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Commentary

Stress-Strain Interactions in the Cornea due to Collagen Fibril Crimping

Sang Leo*

Department of Biosciences, Rice University, Houston, United States of America

DESCRIPTION

The cornea is the transparent, outermost layer of the eye and its structural integrity is most important to maintaining proper vision. Composed mainly of collagen, the corneal stroma contributes significantly to its mechanical strength, transparency and curvature, all of which are essential for focusing light onto the retina. A particular feature of corneal collagen is its fibril organization, which provides the necessary strength and elasticity to withstand external forces and maintain the shape of the cornea. Understanding how these collagen fibrils behave under mechanical stress is essential for developing accurate biomechanical models of the cornea.

One of the most important mechanisms that contribute to the biomechanical behavior of the cornea is collagen fibril crimping. This phenomenon refers to the wavy or crimped nature of collagen fibrils in their relaxed state, which allows them to straighten when subjected to tensile forces. The collagen fibril crimping constitutive model describes how this structural arrangement affects the overall mechanical response of the cornea under different loading conditions. This article explains the structure and function of collagen fibrils in the cornea, the concept of crimping and how constitutive modeling is used to describe the mechanical behavior of the cornea.

The cornea is composed of five distinct layers: The epithelium, bowman's layer, stroma, descemet's membrane and endothelium. The stroma accounts for nearly 90% of the cornea's thickness and consists primarily of collagen fibers arranged in a lamellar structure. These collagen fibrils are essential for maintaining the mechanical properties of the cornea, as they provide resistance to external forces, such as intraocular pressure and allow the cornea to retain its shape.

Collagen fibrils in the stroma are arranged in a highly organized manner, with adjacent fibrils running parallel to each other within a lamella. The orientation of these fibrils changes between lamellae, with the fibrils in each layer running at different angles relative to those in the adjacent layers. This arrangement provides the cornea with multidirectional strength, allowing it to resist mechanical stress from different directions.

Crimping is a unique structural feature of collagen fibrils in which the fibrils exhibit a wavy or undulating pattern when relaxed. This crimped configuration allows the fibrils to straighten when stretched, providing the cornea with its characteristic nonlinear stress-strain response. In the absence of mechanical stress, the fibrils remain crimped, but as tensile forces increase, the crimp is gradually removed and the fibrils become more aligned with the direction of the applied load. This behavior is central to the biomechanical properties of the cornea and is a key component of constitutive models that describe corneal mechanics.

The crimping of collagen fibrils plays a vital role in the mechanical response of the cornea to external forces. In the relaxed state, the crimped fibrils can deform without generating significant resistance to stress. However, as tensile forces increase, the fibrils straighten, leading to a more rapid increase in stiffness. This nonlinear behavior allows the cornea to maintain flexibility at low stress levels while providing increased resistance at higher stress levels.

This crimping behavior is essential for protecting the cornea from damage under varying mechanical conditions. For example, during blinking, eye rubbing, or changes in intraocular pressure, the cornea must withstand forces without losing its structural integrity or transparency. The collagen fibril crimping mechanism allows for this adaptability, ensuring that the cornea can maintain its shape and function under different loading conditions.

A constitutive model is a mathematical framework used to describe the mechanical behavior of materials, taking into account their internal structure and response to stress and strain. For biological tissues like the cornea, constitutive models must account for the complex arrangement and mechanical properties of collagen fibrils, including their crimping behavior.

The collagen fibril crimping constitutive model specifically incorporates the effect of fibril crimping into the overall

Correspondence to: Sang Leo, Department of Biosciences, Rice University, Houston, United States of America, E-mail: sang@leo.edu

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mechanical response of the cornea. This type of model typically uses a multi-scale approach, considering both the behavior of individual collagen fibrils and the collective behavior of the entire tissue. By integrating the crimping mechanism into the model, researchers can more accurately predict how the cornea will respond to different types of mechanical stress. One of the primary factors influencing the mechanical response of the cornea is the orientation of collagen fibrils within the stroma. As mentioned earlier, collagen fibrils are arranged in lamellae, with different layers exhibiting different orientations. The fibril orientation distribution must be included in the constitutive model to capture the anisotropic (direction-dependent) behavior of the cornea. In the crimping model, the fibril orientation is described using a probability distribution that accounts for the varying angles of fibril alignment in different lamellae. This distribution affects how the crimped fibrils straighten in response to stress and how the cornea behaves under tension in different directions.