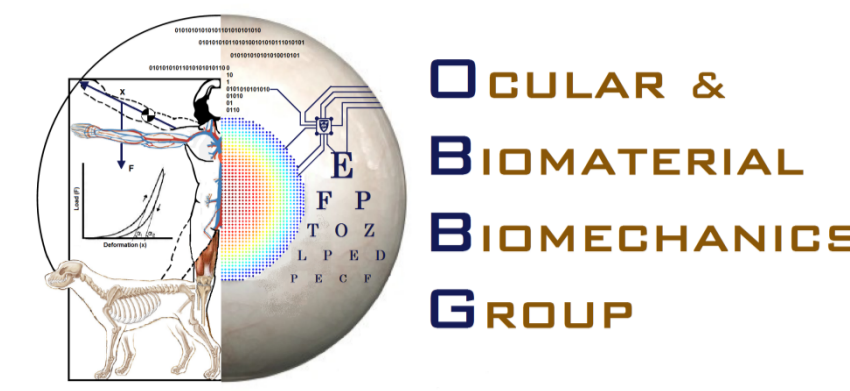# Numerical Representation of Collagen Fibril Anisotropic and Density Related Stiffness for the Intact Human Eye Globe

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Abstract

This study aims to develop a reliable method to numerically represent the regional and directional variation in mechanical stiffness across the surface of the human cornea and sclera.

The method is based on analysis of X-ray scattering data describing the microstructure of the cornea and sclera in human eyes. The data was analyzed to determine the regional variation of stiffness and the anisotropy with a high level of control down to individual elements in a finite element model (FEM) of the eye.

Methods

Two human eyes were analyzed using wide angle X-ray scattering (WAXS) to determine the density and distribution of collagen fibrils across the ocular surface at discrete points with a 0.5mm grid spacing. [1]

Bespoke software was developed to process the WAXS data as shown in Figure 1.

Method (cont'd)

The software integrated several processes including: local noise filtration (to identify main directions of fibril distribution at each measurement point, Figure 2), Zernike surface fitting (to identify main, global trends in fibril distribution and eliminate sudden changes in fibril density, Phase 4, Figure 1) and spatial interpolation to define the fibril density and anisotropy at each element of a finite element model of the eye).

The software is also able to (1) construct an eye specific FEM of each tested eye using the topography and thickness distribution measured experimentally, (2) utilize the internal pressure – deformation behavior obtained experimentally for each eye under inflation conditions, and (3) conduct an inverse modelling exercise using the eye-specific models, the pressure-deformation data and the fibril density and anisotropy data to determine parameters describing the material behavior at each element of the FEM. This work adopted the constitutive model developed by Harald et al [2] which considered both material hyperelasticity and anisotropy. This
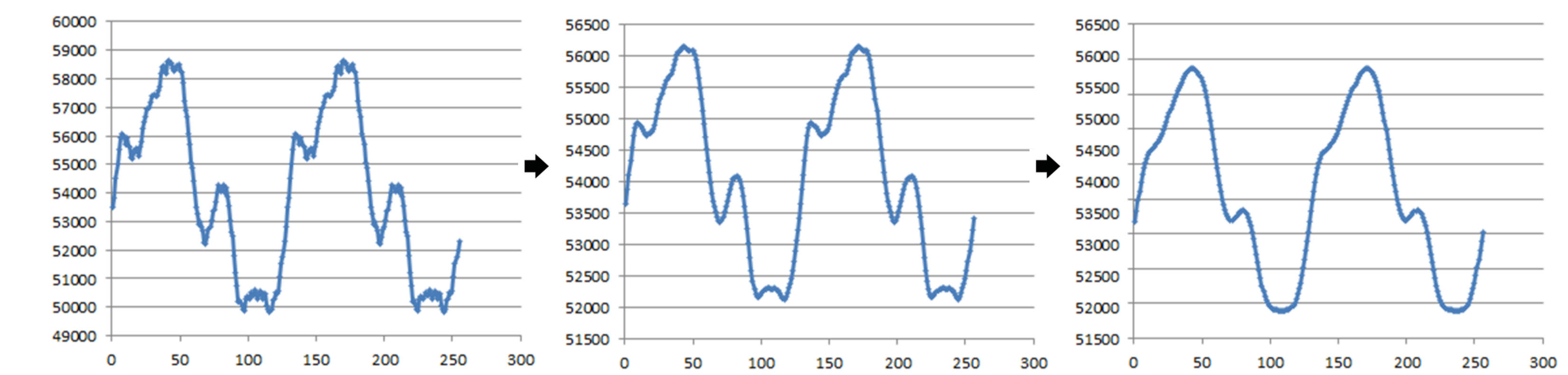
Method (cont'd)

Figure 2 Noise filtration (using a low-pass filter) to determine the main directions of fibril angular distribution at each measurement point

constitutive model was developed further to include representation of fibril density. Directional, and location, based stiffness relationships were calculated and represented by discretizing fibril properties into angular directions. This representation was achieved within continuum mechanics theory.

Results

The method led to a stiffness distribution that was consistent with the variation in collagen density and anisotropy observed using X-ray scattering. Stiffness was highest at the limbus in the annular direction, where the circumferential collagen arrangement there is responsible for preserving the bi-radial topography. The area around the optic nerve was also found to have relatively high annular stiffness able to restrain the deformation of the lamina cribrosa. Areas of lower stiffness were found in the peripheral cornea and the posterior sclera.

Conclusions

Representing collagen fiber distribution obtained using X-ray scattering techniques in finite element models has produced an important advance to accurately simulate the mechanical behavior of human eye globes. With this level of representation of ocular microstructure, the resulting models are expected to lead to better accuracy in understanding ocular response to disease and surgery and in optimization of diagnostic and treatment devices and procedures that interact mechanically with the eye.
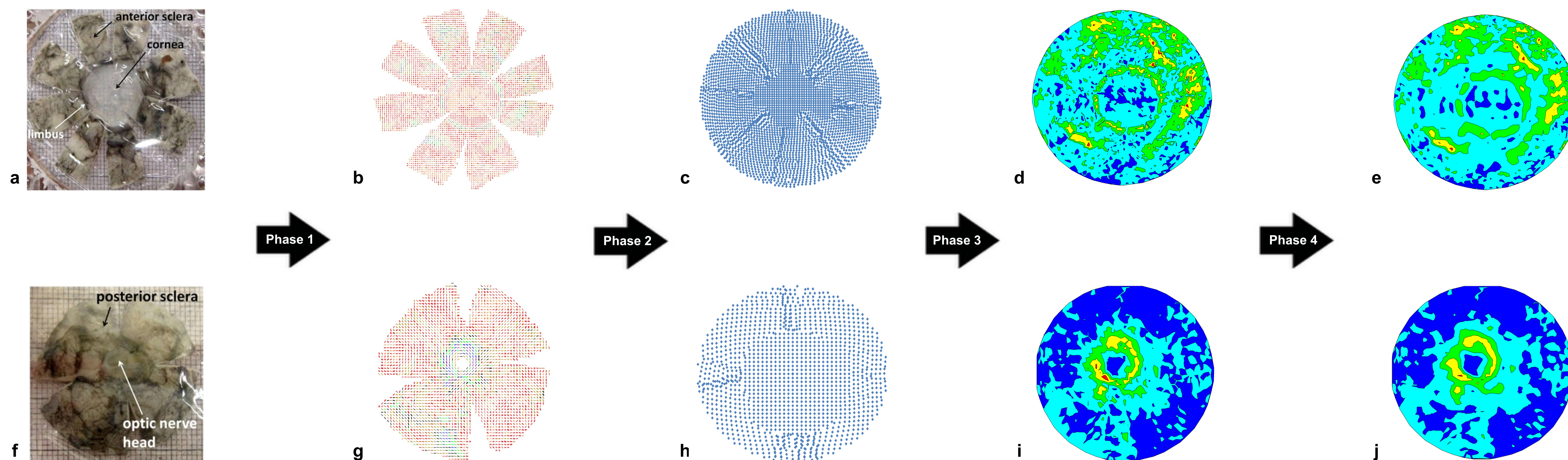

Figure 1 The complete process of attaining collagen fibrils density and distribution across the ocular surface of the human eye. The Anterior cup (top) is represented by figures (a) through (e), while the Posterior cup (bottom) is represented by figures (f) through (i). The blocks below explain each process briefly.

Phase 1
Prior to the WAXS method, the intact human specimen undergoes dissection according to the flattened layout presented in figures (a) and (f). WAXS is then used to determine fibril density and angular distribution at points with a 0.5mm grid spacing.

Phase 2
Using bespoke software, all the data points were analyzed and the maps were expanded to eliminate all gaps artificially created during dissection. The results are shown in figures (c) and (h).

Phase 3
The data collected at discrete points were separated into 6 maps representing the fibril density, isotropic distribution, two main angles of anisotropic distribution and the associated fibril densities.

Phase 4
Each of the 6 maps was fitted to Zernike polynomials (with a high order of 60) to remove global noise in data and sudden changes in data values that could cause instability in numerical modelling.

References

[1] Pijanka J. et al., (2013) 'A WAXS fibre diffraction method for quantifying collagen orientation', Journal of Applied Crystallography, v. 46, p. 1481-1489.
[2] Studer H. et al., (2010) 'Biomechanical model of human cornea based on stromal microstructure', Journal of Biomechanics, v.43, p. 836-842.

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