Intraocular Pressure Monitoring Using Moiré Patterns Generated from a Contact Lens

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Abstract
Intraocular pressure (IOP) is a critical indicator in the diagnosis of glaucoma. It is known that 1 mmHg of IOP may induce a change of 3 µm in the radius of curvature of cornea. In this work the variation of the radius of curvature of cornea is obtained by characterizing the moiré fringes generated from a wearable soft contact lens. The contact lens is made of two layers; each layer has a circular grating. The measured results prove the effectiveness of the IOP monitoring method.

1. Introduction
The causes of glaucoma disease are complex, and abnormal IOP may lead to the damage of the optic nerve, causing blindness in the worst case. Hence, the monitoring of IOP is vital to a glaucoma patient. IOP can be measured by invasive and non-invasive methods. Using ocular implants [1] is the common invasive method while using air puff tonometry [2], Goldmann tonometer [3], and contact lens are also well known as non-invasive methods of measuring IOP. Abrupt increase in IOP is known to lead to the aggravation of the glaucoma disease. Therefore, continuous monitoring of the variation of IOP is required. Most of the methods, however, cannot be used for such a vital situation. Recently, a contact lens embedded with micro-inductor sensors [4] was reported to relate the radius variation of the corneal curvature to the inductance values. In this work, a contact lens generating moiré fringes is used for the monitoring of IOP variations. The design principle and the fabrication method will be described, and followed by the measured results.

2. Sensor Design and Fabrication
1. Sensor design
The increase of IOP may induce more aqueous humor in the anterior chamber, leading to the pressure increase of the chamber and the subsequent radius variation of the cornea. It is known that when the pressure of the chamber is increased by 1 mmHg, the radius of the cornea is changed by 3 µm. To measure the radius variations of cornea, a contact lens with double-layer structure is proposed. Fig. 1 shows the schematic structure of the contact lens which consists of two layers. The two-layer structure is designed so that when subjected to IOP variation, the pattern will vary and the amount of variation can be characterized and used as an indicator for the change of IOP. The inner layer of the contact lens is composed of hydroxyethyl methacrylate (HEMA) material. HEMA is a popular copolymer widely used for the manufacturing of soft contact lenses. The hydrophilicity of the inner layer is good for fitting and bending with the circumference of the cornea. The outer layer to be used as a reference layer for producing moiré fringes is made from polydimethylsiloxane (PDMS), a hydrophobic material. Due to its hydrophobic characteristic, the outer layer is not easily stick to the inner layer, preserving a gap between the two layers, and allowing the inner layer to be bent freely with the cornea surface.

Fig. 1 A double-layer structured contact lens.

Fig. 2 Concentric circle grating observed by optical microscopy.

2. Fabrication
Both layers of the contact lens are made by molding method. The concentric circle gratings are initially made on a mold by precision machinery. Then HEMA material is dropped into the mold and followed by UV light curing to produce the inner layer, and the process is repeated but with the use of PDMS and curing agent for the outer layer. Fig. 2 shows the concentric circle grating on the contact lens observed by an optical microscope, and the period of the gratings is seen 40 µm.

(a)  (b)
Fig. 3 (a) The simulation result of the moiré fringes on the contact lens used as sensor, (b) the measured moiré fringes captured by a digital microscope.

After being peeled off from the mold, the two layers are superimposed to produce moiré fringes. Fig. 3 (a) shows the simulation result of the moiré fringe on the contact lens sensor, and Fig 3 (b) shows the moiré fringe image captured by a digital microscope.

3. Measurement results
To verify the relationship between the variations of moiré fringes with the changes of IOP, an artificial cornea model is made, in which the radius of the cornea can be varied by injecting the controlled amount of water into the chamber of the model. The relationship of the water pressure variation with the variation of the radius of the artificial cornea is shown in Fig. 4. For every 1 mmHg pressure increment, the radius of the artificial cornea is changed by around 40 μm.

Fig. 4 Measured radius variation of the artificial cornea versus water pressure.

The contact lens as sensor is then worn on the artificial cornea model. From Fig. 5(a) to Fig. 5(d) show the images of moiré fringes corresponded to 0, 180, 300, and 480 μm variations in the radius of the artificial cornea, respectively. In Fig. 5(a), there is no radius variation, and the number of spacing between fringes in the upper half of the image is 6. With the 180 μm variation in the radius of the artificial cornea, the number of spacing is increased to be 7 as shown in Fig. 5(b). When the radius variation comes to 300 μm in Fig. 5(c), another order of the fringe is about to show up. And the number of spacing is increased to 8 with the 480 μm variation as shown in Fig. 5(d). The measurement results show that the moiré fringes are changed with the radius of the artificial cornea, proving the effectiveness of using a contact lens sensor based on the moiré fringes method to characterize the radius of the cornea and thus subsequent IOP. However, it is known that the radius variations in a normal person’s eye is around 10 to 20 μm, therefore, the further improvement on sensitivity of measuring the radius variations is needed.

4. Conclusions
The contact lens sensor using moiré fringes to characterize the radius of the cornea is proposed, and the measurement results show that the moiré fringes are changed with the radius variations in the artificial cornea. Although the sensitivity of measuring the variations in the radius of the human cornea by the contact lens sensor is currently not enough, this work proves the effectiveness of the IOP monitoring method.

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References

Appendix
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