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A mesh-free approach to cornea -aqueous humor interaction during tonometry tests

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Abstract

The dynamic tonometer test (air-puff test) is an *in-vivo* investigative procedure routinely utilized in ophthalmology to estimate the intraocular pressure (IOP). A rapid, localized air jet applied on the anterior surface induces the inward motion of the cornea, which interacts with the aqueous humor — filling the narrow space between cornea and iris — and has a strong influence on corneal dynamics. Potentially, this quick and painless test could be combined with inverse analysis methods to characterize the patient-specific mechanical properties of the human cornea. As a step towards this aim, the present study describes a fluid-structure interaction (FSI) approach based on a simplified geometry to simulate the anterior chamber of the eye undergoing the air-puff test. We regard the cornea as a non-linear, elastic, and isotropic membrane described through an analytical model, discretizing the weakly compressible Newtonian fluid with a mesh-free particle approach. Numerical analyses reveal a marked influence of the fluid on corneal dynamics. Additionally, we investigate the possibility of using the test dynamics to estimate IOP.

Keywords: air-puff test, collocation methods, fluid-dynamics, fluid-solid interaction, mesh-free methods, particle methods

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1. Introduction

Experimental data on the human cornea obtained from *in-vivo* tests are of paramount importance for the design and implementation of predictive numerical methods in support of customized corneal refractive surgery. Patient-specific material properties must be determined necessarily by means of non-damaging tests performed on the anterior surface of the cornea. The most promising tests are based on the dynamic deformation of the cornea induced by a localized pressure following an assigned time history. During the test, the cornea snaps from the original convex shape to a locally concave shape and back. The inward deflection is contrasted by the presence of filling fluids (aqueous humor). In normal physiological conditions, fluids exert a uniform IOP on the posterior surface of the cornea, but during a dynamic test, the fluid pressure changes locally and loses uniformity. Advanced optical instruments (such as the Ocular Response Analyzer [Reichert Inc.; Buffalo, NY, USA] and the Corvis ST [Oculus Optikgerate GmbH; Wetzlar, Germany]) use a single rapid air jet applied at the center of the cornea to provide an estimate of the IOP together with diagrams of the evolution of the corneal apex displacement in the direction of the optic axis. Current numerical approaches to model the air-puff test are based on finite element technology. They use advanced solid models that reflect the complex collagen structure of the stroma and adopt anisotropic fiber reinforced material models for the solid parts.[1-7] Regrettably, the aqueous humor is always disregarded. A few attempts to account for the presence of the fluid include the use of spring-like elements or added fluid masses.[8,9] In this study, the interaction between aqueous humor and cornea is modeled explicitly to elucidate the influence of eye fluids on air-puff test dynamics.

The model comprises a membrane structure for the cornea and a mesh-free discretization (modified finite particle method, MFPM) for the fluid domain.[10] The dynamics of the anterior chamber of the eye undergoing an air-puff test are modelled as a FSI problem. For the sake of simplicity, axial symmetric conditions are considered and a non-linear isotropic material model is assumed for the solid. The solution is based on a partitioned approach. The simplified approach is the starting point for the development of an advanced 3-D model that will be employed to estimate the IOP and material properties by means of inverse analysis of multiple tests.

2. Model and results

2.1. Simplified model of the cornea and aqueous humor

The cornea is approximately a spherical cup (Fig 1a), but for modeling the air-puff test, a simplified axisymmetric configuration can be considered. Thus, the cornea reduces to a circular line, and the anterior chamber that contains the aqueous

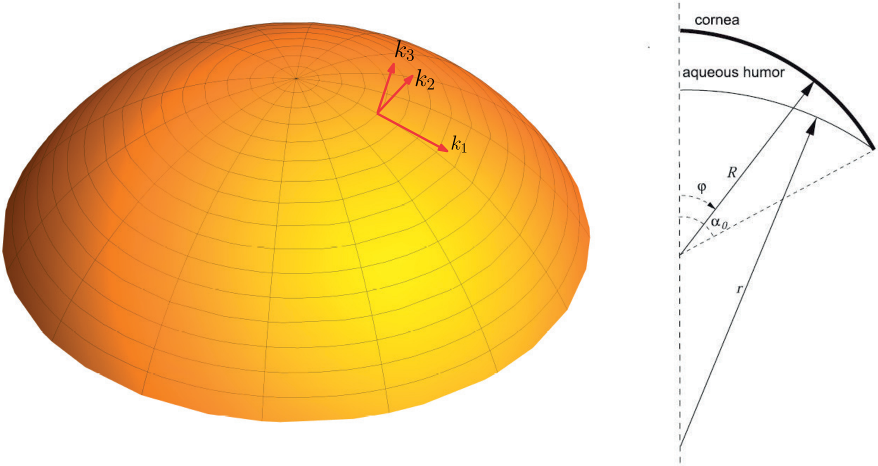

Fig. 1. (*a*) 3-D cornea spherical cup. (*b*) 2-D axis-symmetric approximation of the geometry of the cornea and anterior chamber.

humor becomes a closed surface (Fig. 1b). The posterior surface of the chamber, corresponding to iris and lens, is considered rigid.

The cornea is assumed to follow a classic isotropic hyperelastic material model able to capture the main non-linearities of biological tissues:

$$W = A\left[e^{\mathbf{C}(\mathbf{E}-\mathbf{E}_0)\cdot(\mathbf{E}-\mathbf{E}_0)} - 1\right] \tag{1}$$

where A is a material constant with the dimension of an elastic modulus, $\mathbf{C}$ denotes a dimensionless fourth order elasticity tensor, and $\mathbf{E}$ the Green-Lagrange strain. The strain energy attains a minimum at the reference configuration $\mathbf{E}_0$, where the corresponding stress is null. The physiological state is characterized by $\mathbf{E} = \mathbf{0}$ and non-zero values of energy and stress. Corneal dynamics is governed by a non-linear equation of motion, solved with finite differences in space and an explicit Newmark algorithm in time.

The aqueous humor is modeled as a Newtonian, weakly compressible fluid, and its behavior is described by mass and linear momentum balance equations. Within the MFPM approach, the fluid domain is discretized in a finite number of nodes where the differential operators of the fluid equations are approximated. The FSI solution strategy adopted in the present study is based on a partitioned algorithm. The solid and fluid problems are solved independently, and coupling is enforced by means of an iterative procedure involving the actions at the boundaries where solid and fluid interact.

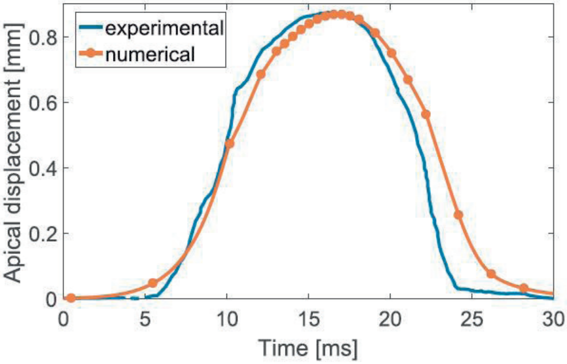

Fig. 2. Apex displacement vs time. Comparison between experimental data and numerical calculation.[7]

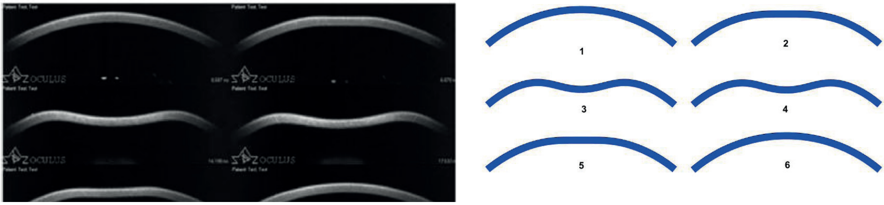

Fig. 3. Comparison between experimental and numerical results for the air-puff test at six different times. (*a*) Images of the Corvis ST output (http://www.healio.com). (*b*) Simulation results of the air-puff test with the present model.

2.2. Air-puff test simulation

The portion of the anterior surface of the cornea in proximity to the optic axis is loaded with the air-jet pressure, with a time history and a spatial distribution expressed by the equation:

$$p(t,\varphi) = p_{max} \exp[-a \sin^2 \varphi] \exp\left[-b\,\frac{(2t-T)^2}{4T^2}\right] \qquad (2)$$

where T (duration) is 30 ms, p_{max} (peak pressure) is 10 kPa, and the constants are set, a = 21.5 and b = 25, respectively.

Figure 2 shows a comparison between the experimental data provided by the Corvis ST and the numerical simulation of the present model in terms of time history of the apex displacement.

A qualitative comparison between the images recorded by the Corvis ST (http://www.healio.com) during an air-jet test and a few snapshots of the simulation are shown in Figure 3. The numerical and experimental shapes of the cornea profiles at different times of the test compare rather well.

3. Conclusions

The model captures two important features of the time history of the apex displacement:

1. the delay in corneal response, *i.e.*, the displacement of the apex occurs at a distinct time interval after the action of the air-jet pressure over the whole process; and
2. the lack of symmetry of the apex displacement history.

These features must be attributed to the motion of the fluid. In fact, in the case of dynamic analysis without explicit modeling of the fluid, both effects appear less marked.[8,9] Evidently, the presence of the fluid causes a general deceleration of corneal motion due to the time needed by the speed front to cross the fluid domain, which possesses its own inertia. Note that, in the interpretation of the air-puff test, response delays, which are dynamic effects, are often mistakenly associated to a viscous behavior of the corneal material.

The approach presented here is oversimplified, given that it is based on sweeping assumptions of axis-symmetric geometry and isotropy of the material. Therefore, it is far from possessing any predictive ability. Nonetheless, it represents the very first application of a mesh-free method to the study of corneal dynamic behavior. In its simplicity, the model is sufficiently advanced to demonstrate the need for modeling the filling fluid in the dynamic analysis of the cornea undergoing the air-puff tests in order to avoid a wrong estimate of the material properties of ocular tissues.

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