组压贴三棱镜样片的棱镜度测试结果与理论值的偏差分别为 0.01Δ、0.04Δ 和0.02Δ.所有样品的棱镜度偏差均符合国家医用棱镜的标准.因此,所制作的压贴三棱镜样片具有较高的光线偏折精度,为治疗儿童斜视疾病提供了一种高质量、低成本的产品方案.

关键词:菲涅尔棱镜;贴压三棱镜;斜视;透过率;棱镜度
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Design and Fabrication of Rigid Fresnel Prisms for Complex Treatment of Strabismus in Children

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Abstract: In this paper, we present our design of a rigid Fresnel prism and derive the calculations of its transmittance and distortion. The transmittance of prisms made of different kinds of polymers and their distortion were numerically simulated. Simulation results showed that polymethyl methacrylate (PMMA) had a larger Abbe coefficient and a lower material absorption rate than polyvinyl chloride (PVC). Then, on the basis of the simulation, stamps for the prisms were machined using the diamond-cutting method; the surface roughness of the stamps reached class 14. We verified that low-cost prisms can be fabricated from PMMA using the thermopressing method under the conditions of 180 ℃ and 130 kg/cm^2. A system was constructed to test the prism diopter (PD) values of the samples. Experimental results showed that the deviations between the

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calculated and actual PD values for 10Δ (low PD), 20Δ (medium PD), and 30Δ (high PD) prisms were 0.01Δ, 0.04Δ, and 0.02Δ, respectively. The PD deviations of the sample prisms all agreed with the Chinese tolerance standard for a medical prism. Hence, we verified that the rigid prisms fabricated in this study are sufficiently precise to reflect light and are a high-quality, low-cost solution for the treatment of strabismus in children.

Key words: Rigid Fresnel prisms; Press-on prisms; Strabismus; Transmittance; Prism diopter

OCIS Codes: 230.5480; 170.4460; 220.4840; 330.1400

0 Introduction

Strabismus is an eye disease common in children, in which, according to a survey, the incidence rate is close to 5%[1]. Strabismus can seriously affect the physical and mental health of children, so early treatment is very important[2]. Eyeglasses with rigid Fresnel prisms are prescribed for children at least two years of age, when, according to current understanding, the active development of the visual system (including binocular interaction) commences. The prisms promote the formation of normal binocular connections long before surgical intervention is used when the patient is an adult[3]. Some strabismus patients are not suitable for surgical treatment for medical reasons[4]. Therefore, a good solution for these cases is to wear glasses made of rigid or press-on Fresnel prisms in combination with other methods for the complex treatment of strabismus[4-5].

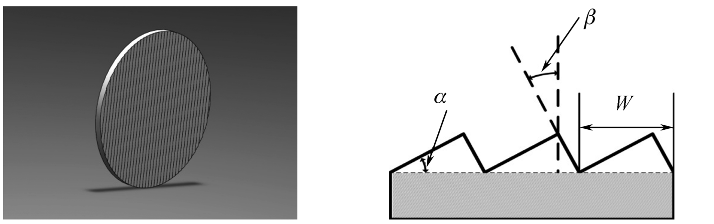
Compared to traditional prisms, Fresnel press-on prisms have many advantages, including their light weight and ease of use[6-7]. The two most well-known brands of Fresnel press-on prisms are the 3M prism (USA) and the Trusetal prism (Germany)[8]. The 3M™ Press-on™ Prism is made of polyvinyl chloride (PVC)[6,9], which has a high refractive index but a small Abbe coefficient ($k_{AB}=34$)[10]. Thus, the dispersion phenomenon of PVC is relatively obvious and results in a decrease in the acuity of a patient while wearing these prism eyeglasses[6-7,11].

The Institute for Information Recording, NAS of Ukraine, was the first to produce the rigid Fresnel prism made of PMMA in 2009[7]. PMMA has a higher Abbe coefficient ($k_{AB}=57.53$) and better transmittance in visible light than does PVC[10]. Since 2014, our research group at Zhejiang University of Technology has collaborated with the Institute for Information Recording, NAS of Ukraine, to study and promote the key techniques of rigid Fresnel prisms in China[6,10-11]. This paper reports the progress on the design, fabrication, and testing of these prisms in China.

1 Design and numerical simulation of a rigid Fresnel prism

1.1 Device design

As shown in Fig. 1(a), a rigid Fresnel prism is a disc with a series of grooves in its surface. Fig. 1(b) shows the section of a rigid prism designed using the Fresnel principle. The refractive angle α, reverse angle β, and relief pitch W determine the design of the rigid prism, and α determines the prism diopter (PD). The dependence of PD on α and on the refractive index n of a material is discussed in section 1.2. The transmittance of the prism is affected by β, the optimal value of which is 2°～3°[7]. The diffraction phenomenon in the prism is caused mainly by a small W[8,11]. Thus, the best range for W is 600～800 μm[11].



(a) Model of a rigid Fresnel prism (b) Cross section of a rigid Fresnel prism

Fig.1 Model of a rigid Fresnel prism and the cross section of a rigid Fresnel prism

1.2 Theoretical model of prism diopter

A rigid Fresnel prism can have Outward Prism Serrations (OPS) [Fig. 2(a)] or Eyeward Prism Serrations (EPS) [Fig. 2(b)][12]. When a light beam passes through an OPS prism, it is deflected and the relationship between the PD and α is determined by Snell's law and is written as[12]

$$\mathrm{PD}_{\mathrm{OPS}} = 100 * \tan\left(\arcsin\left\{n * \sin\left[\alpha - \sin\left(\frac{\sin\alpha}{n}\right)\right]\right\}\right) \tag{1}$$

Similarly, for an EPS prism, the relationship between the PD and α is written as

$$PD_{EPS} = 100\tan[\arcsin(n\sin\alpha) - \alpha] \quad (2)$$

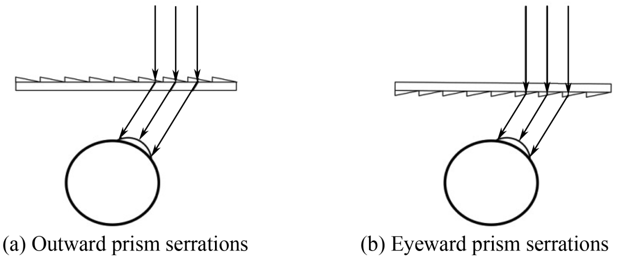


Fig.2 Rigid Fresnel prism with outward prism serrations and eyeward prism serrations

We chose to use polymethyl methacrylate (PMMA) for our rigid Fresnel prism. Thus, n, which is in Eq.(1), is in the range of 1.48～1.50 for visible light[13]. For calculations, n is usually 1.492[10].

Fig. 3 shows the relationship between α and the PD of the OPS and EPS prisms made of PMMA. The calculated PDs obviously differ when $\alpha > 25°$.

Because a high-PD rigid Fresnel prism with EPS has obvious visual field loss[14], only OPS prisms are discussed in this paper. Table 1 presents the calculated values of α for OPS prisms with different PDs.

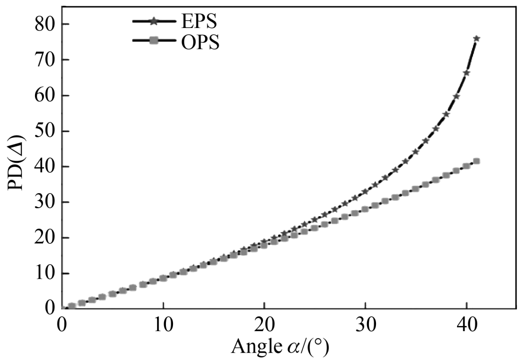


Fig.3 PD as a function of α for rigid Fresnel prism made of PMMA

Table 1 Angle α for an OPS rigid Fresnel prism with different PDs

OPS PD (Δ)	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
Angle α/(°)	2.33	4.65	6.96	9.25	11.51	13.74	15.94	18.09	20.20	22.26	24.27	26.23	28.13	29.98	31.77

1.3 Theoretical model of transmittance

Transmittance, an important parameter of the rigid Fresnel prism, is directly related to the loss of light when it passes through the prism. Absorption and reflection of light by the surface of the prism cause the loss of light. A rigid Fresnel prism is approximately 2.4 mm thick, so light loss due to absorption may be ignored because of a low absorption coefficient of 0.02 cm^{-1} in the visible light region[15].

Light is reflected by the surface of a rigid Fresnel prism three different ways, as described below.

Fig. 4(b) shows the reflection of face AB, where the rate of light loss is characterized by k_1. Using the Fresnel formulas, k_1 can be determined as

$$k_1 = 0.5 \times \left[\frac{\tan^2\theta}{\tan^2(2\alpha - \theta)} + \frac{\sin^2\alpha}{\sin^2(2\alpha - \theta)}\right] \quad (3)$$

where θ is the first deflection angle and α is the refractive angle of rigid Fresnel prism, as shown in Fig. 4(a).

Fig. 4(c) shows the reflection of face AC, where the rate of light loss is characterized by k_2, which is defined as

$$k_2 = 0.5 \times \left[\frac{\tan^2(\gamma - \theta)}{\tan^2(\gamma + \theta)} + \frac{\sin^2(\gamma - \theta)}{\sin^2(\gamma + \theta)}\right] \quad (4)$$

where γ is the second deflection angle, as shown in Fig. 4(a).

Fig. 4(d) shows the reflection and transmission of face BC. The light in the area BE does not contribute to useful imaging, and for a rigid Fresnel prism with a high PD, the light reflected by face BC would cause monocular visual confusion[10]. Therefore, the reflection and transmission of face BC cause light loss, the rate of which is characterized by q and defined as

$$q = FC/AC = (\tan\alpha\tan\theta)(1 + \tan\alpha\tan\theta) \quad (5)$$

Therefore, the transmittance of the Fresnel prism is[9]

$$T = (1 - k_1)(1 - k_2)(1 - q) \quad (6)$$

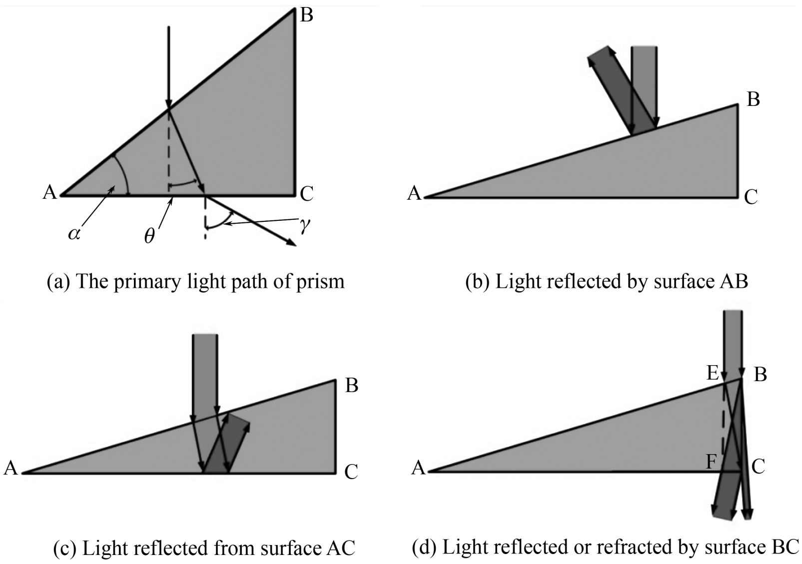


Fig.4 Beam path and the loss of light on the relief of a rigid Fresnel prism

According to Eqs. (3)～(6), the relationship between the transmittance and prism diopter can be calculated. Fig. 5 shows that as PD increases, the transmittance of the prism decreases. In addition, the transmittance of the rigid Fresnel prism made of PMMA is higher than that of prisms made of PVC and polystyrene (PS) when PD⩽25Δ.

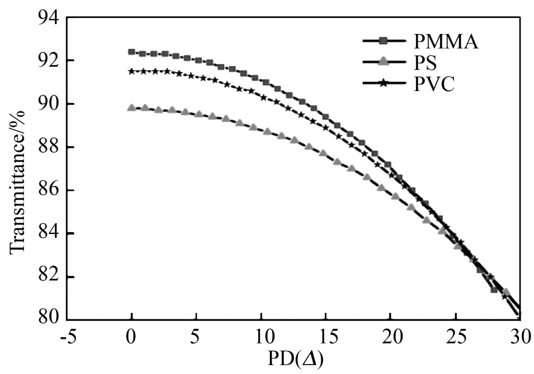


Fig.5 Relationship of transmittance and PD for rigid Fresnel prisms made of different materials

1.4 Theoretical model of distortion

The Fresnel prism is used to eliminate diplopia and help children form binocular vision[3]. The Fresnel prism distorts the image, so the normal eye and the oblique eye with the Fresnel prism receive different images, which hinders the fusion of binocular vision. Therefore, it is very important to study quantitatively the image distortion caused by the Fresnel prism.

The main cause of the distortion by the Fresnel prism is that the deflection angles of the incident light are different. As shown in Fig. 6, the light is incident on the prism at angles θ_L and θ_R, which, after the light passes through the prism, become θ'_L and θ'_R, respectively. However, θ'_L is not equal to θ_L and θ'_R is not equal to θ_R. Using Snell's law, θ'_L and θ'_R can be determined from formulas (7) and (8)

$$\theta'_L=\arcsin\left\{n\sin\left[\alpha-\arcsin\left(\frac{\sin\alpha}{n}\right)\right]\right\}-\arcsin\left\{n\sin\left[\alpha-\arcsin\left(\frac{\sin(\theta_L+\alpha)}{n}\right)\right]\right\} \tag{7}$$

$$\theta'_R=\arcsin\left\{n\sin\left[\alpha+\arcsin\left(\frac{\sin(\theta_R-\alpha)}{n}\right)\right]\right\}-\arcsin\left\{n\sin\left[\alpha-\arcsin\left(\frac{\sin\alpha}{n}\right)\right]\right\} \tag{8}$$

The distortion of the Fresnel prism, caused by θ'_L and θ'_R not being the same as θ_L and θ_R, can be expressed by formulas (9) and (10)

$$D_L(\alpha,n,\theta_L)=\frac{\partial\theta'_L}{\partial\theta_L}=\frac{-\cos\left[\alpha-\arcsin\left(\frac{\sin(\theta_L+\alpha)}{n}\right)\right]\cdot\cos(\theta_L+\alpha)}{\sqrt{\left(1-\left\{n*\sin\left[\alpha-\arcsin\left(\frac{\sin(\theta_L+\alpha)}{n}\right)\right]\right\}^2\right)\cdot\left[1-\left(\frac{\sin(\theta_L+\alpha)}{n}\right)^2\right]}} \tag{9}$$

$$D_R(\alpha,n,\theta_R)=\frac{\partial\theta'_R}{\partial\theta_R}=\frac{\cos\left[\alpha+\arcsin\left(\frac{\sin(\theta_R-\alpha)}{n}\right)\right]\cdot\cos(\theta_R-\alpha)}{\sqrt{\left(1-\left\{n*\sin\left[\alpha+\arcsin\left(\frac{\sin(\theta_R-\alpha)}{n}\right)\right]\right\}^2\right)\cdot\left[1-\left(\frac{\sin(\theta_R-\alpha)}{n}\right)^2\right]}} \tag{10}$$

where D_L and D_R denote the distortion of the image on the left and right sides after passing through the Fresnel prism at different angles, and the dividing line of the left and right sides is the vertical incident light ray. As shown in Fig. 6, θ_L and θ_R are the angles of the left and right incident rays, θ'_L and θ'_R are the angles of the left and right emitted rays, α is the refractive angle of rigid Fresnel prism, and n is the refractive index of the Fresnel prism material.

According to formulas (9) and (10), the distortion of the Fresnel prism can be determined by numerical simulation. Fig. 7 presents the distortion of the PVC and PMMA Fresnel prisms, both of which have PD=30Δ. The ordinate is the magnification of the image by the Fresnel prisms relative to the source image and the abscissa is the angle of incidence, where a negative angle indicates that the light was incident on the left side and a positive angle indicates that the light was incident on the right side. Fig. 7 shows that the image for both Fresnel prisms is gradually compressed from right to left. Compared to that of the PVC Fresnel prism, the image on the right side of the PMMA Fresnel prism is closer to the original image, while the image near 0° or on the left side of PVC Fresnel prism is closer to the original image. In general, in terms of distortion, the PMMA Fresnel prism is slightly worse than the PVC Fresnel prism.

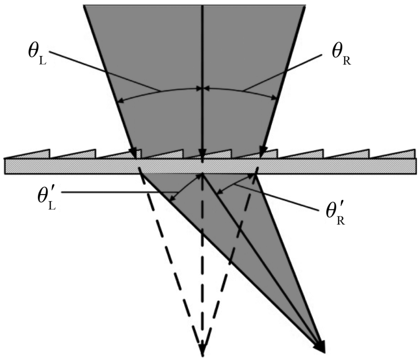


Fig.6 Distortion in the Fresnel prism

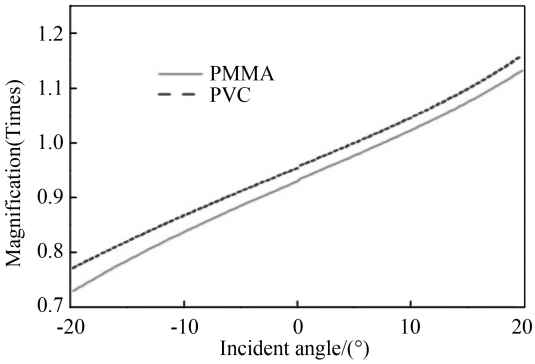


Fig.7 Distortion of Fresnel prisms made of PVC and PMMA

2 Fabrication and testing of rigid Fresnel prisms

2.1 Fabrication of rigid Fresnel prism samples

We fabricated a series of stamps for producing rigid Fresnel prisms with different PDs; all stamps had a surface roughness of class 14. The stamps were made of 7 075 aluminum alloy because of its appropriate mechanical properties. Because the stamps were to be used to thermopress blank PMMA discs with a small surface roughness, ultraprecision machining (UPM) was used to machine the stamps. Diamond cutting is an effective method in UPM because of its high rigidity, high capability as an arc-cutting tool of up to a few seconds, high thermal conductivity, low friction, and high resistance to wear[16].

Fig. 8 presents the fabrication process of the rigid Fresnel prisms. In the first stage [Fig. 8(a)], the prepared PMMA blank disc is fixed onto the base, which has mirror surface. In the second stage [Fig. 8(b)], a series of grooves are formed in the surface of the PMMA blank disc via simultaneous thermal treatment (at T=180 ℃) and pressure (P~130 kg/cm^2). The demolding temperature of the PMMA substrate is in the range of 50~60 ℃ and should not be >80 ℃[17]. Therefore, in the third stage [Fig. 8(c)], when the temperature is decreased to 70 ℃, the PMMA substrate separates from the stamp. Finally, in the fourth stage [Fig. 8(d)], the rigid Fresnel prism

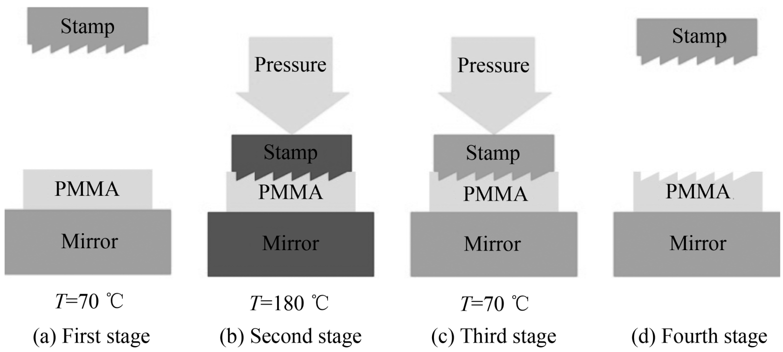
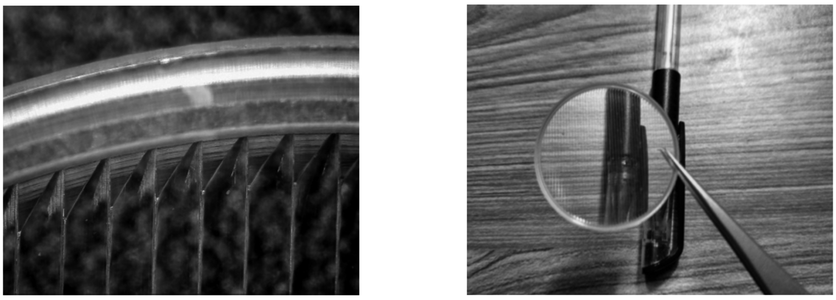


Fig.8 Fabrication of rigid Fresnel prism samples by thermopressing

sample is ready.

Fig. 9(a) shows the magnification of part of the rigid Fresnel prism (white spots on the background are the image of the object stage of the microscope). The rigid Fresnel prism sample demonstrated a good image-shifting effect, as shown in Fig. 9(b).



(a) Magnification of part of the sample (b) Image-shifting effect of the sample

Fig.9 Sample of a fabricated rigid Fresnel prism

2.2 Prism diopter test system

To test the PD of the prism samples, a testing platform was designed[18]. Fig. 10 shows the schematic diagram of the testing platform, and Fig. 11 is a photo of the testing platform in the lab. The testing platform works as follows: A He-Ne laser (λ=632.8 nm) has two polarizers that are set to weaken the laser beam; thus, a procedure to adjust the testing platform is needed. The rigid Fresnel prism sample is fixed at the sample holder. The laser beam is deflected as it passes through the prism. According to the definition of PD, the distance between the digital vernier caliper and the rigid Fresnel prism must be 1 m. A receiving photodiode is fixed on the slider of the digital vernier caliper. When testing the sample prism, the operator moves the photodiode by moving the slider. The operator stops moving the slider when the signal from the photodiode reaches its maximum value, i.e., the photodiode has detected the deflected laser beam. The operator then reads the measured value (in cm, with an accuracy of $\pm$0.001 cm) on the screen of the digital vernier caliper. The measured value is equal to the PD of the tested sample prism.

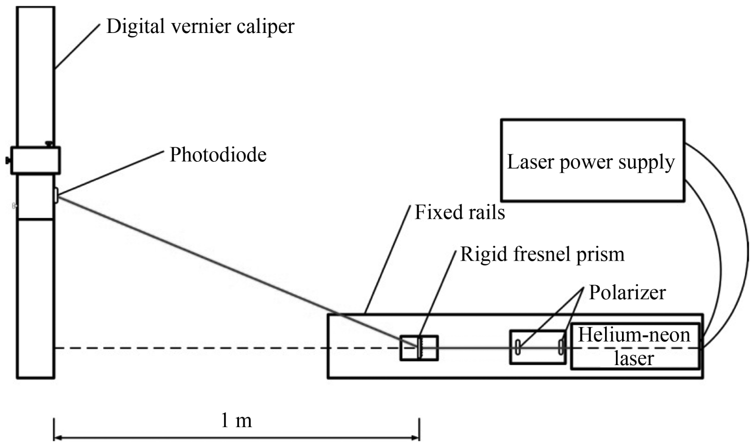


Fig.10 Schematic diagram of the prism testing system

2.3 Results of PD test of the samples

We tested the PD of three groups of sample prisms, with eight samples, numbered 1~8, in each group. The samples of the first group had a theoretical PD of 10Δ, that of the second group had a PD of 20Δ, and that of the third group had a PD of 30Δ, which represented the low, middle, and high values of PD, respectively. Table 2 presents the test results for the first group of samples, for which the average deviation between the theoretical and test values was 0.01Δ.

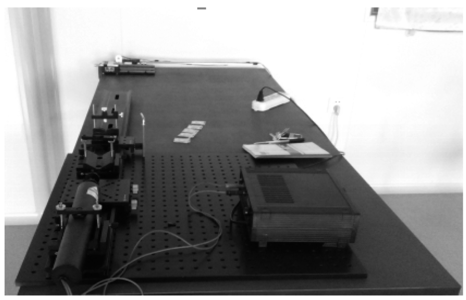


Fig.11 Photo of the prism testing system

Table 3 presents the test results for the second group of samples, for which the average deviation between the theoretical and test values was 0.04Δ. Table 4 gives the test results for the third group of samples, for which the average deviation between the theoretical and test values was 0.02Δ. The reported tolerance of the PD of a medical prism is ±0.25Δ[19]. The PD deviations of the samples were all within the Chinese national tolerance standard[19] for medical prisms. The test results verified that the prism samples were high quality and highly precise for reflecting light.

Table 2 Test results for rigid Fresnel prism samples with PD=10.0Δ

Sample No.	1	2	3	4	5	6	7	8	AVG
PD (Δ)	9.95	9.99	9.97	10.02	10.00	10.00	10.01	9.98	9.99
Deviation (Δ)	−0.05	−0.01	−0.03	+0.02	0.00	0.00	+0.01	−0.02	−0.01

Table 3 Test results for rigid Fresnel prism samples with PD=20.0Δ

Sample No.	1	2	3	4	5	6	7	8	AVG
PD (Δ)	19.97	19.99	19.96	19.97	19.96	19.96	19.95	19.92	19.96
Deviation (Δ)	−0.03	−0.01	−0.04	−0.03	−0.04	−0.04	0.05	−0.08	−0.04

Table 4 Test results for rigid Fresnel prism samples with PD=30.0Δ

Sample No.	1	2	3	4	5	6	7	8	AVG
PD (Δ)	30.01	30.04	30.00	30.08	29.99	30.02	29.96	30.02	30.02
Deviation (Δ)	+0.01	0.04	0.00	+0.08	0.01	+0.02	0.04	+0.02	+0.02

3 Conclusions

In this paper, we presented our design of a rigid Fresnel prism and analyzed the relationship between the PD and the angle α. The method of calculating the transmittance and distortion of the rigid Fresnel prism in theory was proposed. Results from numerical simulation showed that a PMMA rigid Fresnel prism has a higher transmittance but greater image distortion than a PVC prism. On the basis of these results, we fabricated stamps using the diamond-cutting method and used them to manufacture samples of rigid Fresnel prisms using thermopressing. Tests of the prismatic force (PD units) and transmittance of the sample prisms showed that the PD deviation of the samples and their transmittance were within the Chinese national tolerance standard for medical prisms. However, there are still many technical challenges to improving the quality of our rigid Fresnel prism. In the future, we may use a different material, such as nickel alloy, to machine the stamps.

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