Simultaneous imaging and measurement of tensile stress on cornea by using a common-path optical coherence tomography system with an external contact reference

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The objective of this study is to demonstrate that tensile stress resulting due to applied force on cornea can be accurately measured by using a time-domain common-path optical coherence tomography (OCT) system with an external contact reference. The unique design of the common-path OCT is utilized to set up an imaging system in which a chicken eye is placed adjacent to a glass plate serving as the external reference plane for the imaging system. As the force is applied to the chicken eye, it presses against the reference glass plate. The modified OCT image obtained is used to calculate the size of contact area, which is then used to derive the tensile stress on the cornea. The drop in signal levels upon contact of reference glass plate with the tissue are extremely sharp because of the sharp decline in reference power levels itself, thus providing us with an accurate measurement of contact area. The experimental results were in good agreement with the numerical predictions. The results of this study might be useful in providing new insights and ideas to improve the precision and safety of currently used ophthalmic surgical techniques. This research outlines a method which could be used to provide high resolution OCT images and a precise feedback of the forces applied to the cornea simultaneously.

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Minimally invasive surgical (MIS) procedures provide several advantages over conventional surgical techniques including minimization of pain and suffering, increased safety, and faster healing. Robotic-assisted surgeries using mechanical arms and devices can enhance surgical precision and minimize invasiveness[1,2]. Clinical as well as laboratory usage of sophisticated robotic surgical systems such as da vinci and Hippocrate have been successfully demonstrated to assist MIS[3,4]. US Food and Drug Administration (FDA) cleared commercial da vinci surgical system provides three-dimensional (3D) visualization of the subject and hence assists in image guided precise surgery. Although it provides a steady hand with seven degrees of freedom and an improved 3D visual feel, it lacks in providing a direct feedback of the applied force on the tissue or any high resolution deformation details. Lack of a quality feedback mechanism, capable of measuring the force exerted by the surgical arm on the tissue or detecting any slippage of the operating arm, could severely restrict the utility of a surgical device. A force sensor used in conjunction with these devices can prevent excessive force applied to the surgical sites and thus minimize catastrophic damage to the tissue[5,6]. The use of a high resolution, non invasive imaging technique, such as optical coherence tomography (OCT), which is also capable of measuring the force applied on the tissue, could prove to be invaluable asset; especially when operating on a delicate organ, such as cornea. In this work, we demonstrate that a fiber optic common-path OCT system with an external reference plate can be used to measure the applied tensile stress (proportional to force) accurately. Besides, the potential to provide a feedback mechanism to control the exerted pressure, a successful integration of the OCT device along with the surgical probes could also assist as an invaluable guiding tool by providing high resolution images.

Common-path coherence domain imaging methods have generated considerable research interest because of its unique topology which could simplify OCT instrumentation and counter the issue of 'downlead sensitivity' (polarization fadings caused by variable polarization mismatch between sample and reference arm)[7−11]. Unlike in conventional OCT, there is no separate reference and sample arms in a common-path interferometer based OCT, as the reference signal is derived from the sample arm itself. In this research, the experiments were performed using an all-fiber common-path optical coherence tomography system similar to the one used in our previous publications[9−11]. We used a side-viewing bare fiber (angle cleaved at $\sim 49°$) in series with an anti-reflection (AR)-coated lens (focal length is 11 mm), mounted on a translational stage. A 5-mm thick glass plate with AR-coated side towards the lens, and uncoated side towards the cornea sample, was placed between the lens and the sample (Fig. 1). The strong Fresnel reflection at the interface of uncoated side and air acts as the principal reference plane. Changing the position of the glass plate would result in change in reference power levels as well as signal levels. As expected, the position of the reference plane with respect to the beam waist position will determine the reference power levels. Hence the plate was carefully positioned and translated along the beam

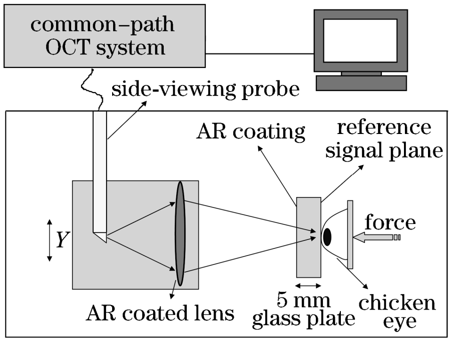

Fig. 1. Experimental setup for using common-path OCT system with an external reference plate to measure tensile stress on a chicken eye.

axis so that the signal was optimized. The 49° end-cut was used in order to reduce the back reflection coupling from the side of the fiber. The optimized distances from fiber-end to lens and lens to the reference plane were approximately 16 mm and 32 mm, respectively. Known forces were applied to the chicken eye, pushing it in the direction towards the reference plane, resulting in the formation of force dependent contact area between the reference glass plate and the cornea. A schematic of the experimental setup is shown in Fig. 1.

For various applied forces, we performed cross sectional OCT imaging of the cornea and deduced the size of the contact patch. This was done by translating the fiber probe and the lens together while the reference glass plate remained stationary in contact with the cornea.

When the reference glass plate is not in contact with the cornea (i.e., no applied force), it reflects ~ 3.5% percent of the incident optical power due to the Fresnel reflection and provides a clean reference signal for the common-path OCT. The reference power (air glass interface) will be proportional to

$$P_{\mathrm{r\_nc}} = \left(\frac{n_{\mathrm{g}} - n_{\mathrm{air}}}{n_{\mathrm{g}} - n_{\mathrm{air}}}\right)^2 P_{\mathrm{in}}, \tag{1}$$

where $n_{\mathrm{g}} = 1.46$ is the glass refractive index, and P_{in} is the incident power.

However, if the reference glass plate is in contact with the cornea, the reference signal from the contact patch becomes significantly reduced due to the reduced back reflection. The refractive index of cornea and other tissues in the eye can be approximated to be around 1.36 to 1.38[12]. The reference power in this situation (glass-cornea tissue interface) will be proportional to

$$P_{\mathrm{r\_c}} = \left(\frac{n_{\mathrm{g}} - n_{\mathrm{c}}}{n_{\mathrm{g}} - n_{\mathrm{c}}}\right)^2 P_{\mathrm{in}}, \tag{2}$$

where $n_{\mathrm{c}} = 1.37$ is the refractive index of the cornea tissue. The Fresnel reflection gets reduced to approximately 0.13%. This is more than an order of magnitude decrease in the reference power levels. This causes a significant reduction in reference signal levels, the effects of which can be noticed through the lightened section in the part of the OCT image as shown in Fig. 2. Due to this significant signal reduction, we can easily measure the width of the contact patch and, at the same time, obtain an OCT image of the deformed cornea (Fig. 3). If we assume that our OCT system is operating near shot noise limited regime, then the drop in reference signal-to-noise ratio (SNR) can be approximated as

$$\Delta\,(\mathrm{SNR}) = 10\lg\left(\frac{P_{\mathrm{r\_nc}}}{P_{\mathrm{r\_c}}}\right) = 15.3\ \mathrm{dB}. \tag{3}$$

The calculated value of the drop in the reference signal levels is very close to the experimental measured value of

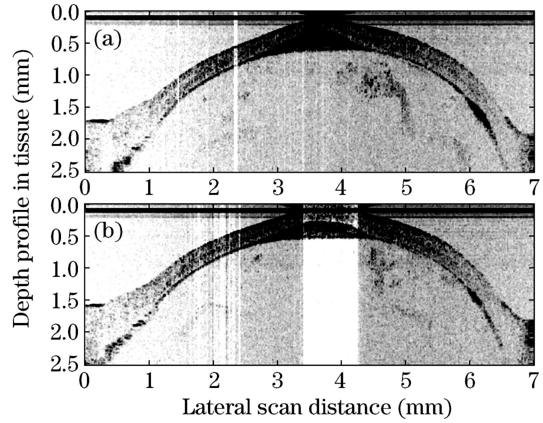

Fig. 2. OCT images of the chicken cornea under different levels of applied force. (a) Retina is barely touching the reference glass plate when no external force is applied on it; (b) retina is pressed against the reference window as a result of externally applied force. Loss of signal can be observed in the contact area.

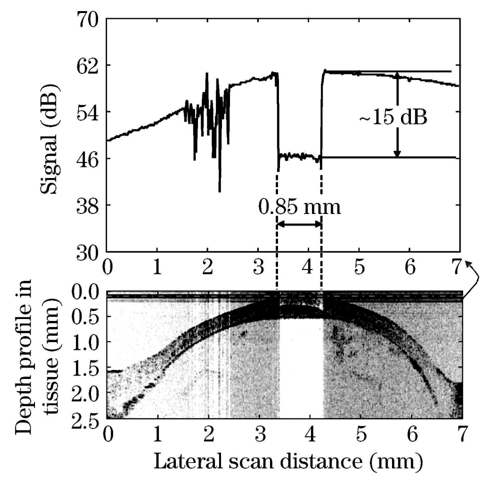

Fig. 3. Plot of the signal obtained at the reference plane. A sharp drop in the reference signal levels is produced at the point of tissue-glass plate contact.

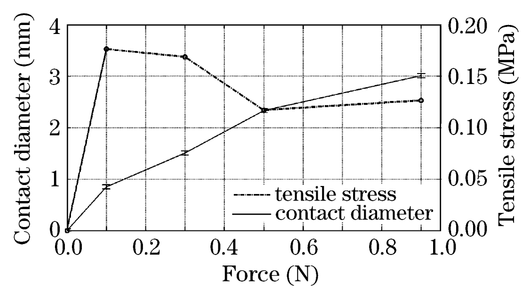

Fig. 4. Measurement summary showing the widths of the contact patch (left axis) and tensile stress (right axis) versus applied force.

$\sim$ 15 dB as shown in Fig. 3. The reference signal level is not constant along the transverse scanning length due to the imperfect alignment. A patch of noisy signal observed to the left of contact area is due to the damaged surface of the reference glass plate.

OCT images of the chicken eye were obtained for different values of applied force. As expected, the size of the contact patch increased with the increase of the applied force. The relationship between the widths of the contact patch versus applied force is summarized in Fig. 4. The known force was applied to the cornea by putting weights on the back of the cornea which pressed the cornea towards the contact reference. The tensile stress is calculated by dividing the applied force with the contact area. The tensile stress as a function of the applied force has been shown in Fig. 4. Assuming that the tensile stress response function of any particular tissue does not alter significantly amongst the sample size[13], the increase in the contact patch size as a function of applied force allows us to propose a method in which size of contact patch could be used to calculate the applied force. The measured value of tensile stress in our experiment ranges from $0.12 - 0.17$ MPa, which is two orders of magnitude smaller than the tensile strength of typical corneal tissues ($12 - 20$ MPa)[13].

In conclusion, we experimentally demonstrate that tensile stress on a cornea can be measured by a fiber optic common-path OCT system with an external contact reference.

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