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Understanding eye deformation in non-contact tonometry

Roland KEMPF, Yuichi KURITA, Yoshichika IIDA, Makoto KANEKO,
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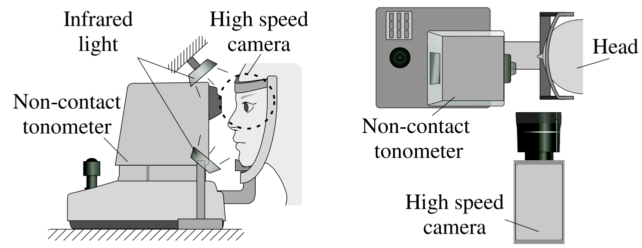
Abstract— **Non-contact tonometers are widely used to measure the internal eye pressure, i.e. the IntraOcular Pressure (IOP), which is an important parameter for the diagnosis and treatment of glaucoma. During the measurement, the eye is deformed by a short air pulse. Commonly the pressure dependent deformation is estimated from the time when the eye becomes flat, which is derived from the monitored reflection of an incident infrared light. We used a high speed camera to capture the complete motion of the eye directly and obtain more data during the pressure measurement. Assuming a simple eye model with non-linear material properties of the cornea, we extend our previous analysis of the motion of the eye, and obtain a similar principle shape of the eye deformation as observed in the experiments.**

Index Terms— **Human Eye, Glaucoma, Non-contact Tonometer, High speed camera**



(a) Side view (b) Top view

Fig. 1. Experimental system.

I. INTRODUCTION

For the diagnosis and treatment of glaucoma the internal eye pressure, also known as IntraOccular Pressure (IOP), is an important parameter. It can be measured in a gentle, non-invasive, way by a non-contact tonometer. The principle of the measurement is as follows: The tonometer applies a force on the eye by using a short air pulse. The tip of the cornea is deformed and changes from a convex to a concave shape. When the cornea is nearly flat, during the shape change, it acts like a mirror for an installed infrared light source and so the force needed to flatten the cornea can be estimated. If an eye has a high internal eye pressure, a high external force is needed to flatten the tip of the cornea. This high force is reached late during the air pulse, and thus the time of the flattening is related to the internal eye pressure. If the examined eye is similar to a standard eye, for which the tonometer is calibrated, the internal eye pressure can be estimated. This method is valid for the majority of patients, but fails for some patients, who might have non-standard eyes. In order to improve the method, it is desirable to know in detail what is happening during the measurement.

We use a high speed camera to monitor the motion of the eye during the pressure measurement directly [1], [2], as indicated in Fig.1. The captured movement of the eye's surface is not yet fully understood. At this stage, we want to identify the dominant effects involved in the eye deformation. In fact, the deformation of the eye is expected to depend not only on the eye pressure, but also on the structural stiffness of the cornea and its non-linear material parameters. Since the response of the eye to the air pulse is also dynamic, a direct monitoring is crucial to understand this pressure measurement method.

The paper is organized as follows: After a short overview of related works, we describe the experimental set-up and the evaluation procedure. Then we will discuss two eye models based on the given literature and end with a conclusion.

II. RELATED WORKS

There are a number of publications that deal with the modeling of the human eye. Some are based on theoretical assumptions, while others are based on experimental data. Depending upon the modeling and measurement method the resultant numerical values for the corneas' stiffness differ considerably. Orssengo et al. [3] assumed a linear material behavior of the cornea and show that an analytic closed form model is a reasonable approximation for a finite element model of the cornea. Hjortdal et al. [4] measured the deformation of the cornea of intact human eyes in vitro when the internal eye pressure is raised. Their analysis show that the stiffness of the cornea is non-linear and changes slightly with direction and location of the analyzed sections. Anderson et al. [5] measured the rise of the tip of porcupine corneas in vitro under different pressures. Using a membrane model they derive a non-linear stress-strain relationship of the cornea material, which is similar to the one obtained by [3]. They also use their model to predict pressure distributions in different eye pressure measurement methods, including the non-contact measurement. The predicted deformations in the case of the non-contact measurement do not match our experimental results, probably due to the additional dynamic parameters they had to estimate without experimental data.

The first direct monitoring of the eye deformation during

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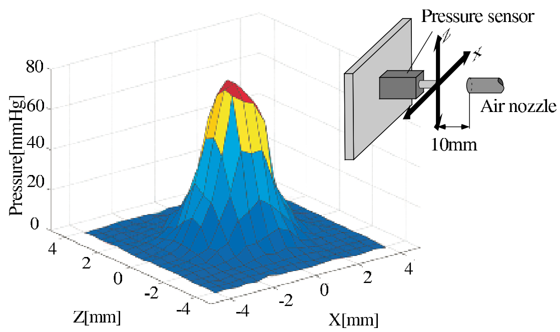

Fig. 2. Pressure distribution.

a non-contact measurement was reported by Kaneko et al. [1]. A phenomenological analysis of the relationship of deformation and internal eye pressure was done in [6] and a first physically motivated dynamic model was presented in [2]. Using our recent results from experiments on the effect of the corneal stiffness to contact experiment [7], we show here a physically motivated, qualitative, description of the eye deformation.

III. Experimental system

A commercial non-contact tonometer (TOPCON CT-80A, Topcon, Tokyo, Japan) was used to measure the eye pressure, in the set-up shown in Fig.1. After the measurement is triggered, the tonometer sends an air pulse to the eye with a pressure profile shown in Fig.2. The time dependent pressure profile and peak pressure were evaluated in advance. Since they are highly repeatable, they can be assumed to be the same during the eye pressure measurement.

The experimental set-up also includes a high speed camera (PHANTOM V7.1, Vision Research, Wayne, New Jersey, USA). The trigger signal of the tonometer was used to synchronize the camera with the starting time of the air pulse. The camera provides a resolution of 14 [μm/pixel] and a frame rate of 5000 [fps]. This is sufficient to monitor the deformation of the eye that takes place during a time interval lasting 20 [ms] and that ends before the eye closes. Since the deformation is roughly axially symmetric, the profile of the cornea can be directly seen in the camera, as long as the cornea is concave shaped. The convex part is hidden.

The visible shape of the cornea is extracted from the movies by image processing. From 110 subjects, we show results for a young and a senior subject, respectively, in Fig.3, which illustrate the spectrum of typical responses of eyes to the applied air jet. The outer border hardly moves in the case of the young subject, but moves considerably for the senior subject. There are mainly two modes of motion: the movement of the whole eye, detectable at the outer border of the cornea, and the deformation of the cornea, visible in the bending motion of the tip of the cornea [2].

In order to judge the dynamic effects of the experiment, the motion of the tip of the cornea is extracted from the profile shots. The time-dependent displacement of the cornea's tip and the integrated external pressure are shown in Fig.4.

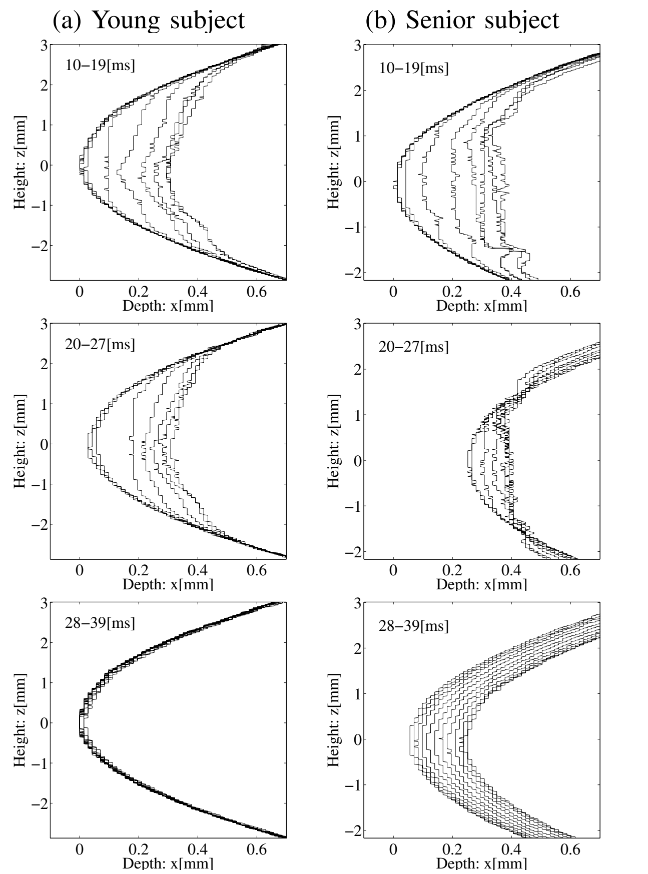

Fig. 3. Snapshots of visible shape of cornea for a (a) young and (b) senior subject at time intervals of 1[ms].

Since we are interested in the deformation, i.e., the bending motion only, the change in the position of the outer border of the cornea was subtracted from the visible boundary of the central position. The result is shown in Fig.7. This mode of motion is the one analyzed by a normal non-contact tonometer and is thought to be dependent on the internal eye pressure. In order to analyze the effect of the external force on the eye, an eye model has to be set up.

IV. Eye model

In this section we will show that the principle shape of the eye deformation can be understood when we assume certain non-linear material properties of the cornea. Starting with a linear material model, the internal eye pressure causes a homogeneous pre-strain in the cornea. A finite element simulation of the pressure distribution on the hard shell of the cornea shows a nearly linear dependence between applied peak pressure and displacement of the tip in agreement with the analytic solution for small deformations (cf. Table 13.3.2 in [8]). However, such a behavior is not apparent in the experiment. Specifically, it cannot explain the sharp rise in the displacement at around 13 [ms] after the trigger signal. Furthermore it cannot explain why there is an apparent time delay between the start time of the applied force and the start time of the displacement.

Now, we will use a simple description of the non-linear

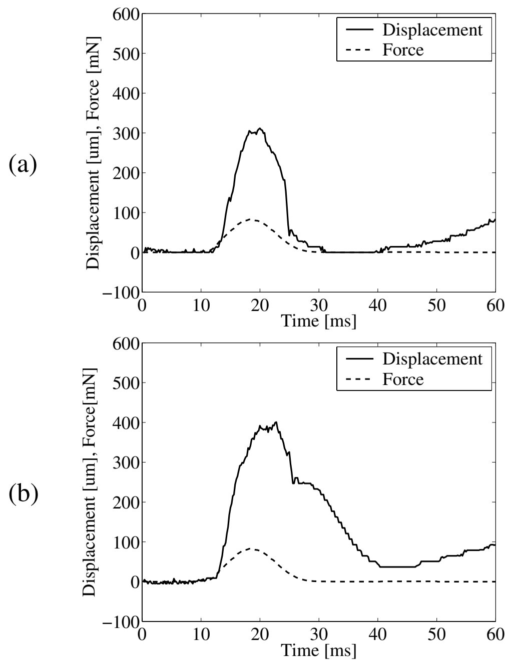

Fig. 4. Applied force and time series of the dynamic response of the tip of the cornea for (a) young and (b) senior subject.

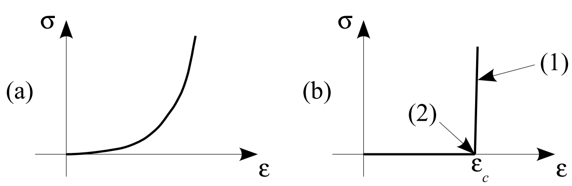

Fig. 5. (a) Realistic and (b) simplified stress-strain relationship of cornea.

material properties of the cornea. Since the cornea is built up by a mesh of collagen fiber, it shows a small resistance to compressing but a high resistance to stretching, which is reported in [4], [5] and depicted in Fig.5(a). In order to simplify the model, we exaggerate the mechanical properties and assume the cornea material to be similar to a mesh of loosely interlinked chains: We assume that the cornea shows no resistance to deformation until the elongation ε reaches a critical value ε_c. Then a very high stress σ is needed to cause further elongation. Instead of a roughly quadratic stress-strain relation, we use the stress-strain relation shown in Fig.5(b). A cornea in a natural eye is prestrained by the internal eye pressure and is in the state (1) indicated in Fig.5. When the strain is locally reduced by compensating the internal eye pressure with an externally applied pressure, the cornea hardly deforms until the local strain is nearly zero. This corresponds to state (2) in Fig.5. When the external pressure exceeds the internal pressure, the cornea can be easily deformed and assumes a concave shape, in which it can again resist the pressure difference. This simplified model allows to derive an analytic description of the deformation taking place during a non-contact eye pressure measurement as can be seen in the next section.

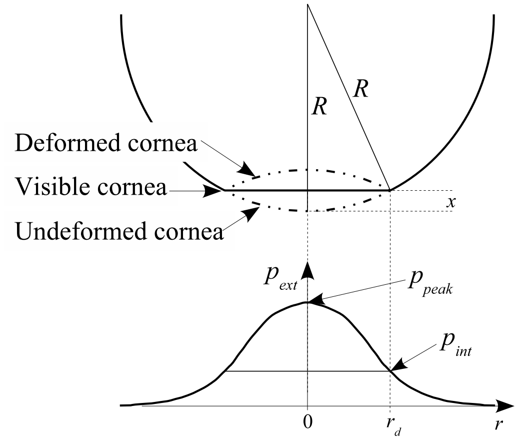

Fig. 6. Air pulse and area of deformation on cornea.

V. EVALUATION OF NON-CONTACT MEASUREMENT

The external pressure distribution of the non-contact tonometer, as shown in Fig.2, has the form of a Gaussian bell curve. Its peak pressure changes with time, while its width stays nearly constant. Thus the external pressure p_{ext} can be approximately described by

$$p_{ext}(t,r) = p_{peak}(t) \cdot e^{-r^2/r_0^2}, \tag{1}$$

where p_{peak}, r, and $r_0 = 1.5$ [mm] are the peak pressure, the distance from the central axis and the pulse width.

We assume that a visible deformation of the cornea takes only place in an area where the external pressure exceeds the internal pressure, as indicated in Fig.6. When a deformation takes place, i.e., when $p_{peak} \geq p_{int}$, the external pressure p_{ext} equals the internal pressure p_{int} at the boundary radius r_d of the deformation, i.e.

$$p_{int} = p_{ext}(t, r_d). \tag{2}$$

The radius r_d can be estimated by considering the visible boundary x (cf. Fig.6) of the deformation. From Pythagoras we know that

$$R^2 = r_d^2 + (R - x)^2. \tag{3}$$

Since, typically, $x < 300[\mu$m] and $R \approx 7.8$[mm] and thus $x \ll R$, we can omit the small quadratic term in x and obtain

$$r_d^2 \simeq 2Rx. \tag{4}$$

After combining Eq. (1), (2) and (4), we obtain the relationship

$$\ln p_{peak} - \ln p_{int} = \frac{2R}{r_0^2} x \tag{5}$$

for $p_{peak} \geq p_{int}$.

Assuming we know the internal eye pressure from the conventional pressure measurement, we can use the equation above to estimate the visible deformation x. In addition, we can obtain the deformation x from the experimental data by subtracting the background movement of the whole eye [2]. Fig.7 shows a comparison between the measured deformation x and the deformation obtained by the model for a young and a senior subject.

(a)

(b)

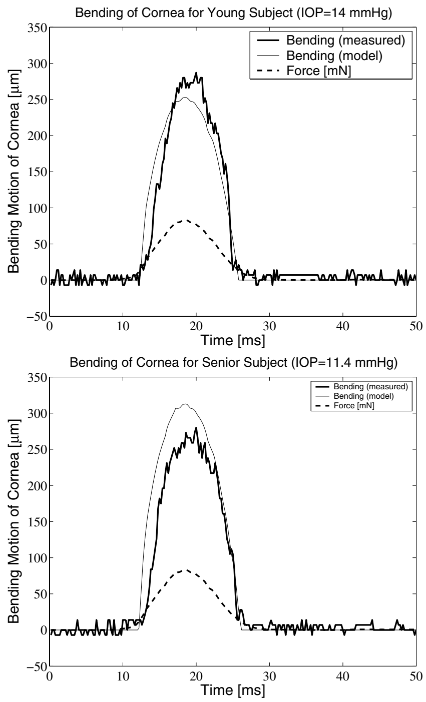

Fig. 7. Measured and estimated visible bending mode of cornea for a (a) young and (b) senior subject.

(a)

(b)

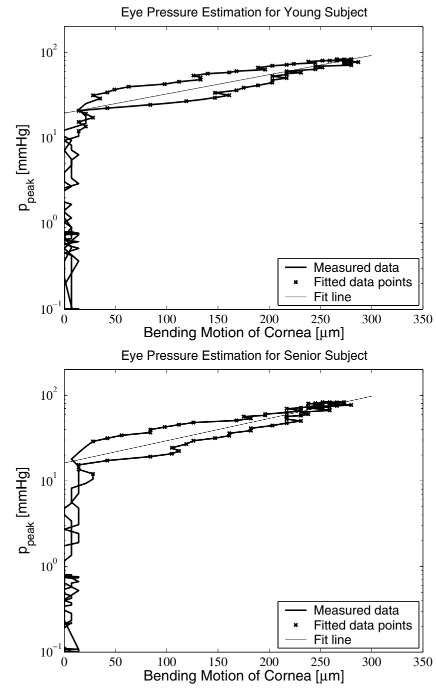

Fig. 8. Semilogarithmic plot of external peak pressure over the visible bending mode for a (a) young and (b) senior subject.

When comparing the measured and the estimated visible deformation one should consider the following items:

- Unlike the applied pressure, the deformation starts and ends abruptly. This behavior can be seen in the measurement and in the non-linear eye model.
- The order of magnitude of the modelled deformation matches the measured deformation. All used parameters have a direct physical interpretation and were measured. No fitting is involved.
- The time shift between the applied pressure and the deformation hints that the experiment involves some dynamic, which is not considered in the quasi-static model above.

By using Eq. (5) it is also possible to estimate the internal pressure p_{int}. In a semilogarithmic plot of the external peak pressure $p_{peak}(t)$ over the bending motion $x(t)$, it appears as the offset value in the linear fit, shown in Fig.8. The measured and derived internal eye pressures are 14[mmHg], 18[mmHg] and 11.4[mmHg], 15[mmHg] for the young and senior subject, respectively. It should be noted that the shape of the piecewise linear relationship between x and p_{peak} can be seen and the order of magnitude for the pressure values is correct. For a diagnosis, however, the precision of the evaluation is not good enough yet. We are currently increasing the precision of the eye model by using the non-linear material properties known in literature to reach a better matching between the measured and theoretical values.

VI. Conclusion

In this paper, we showed that the deformation of the cornea seen during a non-contact pressure measurement can be qualitatively explained by using a simple eye model. The steep rise in displacement can only be obtained by assuming that the material properties of the cornea are non-linear. This is the starting point for a more detailed model, which has the goal of quantitatively describing the effects taking place during a non-contact eye pressure measurement.

VII. Acknowledgments

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