Measurement of the applanated diameter of ocular cornea using a novel optical probe*

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A precise measurement of the applanated diameter of the ocular cornea with the optical probe is very important in applanation tonometry. A novel optical probe with a common path configuration is presented. The optical probe mainly consists of a cone-shaped prism and a photodetector. The former serves as a measuring body touching the ocular cornea to shape the area to be measured, and the latter converts the quantity of the luminous flux returning from the cone-shaped prism into one electronic current signal. Laboratory experiments are carried out on a simulated eyeball, followed by an enucleated porcine eyeball specimen. Experimental results show that there is a significant rise of the normalized variational current with increasing the applanation diameter of the ocular cornea, and the sensitivity is 0.2111/mm with an error of 0.00263/mm. Measurements of the normalized variational current on the porcine eyeball have good agreement with those on the simulated eyeball.

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Applanation tonometry is the widely accepted and generally preferred method for measuring intraocular pressure (IOP)[1-4]. The basic principle of applanation tonometry relies on the Imbert-Fick law, which states that the force to applanate the anterior corneal surface is equal to the true IOP multiplied by the applanated area at the posterior corneal surface[5, 6]. Thus, the applanation tonometers measure either the force required to applanate a given area of the ocular cornea or the area flattened by a fixed force[7].

To accomplish the measurement of the applanated area of the ocular cornea, several applanation tonometers usually employ an optical probe to detect the applanated diameter of the ocular cornea firstly[8-10]. An optical probe, which includes an applanation prism consisting of two semi-cone prisms, is used in Goldmann applanation tonometer. With the help of corneal fluorescein dye and a slit lamp biomicroscope, a skilled operator can determine the applanation diameter during Goldmann applanation tonometry[11]. These optical probes can achieve effective applanation diameter measurement, but they are either cumbersome as the optical probe of the Goldmann applanation tonometer or complicated as that of the non-contact tonometer[12].

In this paper, we introduce a new optical probe with a common path configuration for measuring the applanation diameter of the ocular cornea. The relation between the output current of the optical probe and the applanated diameter of the ocular cornea is presented, and the reproducibility of the optical probe measurement is demonstrated.

The optical probe consists of two major components, a cone-shaped prism and a photodetector (PD). The setup configuration is illustrated in Fig.1. A white light bulb is placed at the focal plane of the converging lens. The parallel light emerging from the lens passes through a beam splitter (BS) plate and a shield plate (with a radius of 2.20 mm) by which the light beam that arrives at the bottom surface directly from the top surface of the cone-shaped prism is obstructed. By utilizing a cylindrical lens, the reflected beam returning from the cone-shaped prism is imaged onto the PD, where the silicon photocell outputs an electrical signal corresponding to the luminous flux returning from the cone-shaped prism. In this optical probe, the cone-shaped prism acts as the measurement body touching the ocular cornea to shape the area

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to be measured during the applanation tonometry.

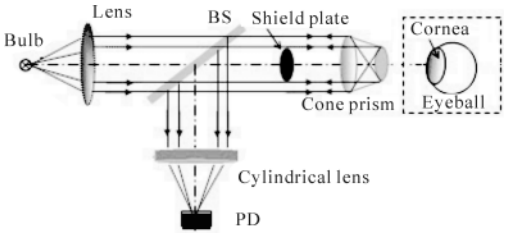

Fig.1 Schematic representation of the proposed optical probe

The schematic diagram of the cone-shaped prism with a taper θ_1 (60°) is shown in Fig.2. Using the total internal reflection principle[13], the cone-shaped prism is designed. D_1(10.40 mm) and D_2(4.40 mm) are the diameters of the top and bottom surfaces of the cone-shaped prism, respectively.

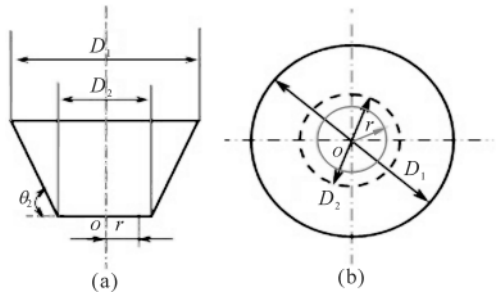

Fig.2 Schematic diagram of the cone-shaped prism: (a) Side view; (b) Plan view

The luminous flux of the circle with an arbitrary radius r on the applanation surface (i.e., the bottom surface of the cone-shaped prism) can be expressed by

$$\phi(r) = 2\pi D_2 I_0 \cos\theta_1 (1+\cos\theta_1)\, r = kr\,, \tag{1}$$

where I_0 is the intensity of the incident light, and the constant $k=2\pi D_2 I_0 \cos\theta_1(1+\cos\theta_1)$. Eq.(1) indicates that the distribution of luminous flux on the applanation surface is a linear function of the applanation radius. Thus, when the cone-shaped prism is not in contact with the cornea of the eyeball, it is known that the luminous flux (φ_0) received by the PD equals the total luminous flux (ψ) entering the cone-shaped prism, i.e.,

$$\varphi_0 = \psi = \phi\,(D_2/2) = kD_2/2\,. \tag{2}$$

However, when the cone prism is in contact with the eyeball, on the flattened portion of the eyeball, there is no reflection or only a weak one because most of the light enters the eyeball. If the medium absorption is not considered, the received luminous flux through the PD can be written as

$$\varphi_1 = \psi - R_t \phi\,(r) = \psi - R_t kr\,, \tag{3}$$

where R_t is the refraction coefficient of the cone prism versus the cornea. Thereby, the corresponding luminous flux can be described as

$$1-\varphi_1/\varphi_0 = 2rR_t/D_2 = dR_t/D_2\,, \tag{4}$$

where d is the applanated diameter of the flattened area. From Eq.(4), we know that the corresponding luminous flux is proportional to the applanated diameter of the ocular cornea. Therefore, the output current signal of the optical probe, properly calibrated, may give the size of the applanated diameter during applanation tonometery.

A tailor-made simulated eyeball made out of silicone and an enucleated porcine eyeball are used in the current experiments, respectively. Both experiments are carried out at room temperature. The porcine eyeball is used due to its relative similarity to the human eyeball in structure and its availability in great numbers. After careful removal of excessive external fascia and extra-ocular muscle attachments, six specimens of the porcine eyeballs are placed in optisol (a high-quality preservation medium) and stored at 4°C before the operation is performed. With an ophthalmometer, the anterior corneal surface curvature of the specimens is accurately measured. A porcine eyeball, with anterior corneal surface curvature radius of 7.8 mm and without ocular diseases, is selected for the experiments.

In order to explore the relation between the output current of the optical probe and the applanated diameter of the ocular cornea, the experiment is firstly carried out on the simulated eyeball with a curvature radius of the anterior cornea of 7.8 mm. The simulated eyeball is securely mounted on a straight guide way where an optical probe is also firmly fixed. The eyeball is coated with a film of mineral oil. A central alignment between the eyeball and the cone-shaped prism is initially achieved. The eyeball could be driven along the guide way towards the cone-shaped prism by a motorized linear displacement actuator which has displacement step as small as 1 nm. The displacement of the actuator (i.e., applanation height h) is precisely controlled at a stepwise increment of 0.01 mm ranging from 0 to 0.16 mm. Over each applanated height, six repeated measurements are performed. The data related to the applanated height, such as output current, is recorded for later analysis. In the experiment, a spray is used to minimize drying of the simulated eyeball. A small water tray is placed beside the guide way to increase the local humidity.

A normalized variational current is defined as $(I-I')/I = \Delta I/I$, where I is the maximum value of the output current of the PD when the cone prism is not in contact with the ocular cornea, I' is the value of the output current when the cone prism is flattening the ocular cornea, and ΔI represents the diminished quantity of the current value. The applanated diameter related to the applanated height can be obtained through the conversion equation[14],

$$d = 2(2Rh - h^2)^{1/2}, \quad (5)$$

where R is the curvature radius of the anterior cornea.

The mean of six normalized variational currents associated with each applanated height is computed, and then is plotted against the applanated diameter of the ocular cornea, as shown in Fig.3. The least square linear regression yields a slope of 0.2111/mm, with an error of 0.0263/mm, and an intercept of 0.00309, with an error of 0.00086. Such an error of 0.00309 ± 0.00086 attributed to the effect of medium absorption around the cone-shaped prism is regarded to be in the acceptable range. This test result on the simulated eyeball shows that the normalized variational current linearly rises with increasing the applanation diameter of the ocular cornea, and the sensitivity is 0.2111 ± 0.00263/mm. Therefore, the normalized variational current can give the size of the applanated diameter of the ocular cornea during the simulated eyeball test. For example, when the normalized variational current rises to 0.65, the corresponding applanated diameter of the ocular cornea is 3.06 mm.

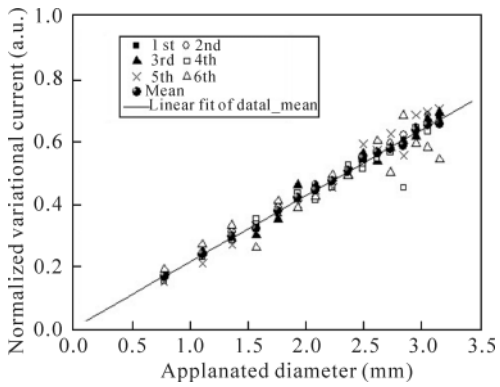

Fig.3 Normalized variational current versus applanated diameter (Regression: y=0.00309+0.2111x, correlation coefficient: r = 0.99883, standard deviation (SD): ± 0.00918)

Using the same test procedure as that of the simulated eyeball, another investigation is carried out on the enucleated porcine eyeball to examine the reproducibility of the optical probe measurements. The porcine eyeball measurements (y-axis) are plotted against the simulated eyeball measurements (x-axis) in Fig.4. The correlation coefficient is 0.97895 and the slope is 0.97581. The experimental results demonstrate that there is a strong correlation between the normalized variational currents measured on the porcine eyeball and the simulated eyeball (P< 0.0001), which indicates that no significant difference exists in the practice. In Fig.4, it is found that the normalized variational current measured from the porcine eyeball is slightly larger than that from the simulated eyeball only in the lower interval. The reason could be interpreted as follows: during an initial measurement stage, the intrinsic hydration of the porcine ocular cornea similar to the human ocular cornea creates a larger and flattened area than the actual situation[15], which makes the normalized variational current larger.

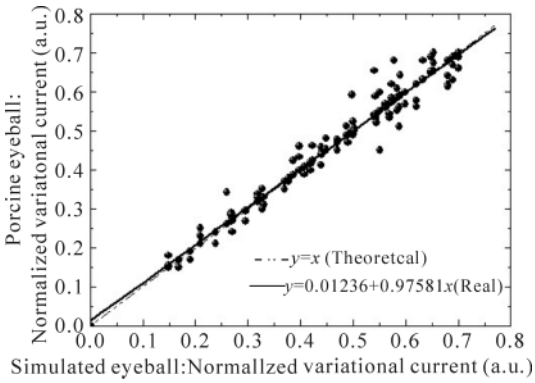

Fig. 4 Correlation between normalized variational currents measured from the porcine eyeball and the simulated eyeball

In conclusion, a new optical probe with a common path configuration is introduced in this paper. Compared with the existing optical probes in several applanation tonometers, it is simpler in the structure, easier to use, and cheaper in expense. Experimental results on a simulated eyeball show that there is a significant rise of the normalized variational current with increasing the applanation diameter. Measurements of the normalized variational current on an enucleated porcine eyeball demonstrate the optical probe's reliability in the practice. The optical probe may be very useful for us to construct a low-cost and miniatured applanation tonometer. Further study, including clinical trials and application, is required to evaluate the accuracy and usefulness of this optical probe on measuring the applanated diameter of the human ocular cornea.

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