Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

Eye Stiffness Measurement by Probe Contact Method

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***Abstract*— The internal eye pressure is an important index for judging whether an eye suffers from glaucoma or not. The conventional eye pressure measurement is valid only under the condition that all subjects have the same structural eye stiffness. This paper challenges the practice of measuring the stiffness of a human eye by pressing the cornea with a contact probe. The displacement of the eye is captured by a camera with high resolution. Experimental results suggest that the measured eye stiffness nicely matches with the theoretical estimation. Based on the experimental results, the difference between the eye stiffness measured by the contact method and the non-contact method is discussed.**

***Index Terms*—** *Eye Stiffness, Contact Method, Spherical Eye Model, Glaucoma.*

I. INTRODUCTION

An increased internal eye pressure may damage the eye nerve system of the retina. The subsequent partial death of the eye nerve system causes gradual loss of the patient's eye sight. In the worst case, the patients completely lose their eye sight. This disease is called glaucoma. Today, there is no essential medical treatment for recovering the lost eye nerve system. An effective treatment to avoid a further progress of glaucoma is decreasing the internal eye pressure by either an eye lotion or a medical operation. In addition to the observation of the abnormality of the eye sight or the optic papilla, the measurement of the internal eye pressure is very important to judge whether the eye suffers from glaucoma or not.

Fig. 1 shows an overview of the eye pressure measurement. There are two kinds of the eye pressure measurement method. The basic working principle is shown in Fig. 2. Fig. 2(a) shows a contact method where the eye is deformed by a rigid probe, and (b) shows a non-contact method where the eye is deformed by an air jet. The contact method [1] provides us with a good example of static based sensing, where a medical doctor presses a rigid probe to an anesthetized eye until the cornea deforms to a prescribed value (circle with a diameter of 3.06[mm]). The conventional eye pressure estimation is valid only under the assumption that all subjects have the same structural eye stiffness. However, it is well known that the cornea thickness affects the estimation of the eye pressure [2], [3], [4]. Some works have also measured the elasticity of the cornea in vitro and shown the individual differences [5], [6]. Considering the difference of the cornea properties, some statistical correction methods have been proposed [7], [8].

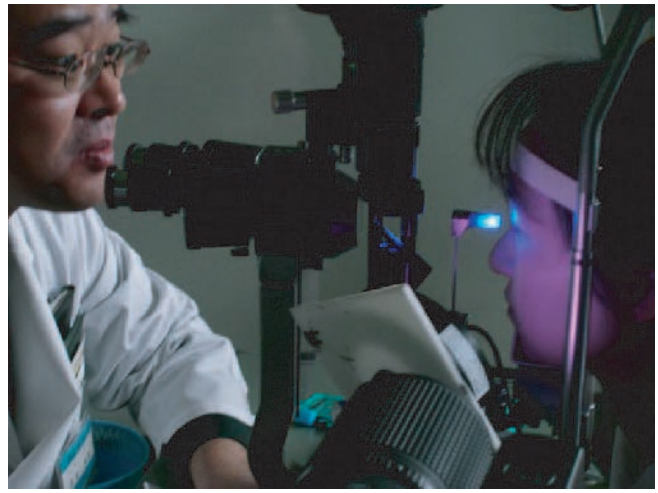

Fig. 1. Contact probe based eye pressure measurement

The total stiffness of a human eye including the structural stiffness can be measured if both the applied force and the displacement are known. Kaneko et al. [9], [10] have captured the dynamic deformation of the cornea and measured the eye stiffness. In their experiment, an air jet has been used for applying the force to the cornea. Because it is difficult to measure the actual applied force on the cornea in real time, they have calibrated the force worked on a prescribed area by the air jet in advance and used the calibrated force as the applied force. However, they have not shown the clear guideline how to prescribe the area affected by the air jet. When we prescribe a different area for computing the applied force, the eye stiffness varies even for the same eyes.

In this paper, a simple spherical eye model is proposed and the analytical eye stiffness is calculated. In order to evaluate the validity of the model, the eye stiffness of a human eye is measured in vivo by using the contact method. Finally, the reason of the difference between the eye stiffness measured by the non-contact method and that by the contact method is discussed.

This work was partially supported by JSPS the 21st Century COE program: "Hyper Human Technology toward the 21st Century Industrial Revolution".

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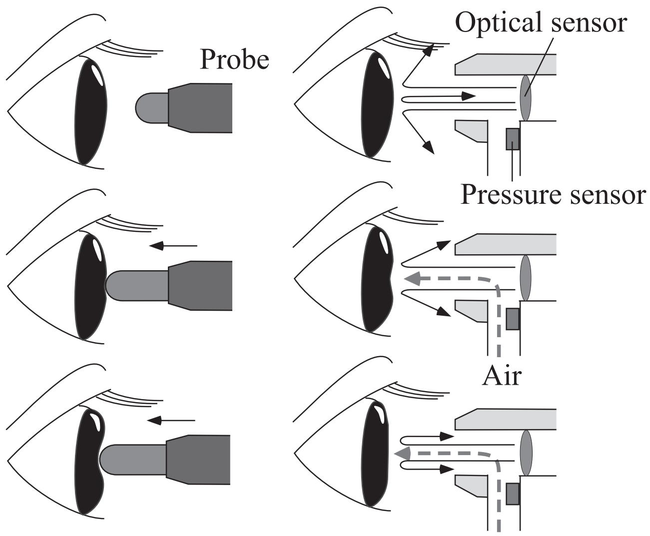


(a) Contact method (b) Non-Contact method

Fig. 2. Two measurement methods of eye pressure

II. Spherical Eye Model

Several works deal with accurate models of a human eye for more precise diagnosis of eye diseases by using FEM models [11], [12]. However, the result of the simulation has not been compared with the experimental result of a real human eye.

In this paper, a simple spherical eye model that has internal pressure p is considered, as shown in Fig. 3 where $R, f, x, A,$ and r are the curvature radius of the cornea, the applied force, the displacement of the cornea, the deformed area due to the applied force, and the radius of the deformed area.

Let us assume that the eye does not change its internal pressure by the deformation and the cornea has neither bending stiffness nor flexibility.

From Fig. 3(b), we can formulate the following geometrical relationship:

$$R^2 = (R - x)^2 + r^2. \tag{1}$$

Assuming x is sufficiently smaller than R, we can derive the following relationship among $r, R,$ and x:

$$r^2 \simeq 2Rx. \tag{2}$$

Multiplying both sides by πp and using $\pi r^2 = A$ results in

$$f = pA = 2\pi Rpx. \tag{3}$$

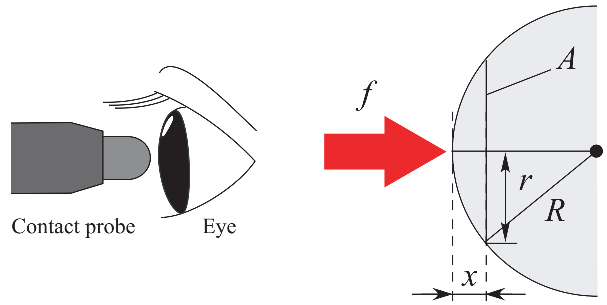
From eq. (3), the analytical eye stiffness k is derived by the following equation:

$$k = \frac{f}{x} = 2\pi Rp. \tag{4}$$

Eq.(4) indicates that the eye stiffness k is proportional to the internal pressure p.

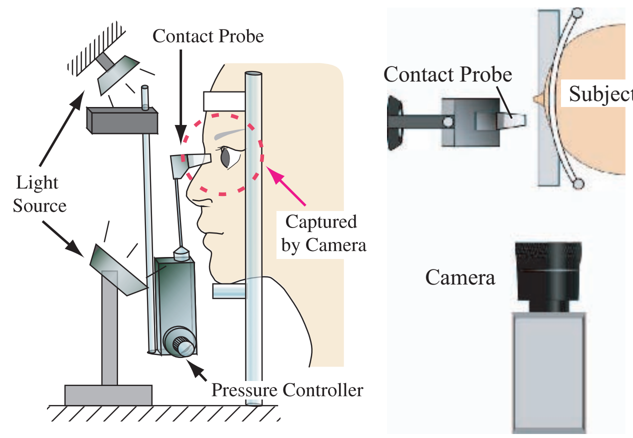
For example, from eq. (4), the eye with a cornea curvature of $R = 8$[mm] and an internal pressure of $p = 20$[mmHg] has the following eye stiffness:

$$k = 2\pi Rp = 2\pi \times 8 \times 10^{-3} \times 20 \times 133 \simeq 130\text{[N/m]}. \tag{5}$$



(a) Actual (b) Spherical model

Fig. 3. Model of human eye



(a) Side view (b) Top view

Fig. 4. Experimental system

These discussions provide us with a good hint for evaluating the validity of experimental results.

III. Experimental System

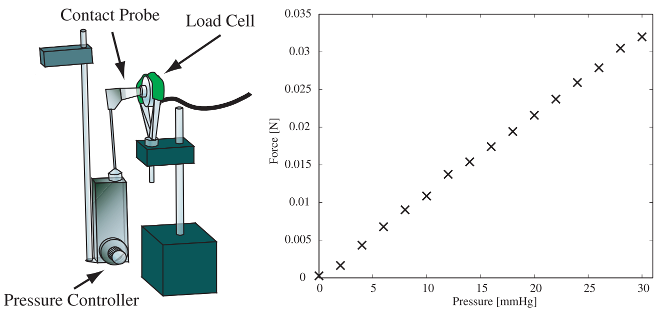
A. System Configuration

The constructed experimental system is composed of a contact-type eye pressure measurement system and a high resolution camera. The contact-type eye pressure measurement system uses a contact probe to deform the anesthetized cornea. The deformation of the cornea is captured by a high resolution camera (Flovel co., Ltd.: ADP-210B). The camera has the spatial resolution of 5.6[μm/pixel] and the image size of 1600×1200[pixels].

Fig. 4(a) and (b) show the side and the top view of the experimental system, respectively. The camera is set up perpendicular to the axial direction of the subject's eyes and additional light sources are installed to ensure sufficient illumination for the measurement.

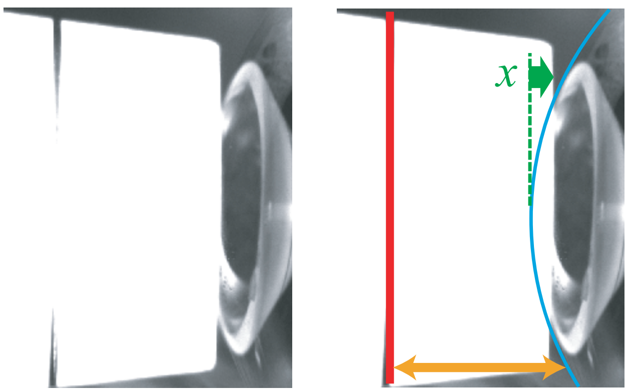
B. Force Calibration

The applied force by the contact probe is measured by a load cell prior to the experiment. Fig. 5(a) shows the overview of the force calibration system. The pressure value can be controlled by rotating the dial connected to the probe link for applying the force to the cornea. The relationship



(a) Overview of calibration system (b) Relationship between pressure value and applied force

Fig. 5. Force calibration



(a) Raw image (b) Detection of tip displacement

Fig. 6. Captured image

between the pressure value and the applied force on the load cell is shown in Fig. 5(b) where a highly linear relationship can be observed.

C. Displacement of the cornea tip

The deformation of the eye is captured by a camera. Fig. 6(a) shows a captured image. Because the subject slightly moves during the experiment, the detection method of the displacement should consider the change in a position of the eye. In this paper, the edge of the corneal surface is detected and the displacement of the corneal tip is calculated based on the position of the corneal edge and the contact probe. Now the distance between a dark line on the probe (the red line in Fig. 6(b)) and the fringe of the cornea (the blue line) is used to obtain the displacement. Although the tip of the cornea is deformed by the contact of the probe, the fringe is hardly deformed. Since the line on the probe can be clearly observed in the captured images, the displacement of the cornea tip can be computed by utilizing the distance between the line and the fringe edge.

IV. Experiment

A. Subjects

11 subjects aged 23∼34 years old (8 males and 3 females) participated in the experiment. The contact probe was controlled by a medical doctor. The overview of the experiment

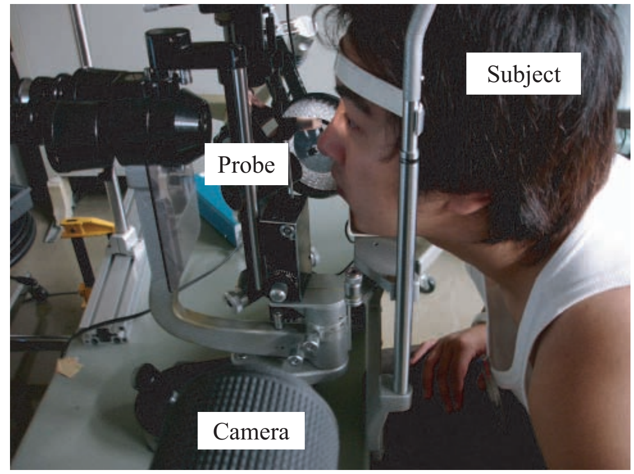


Fig. 7. Overview of experiment

is shown in Fig. 7. In the experiment, the pressure is applied to the cornea in steps of 5[mmHg] from 10 to 30[mmHg].

B. Experimental results

The displacement of the corneal tip is measured for each pressure application. Six representative examples of the relationship between the applied pressure and the tip displacement are shown in Fig. 8. Each line in the figures is computed based on the minimum mean square error. We can clearly observe a linear relationship. Because the pressure value is proportional to the applied force as shown in Fig. 5(b), this nicely agrees with the analytical relationship between f and x shown in eq. (3).

The slope of the approximation line in Fig. 8 is highly correlated with the stiffness of the eye. In this study, the contact eye stiffness $k_{contact}$ is defined by the increase of the displacement and the applied force:

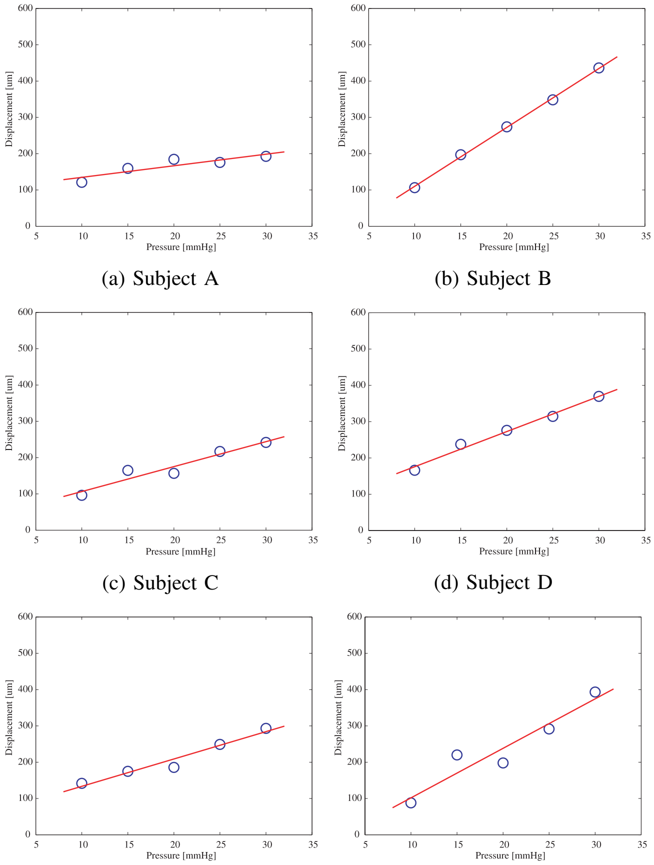
$$k_{contact} = \boldsymbol{\Delta} f / \boldsymbol{\Delta} x \tag{6}$$

where $\boldsymbol{\Delta} f$ is the increase of the applied force and $\boldsymbol{\Delta} x$ is the increase of the displacement. Fig. 9 shows the computed contact eye stiffness for all the subjects.

V. Discussion

Our experimental results show that the contact eye stiffness is about 60 $\sim$ 350[N/m]. On the other hand, Kurita et al. have shown that the cornea displacement at the force application of 0.034[N] by an air jet is 9.86 $\sim$ 56.7[μm] [10]. Calculated stiffness based on their data lies in the range of 600 $\sim$ 3500[N/m], which is 10 times as large as our contact stiffness.

Now let us consider the reason why such a difference can be observed. In the contact method, when the probe touches the cornea surface, a large pressure operates on the contact surface because the contact area is small. In the non-contact method, however, when an air jet is applied on the cornea, the air disperses and affects the cornea surface in a wide area. Therefore, the operated pressure on the cornea tip by the air jet does not become large. This suggests that, if the



(a) Subject A (b) Subject B

(c) Subject C (d) Subject D

(c) Subject E (d) Subject F

Fig. 8. Cornea displacement with respect to applied pressure

same force is applied on the prescribed area, the contact method may be able to deform the cornea more easily than the non-contact method. Accordingly, the measured stiffness by the non-contact method becomes larger than that by the contact-method.

Note that the measured eye stiffness does not simply indicate that the cornea stiffness is individually different. The eye stiffness defined in this study is definitely affected by both the structural stiffness of the eye, which includes the cornea stiffness and thickness, and the internal eye pressure. The investigation of the effect of the structural stiffness will be included in our future works and it leads to a better estimation of the true internal eye pressure.

VI. Conclusion

This paper made a simple spherical eye model and estimated the eye stiffness with respect to the eye pressure. The stiffness of a human eye was measured by using a contact probe. We discussed the difference between the eye stiffness measured by the non-contact method and that by the contact method.

What we have done in this paper can be summarized as follows:

- The deformation measurement system of a human eye composed of a contact-type eye pressure measurement system and a high resolution camera was developed.

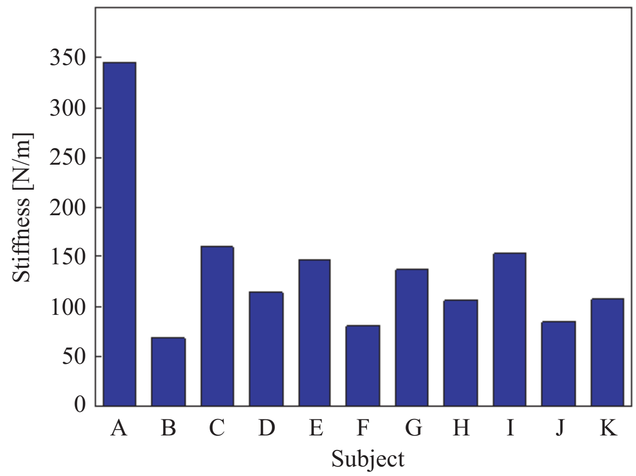


Fig. 9. Eye stiffness measured by contact method

- The eye stiffness was measured in vivo.
- Linear correlation between the applied force and the displacement of the cornea was observed.

For future works, we will conduct the experiment with a large number of subjects for the further investigation.

VII. Acknowledgements

Authors are thankful for Mr. Hiroshi Koizumi (TOPCON corporation) for his meaningful comments on our experiment.

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