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► **To cite this version:**

Qian Wu, Chloé Giraudet, Jean-Marc Allain. Exploration of the mechanical role of stromal striae. 2024. hal-04737975

HAL Id: hal-04737975

<https://hal.science/hal-04737975v1>

Preprint submitted on 15 Oct 2024

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EXPLORATION OF THE MECHANICAL ROLE OF STROMAL STRIAE

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Keywords: Cornea; biomechanics; soft tissue; experimental; DVC

1. Introduction

Cornea is the transparent outermost layer of the eye. It provides approximately two-thirds of the eye's refractive power. Healthy human cornea is spherical-shaped. In patients with keratoconus, the cornea becomes thinner and gradually extends outward into an irregular cone shape. The disease can lead to blurred or distorted vision.

Stroma is the middle and thickest layer of the cornea. It is formed of stacked lamellae made of aligned collagen fibrils. The stroma is responsible for corneal biomechanical stability. Weakened biomechanical properties are believed to cause progressive steepening and thinning in keratoconus [Padmanabhan and Elsheikh 2023, Giraudet et al. 2022].

Vogt's striae are frequently observed in the posterior stroma in advanced keratoconus, undergoing classical clinical evaluation such as slit-lamp examination. However, with more powerful diagnostic techniques such as histology, confocal microscope, full-field optical coherence microscopy, the striae can be detected in 82% of patients with and without keratoconus. Notably, in patients with keratoconus, striae were significantly more numerous than in normal ($p = 0.01$) [Grieve et al. 2017].

Vogt's striae may cause biomechanical deterioration in keratoconus eyes [Rakhshandadi et al. 2021, Mocan et al. 2008]. However, their contribution to stroma mechanical behavior remains poorly understood. In this study, we carried out inflation tests on human

healthy corneas coupled with optical coherence tomography (OCT) imaging, to investigate the mechanical properties of stromal striae.

2. Methods

We performed inflation tests under Optical Coherence Tomography (OCT) on eleven fresh and healthy corneas taken from human donors.

The corneas were placed in deturgescence medium 48 hours prior to the experiments to recover the relative dehydration state of the tissue.

For the inflation test, the cornea was placed on the top of an artificial anterior chamber. A software-controlled injector injected physiological fluid StemAlpha3 and control the pressure inside the anterior chamber. The cornea was brought to high pressure of 200 mbar through small steps of 15 mbar (physiological pressure being 20 mbar).

During the inflation test, OCT 3D images were taken from the central area of each cornea containing stromal striae. The OCT images were then segmented into binary images, with white pixels corresponding to striae and black pixels to other areas. The striae planes were extracted from these binary images, while the principal strain maps were obtained by digital volume correlation (DVC) (Fig.1.A).

3. Results and discussion

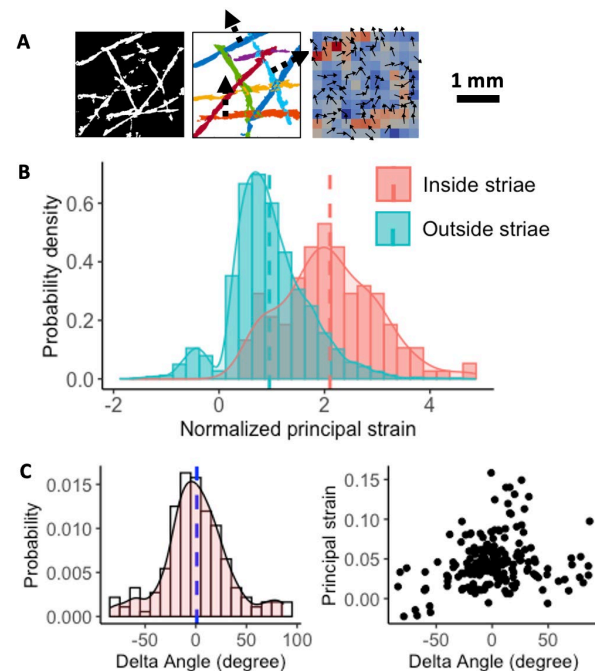


Figure 1. A. Segmented in-plane image (left), extracted striae planes with their normal directions indicated by dashed black arrows (middle) and map of principal strains with directions indicated by grey

arrows (right), obtained at the same depth from the central area of cornea. B. Normalized principal strains inside and outside striae at all the depth levels and from all the cornea samples. C. Angle deviations between normal directions of striae planes and directions of principal strains distributed on 1.04° ($\pm 32.06^\circ$) (left); Angle deviations are affected by principal strains (right).

The principal strains inside striae are higher than outside striae ($p < 0.01$). The mean normalized principal strain in striae group is two times higher than another group. Maximum principal strains are co-localized with the striae (Fig.1.B). Consistently, Hollingsworth (2005) observed stromal banding using confocal microscopy and suggested that these correspond to areas of reduced strength in the cornea.

The distribution of angle deviations between normal directions of striae planes and directions of principal strains is centred on 1.04° ($\pm 32.06^\circ$). The maximum principal strains are oriented mostly perpendicular to the striae (Fig.1.C). The distribution of angle deviations depends on principal strain level: small values are found for high principal strains higher than 5%, while the values are distributed over a much larger range for low principal strains. The large angle deviations at low principal strain could be explained by errors from fitting process of striae plane and correlation process, and noise from experimental measure (Fig.1.C).

We observe that principal strains increase with depth in the cornea. In posterior stroma, the increase inside striae is steeper than outside areas, while in anterior cornea, the increase is almost the same for both. The extra deformability in posterior stroma is due to the presence of striae, which become more and more visible on the OCT images when it approaches the bottom of the cornea. The literature on corneal elastic moduli consistently reported that the anterior stroma is stiffer than the posterior stroma [Leonard et al. 2019]. We observe also that striae pattern and location don't change with pressure, even far above physiological pressure. The striae probably are stable microstructure, as stromal lamellar undulations were discovered in the study of Grieve (2017). The striae become less visible when the pressure increases, likely as their undulation features fade with pressure.

Although keratoconus corneas were not assessed in our study, our findings in normal corneas suggest that the more numerous the striae, the more deformable the cornea, and therefore the more severe the keratoconus. This correlation between the number of striae and the disease severity is well documented in the literature [Zadnik et al 1996, Grieve et al. 2017].

4. Conclusions

Our results indicate that striae are structures associated to higher deformability. The principal strain occurs in the direction almost perpendicular to the striae. The local biomechanical change may be due to microstructural changes in stromal striae such as undulations in continuous lamellae [Grieve et al. 2017, Mocan et al. 2008].

In the posterior stroma, the increase of principal strain inside the striae is steeper than that outside the striae. This means that the striae provide an extra compliance to the stroma in the posterior region.

Next steps would be to observe the behavior and structure of the striae more closely by using second harmonic microscopy, and analyze the strain around the stromal striae at the scale of collagen lamellae. Furthermore, stromal striae should be considered in the biomechanical modelling of the entire cornea.

Acknowledgements

We thank the Banque Française des Yeux for providing the cornea for scientific use, Vincent de Greef for his help in the design of the experiment.

Funding

This work was supported by grant ANR-21-CE19-0010-01 from the ANR.

Conflict of interest statement

The authors declare that there is no conflict of interest.

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Received date:05/04/2024

Accepted date: 28/06/2024

Published date: XX/XX/2024

Volume: 1

Publication year: 2024