CORRECTION OF REFRACTION INDUCED DISTORTION IN OPTICAL COHERENCE TOMOGROPHY CORNEAL RECONSTRUCTIONS FOR VOLUME DEFORMATION MEASUREMENTS

A. Firstauthor, B. Secondauthor and C. Thirdauthor
Department, University
Address, Country
email@address1, email@address2, email@address3
Please underline the name of the co-author who will present the paper at the conference

ABSTRACT: In this project, the depth-resolved full-field deformation of the porcine cornea under changing intraocular pressure was investigated by performing digital volume correlation (DVC) on the reconstructed volume images generated through swept source optical coherence tomography (SS-OCT). Posterior inflation test of porcine cornea sample for two load steps were performed and the distribution patterns of displacement and strain fields were produced. The error sources for the measurements were analyzed. The refraction induced OCT image distortion is a main error source for the measurement results. Then, a methodology was developed to correct the OCT distortion based on the Fermat's principle.

1. INTRODUCTION

The study of the mechanical behaviour of eye cornea under intraocular pressure is important for the assessment of corneal biomechanics and has important application potentials in the ophthalmology [1, 2]. Recent advances in optical coherence tomography (OCT) [3, 4] enable the non-invasive and non-destructive reconstruction of volume microstructure of semi-transparent inhomogeneous samples such as corneas. The swept source optical coherence tomography (SS-OCT) system utilizes the latest swept source based Fourier domain OCT technology to provide an OCT imaging system with detection sensitivity and imaging speed much higher than a conventional OCT system. While being powerful and sensitive tools for characterizing the internal microstructure of an object with high quality, these OCT techniques also have some limitations such as the refraction induced image distortion [5-7]. Digital image correlation can be applied to measure surface full-field deformations of the cornea [8]. However, its internal 3D full-field deformation measurements have rarely been realized. In the present work, digital volume correlation was applied to measure the depth-resolved displacement and strain fields from the volume images generated through SS-OCT of the porcine cornea sample under posterior inflation conditions. Efforts also have been made to correct the refraction induced OCT image distortion.

2. DEPTH-RESOLVED FULL-FIELD MEASUREMENT OF CORNEAL DEFORMATION

2.1 Experimental set-up and image acquisition

Fig.1 shows the schematic diagram of the experimental set-up. The average central thickness of the porcine cornea was measure using a coordinate measuring machine, which is 1.53 mm. The specimen was mounted and fixed on the artificial anterior chamber (AAC). The simulated intraocular pressure was achieved by adjusting a 1 ml micro-syringe and measured using a calibrated pressure sensor unit. During the inflation test, the cornea sample was inflated from 2 kPa to 2.5 kPa. At each pressure increment, a 3D volume image sequence of the specimen was acquired through a SS-OCT system. The SS-OCT system uses a rapidly tuned narrowband source to illuminate the interferometer and records the information with a single photo detector. It measures the magnitude and time delay of the reflected light in order to construct depth profiles (A-scans) of the sample being imaged. Adjacent A-scans are then synthesized to create an image. Multiple adjacent 2D images in the Z direction then form the 3D volume. The reconstructed volumes at both load steps were recorded for digital volume correlation and displacement and strain fields computed.

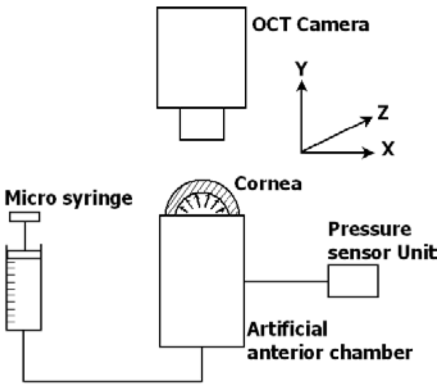

Figure 1- Schematic diagram of the experimental set-up

2.2 Digital Volume correlation

DVC was performed on the reconstructed SS-OCT volumes using the Davis (LaVision) commercial package based on fast Fourier transform. During the DVC procedure, the correlated volumes are first divided into sub-volumes. The displacement vector of each sub-volume is determined by tracking and matching the voxels of the sub-volumes in the reference and deformed states. This is performed by minimizing the correlation coefficient which measures the degree of similarity of the grey level distributions in the sub-volumes in the reference and deformed states. The best prediction of the displacement leads to the highest degree of similarity of the grey level distributions thus the minimal correlation coefficient.

2.3 Results of inflation test

Displacement fields in X, Y and Z directions are given for a central z-slice of the porcine cornea and compared with a finite element (FE) model in Fig. 2. Due to the finite A-scan depth of the SS-OCT system, the bottom region of the porcine cornea specimen is outside the field of view during the OCT image acquisition. Therefore, the reconstructed volume images only represent the upper part of the specimen, as highlighted in the plots on the FE model in Fig. 2 (b). From the DVC results, it can be seen that the horizontal displacement Ux is close to zero near the central region, and increases symmetrically when it moves to two sides. This is expected from the FE model and is the result of applying a normal inflation pressure. The explanation for the distribution of the horizontal displacement Uz is the same as Ux because Z-axis is simply 90 degree revolved from X-axis about the vertical Y-axis. Compared with the horizontal displacement, the vertical displacement Uy is greater. As expected from the FE model, the maximum Uy locates near the central endothelium, and the Uy declines when it moves from inner to outer. From these observations, we can conclude that the displacement fields of the DVC results show a good overall agreement with the results of the FE model, which is consistent with the inflation condition.

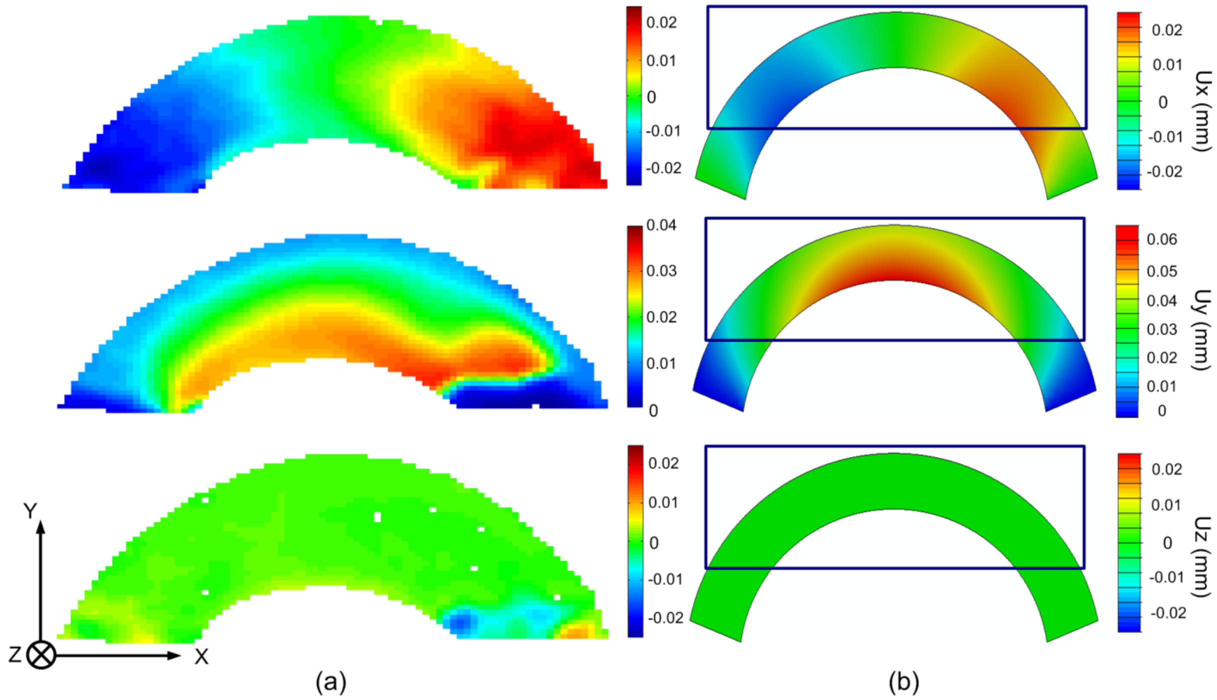

Fig 2 - Displacement fields of the central z-slice from (a) DVC results of porcine cornea and (b) FE model, inflated from 2 to 2.5 kPa

3. CORRECTION OF OCT DISTORTION

3.1 Refraction induced OCT distortion

OCT distortion is an error source when performing DVC on the reconstructed volume images. For a sample with curved surface such as cornea, distortion of the reconstructed volume exists due to the refraction. Fig. 3 illustrates how this distortion happens. In this figure, K is the plane of zero optical path difference. A is an incident point on the epithelium surface from which the scanning light going into the sample. AC is the normal of the incident point A. When a vertical scanning light going through A with an incident angle θ_0, due to refraction, the ray passes through an object point B with a refraction angle θ_1 instead of a further vertical scan. The OCT system then records this refracted optical path in the image as a vertical A-scan line, as denoted OI in Fig. 3, where point I is the corresponding point of the object point B in the image space. As the optical path difference is equal to the physical distance in the medium multiplied by the refractive index, OI in the image space is equal to:

$$|OI| = n_0|OA| + n_1|AB| \quad (1)$$

Therefore, the reconstructed image is actually expanded and deformed outwards compared with the real configuration of the object. The distorted volume images will then introduce errors to the DVC results.

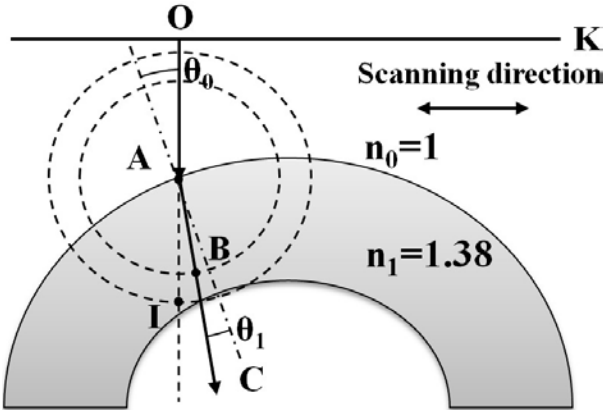

Fig 3 - Schematic of OCT distortion

3.2 Correction methods

Similar correction works have been pursued in the literatures using Fermat's principle and Snell's law [5-7]. In our study, the correction of OCT distortion is based on the Fermat's principle, which states that the path taken between two points by a ray of light is the path that can be traversed in the least time. This principle indicates that each object point B has only one unique incident point A. This unique incident point A can be found using a minimization algorithm of the optical path difference defined in equation (1). Then, the corresponding point I in the image space of the object point B can be searched along the path OA with a distance of $n_1|AB|$ from the incident point A. After determining the exact coordinates of the object point B in the image space, we can then decide the light intensity value on this image point through interpolation, and thus the correction for this object point is accomplished. Applying the same procedure to all other object points, the corrected volume images can be obtained.

3.3 Results

The above method was implemented using MatLab R2007a. Considering the computation time and required memory, this distortion correction was first carried out on a central 2D slice of the reconstructed volume. The 2D slice has an image size of 1024×512 pixels. The computation time varies significantly from performing minimization on all pixels to certain pixels only. Fig. 4 shows the central z-slice before and after OCT distortion correction. Compared with the original image in Fig. 4 (a), the cornea in the corrected image in Fig. 4 (b) is thinner. This is not surprising as cornea in the distorted image has been expanded by a factor of the corneal refractive index, which is about 1.376.

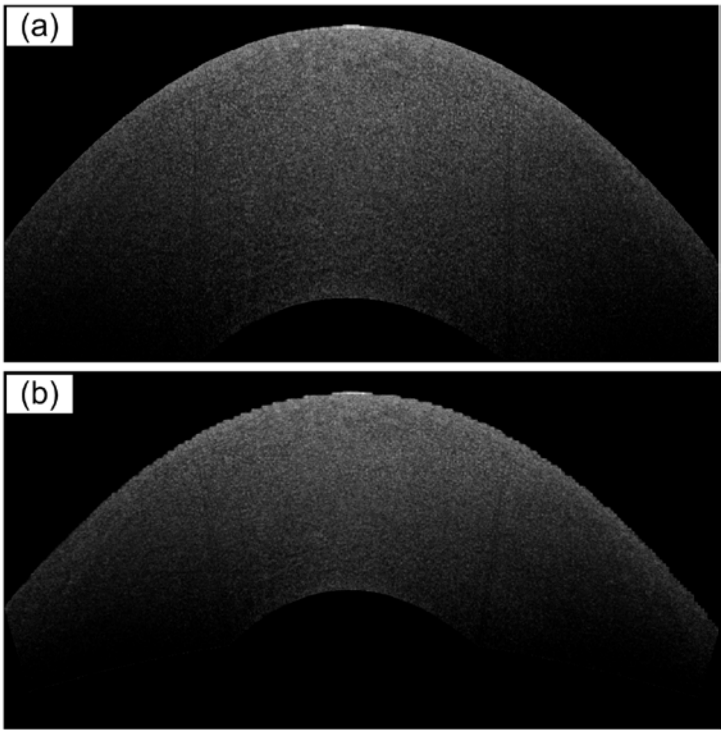

Fig 4 – OCT image for a central slice (a) before and (b) after OCT distortion correction

Same method will be applied to the 3D reconstructed volume in a more efficient way, in which the OCT distortion correction will first be performed on certain grid points only and the correction of the rest points will be accomplished through interpolation. This will greatly reduce the computation time and the requirement for memory. Then, DVC will be performed on the corrected volumes to get a more accurate results.

4. CONCLUSIONS

In the present study, a method was developed to investigate the depth-resolved full-field deformation of the cornea under changing intraocular pressure. DVC was carried out on the reconstructed volume images generated through a SS-OCT system of the porcine cornea sample in the reference and inflated states. A FE model was developed to predict the corneal deformation under changing intraocular pressure. The DVC results show a good overall agreement with the results of the FE model and verify the feasibility of applying this method in investigating the internal deformation of human cornea. OCT distortion is a main error source to the DVC results, which is induced by the refraction on the curved surface of the sample. To enable a more accurate deformation measurement, a numerical method was developed to obtain the real configuration of the sample from its distorted configuration in the raw OCT image based on Fermat's principle. The correction algorithm successfully provided a corrected 2D slice of the porcine cornea sample and will be extended to the 3D volume in a more efficient way.

5. REFERENCES

1. Kwon, T.H., Ghaboussi, J., *et al*. (2008) Effect of cornea material stiffness on measured intraocular pressure. *J. of Biomech*. 41, 1707-1713
2. Pepose, J.S., Feigenbaum, S.K., *et al*. (2007) Changes in corneal biomechanics and intraocular pressure following LASIK using static, dynamic, and noncontact tonometry. *Am. J. of Ophthalmol*. 143, 39-47
3. Kaluzy, B.J., Kaluzny, J.J., *et al*. (2006) Spectral optical coherence tomography: a novel technique for cornea imaging. *Cornea*. 25, 960-965
4. Fujimoto, J.G. (2003) Optical coherence tomography for ultrahigh resolution in vivo imaging. *Nat. Biotechnol*. 23, 1361-1367
5. Podoleanu, A., Charalambous, I., *et al*. (2004) Correction of distortions in optical coherence tomography imaging of the eye. *Phys. in Med. Biol*. 49, 1277-1294
6. Ortiz, S., Siedlecki, D., *et al*. (2010) Optical distortion correction in optical coherence tomography for quantitative ocular anterior segment by three-dimensional imaging. *Opt. Express*. 18, 2782-2796
7. Westphal, V., Rollins, A.M., *et al*. (2002) Correction of geometric and refractive image distortions in optical coherence tomography applying Fermat's principle. *Opt. Express*. 10, 397-404
8. Boyce, B.L., Grazier, J.M., *et al*. (2008) Full-field deformation of bovine cornea under constrained inflation conditions. *Biomaterials*. 29, 3896-3904