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Fluid structure interaction of the non-contact tonometry test

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Abstract

The study of corneal biomechanics has gained interest due to its applications on predicting refractive surgery outcomes and the study of a number of pathologies affecting the cornea. In this regard, non-contact tonometry (NCT) has become a popular diagnostic tool in ophthalmology and as an alternative method to characterize corneal biomechanics. Since identification of material parameters using NCT tests rely on the inverse finite element method, accurate and reliable simulations are required. In this work, we present a full fluid structure simulation of a NCT test accounting for the effect of the presence of the humors. The results indicate that when inertial effects are considered, not including humors may lead to overestimating corneal displacement, and therefore, to an overestimation of the actual corneal stiffness when using the inverse finite element method.

Keywords: corneal mechanics, fluid structure interaction (FSI), non-contact tonometry (NCT)

1. Introduction

NCT has recently gained interest as a diagnostic tool in ophthalmology and as

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an alternative method for characterizing the mechanical behavior of the cornea. In a NCT test, a high-velocity air jet is applied to the cornea for a very short time (< 30 ms), causing the cornea to deform, while corneal motion is recorded by a high-speed camera. A number of biomarkers associated with corneal motion, *i.e.*, maximum corneal displacement and time between first and second applanation, among others, have been proposed to characterize pre- and postoperative biomechanical changes.[1–4] Identification of the material parameters associated with corneal mechanical behavior by means of a NCT test is usually performed using the inverse finite element method.[5-6] Hence, an accurate simulation of the NCT test is required. In this regard, most approaches model the NCT test as a quasi-static problem, considering only the cornea subjected to a constant intraocular pressure (IOP), and neglecting the inner structures of the eye, *i.e.*, the lens, ciliary muscles, and most importantly, the aqueous and vitreous humors. Considering that, during a NCT test, the dynamic pressure on the anterior surface of the cornea rises from 0 to 9~15 kPa in approximately 10 ms — implying a loading rate of approximately 1 MPa/s — neglecting inertial effects may result in inaccurate results. In this work, we perform fluid structure interaction (FSI) simulations in a 2-D model of the eye accounting for inertial effects and evaluating the effect of considering or not the presence of the humors in the model of the eyeball. Results indicate that when inertial effects are accounted for in the simulations, neglecting the humors in the model will lead to non-physiological results.

2. Methods

An axisymmetric 2-D model of the eyeball including the crystalline and ciliary muscles as inner structures as well as both humors — vitreous and aqueous – have been considered, as shown in Figure 1.

The cornea was modeled as an isotropic material described by a strain energy function of the form:[5]

$$W_{cornea} = D_1 \left(e^{D_2(\bar{I}_1-3)} + 1\right) + \kappa(J-1)^2 \tag{1}$$

where $\bar{I}_1$ is the first invariant of the modified right Cauchy-Green tensor, $\overline{C}$, $J = \sqrt{\det C}$ is the elastic volume ration, D_1 = 7.56e-5 MPa and D_2= 99.2 are material constants chosen such that they fit inflation test experiments,[7] and κ is the bulk modulus. The sclera and ciliary muscles were also modeled as isotropic materials with strain energy function:

$$W_{sclera} = C_{10}(\bar{I}_1-3) + C_{20}(\bar{I}_1-3)^2 + C_{30}(\bar{I}_1-3)^3 + \kappa(J-1)^2 \tag{2}$$

where C_{10} = 0.81 MPa, C_{20} = 56.05 MPa, and C_{30} = 2,332.26 MPa. The lens and the

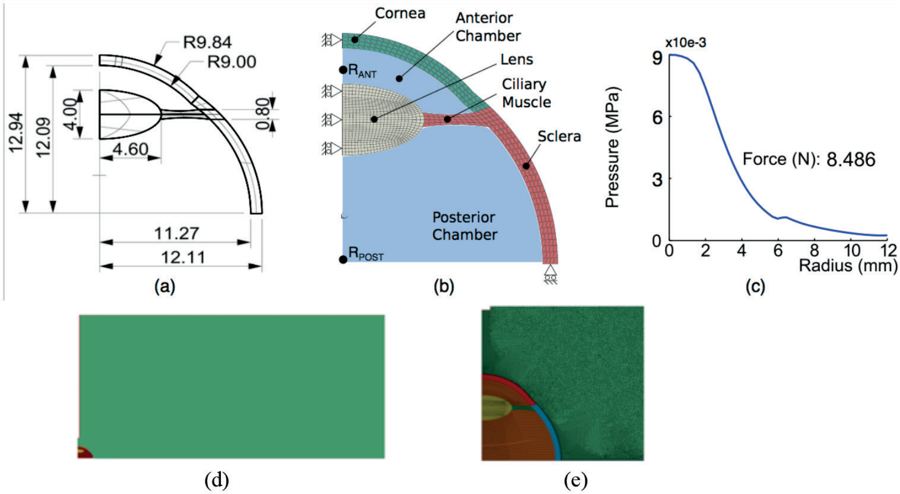

Fig. 1. Eyeball model. (*a*) Geometry. (*b*) Main parts. (*c*) Resulting pressure profile of the cornea. (*d*) Computational domain. (*e*) Detail of the finite element mesh.

muscle have been modeled as linear elastic materials with E = 1.45 MPa and E = 0.35 MPa, respectively, both considered highly incompressible (ν = 0.47). The humors were considered as water.

The air jet was applied as a ramp from 0 to 135 m/s in 10 ms and then back to zero velocity in 15 ms. Zero pressure was imposed as the outflow condition, and a turbulent flow model was used for the simulations. An IOP of 2 kPa was applied before initiating the air jet (Fig. 1). A mesh-sensitivity analysis was performed in the structural part in order to determine the minimum number of elements required for modeling the bending mode of the cornea. All simulations were performed using LS-DYNA Release 9.0 (LSTC, Livermore CA, USA and ANSYS, Inc., Canonsburg PA, USA) with Incompressible Computational Fluid Dynamics (ICFD) as fluid solver.

3. Results

The air jet caused a deflection in the cornea that reached its maximum value of 0.41 mm in correspondence with the peak velocity of the air jet (Fig. 2), as observed in actual application with the CorVis ST (OCULUS Optikgeräte GmbH Wetzlar, Germany) NCT.[4] During loading, the pressure in the anterior and posterior chambers of the eye (aqueous and vitreous humors) increased by three times (from 2 kPa to approximately 6 kPa), indicating that IOP changes due to the air-jet loading. In addition, as shown in Figure 2, the dynamic pressure exerted by the air jet is concentrated in an area of 6 mm in diameter with a Gaussian type spatial dis-

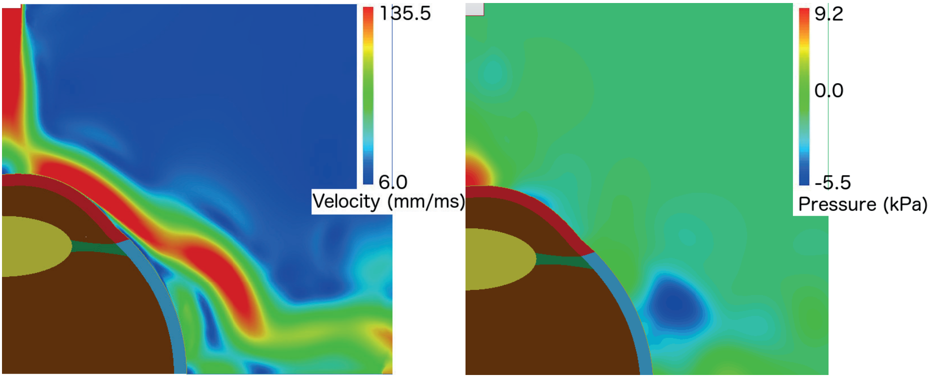

Fig. 2. Velocity field (*left*) and pressure distribution (*right*) of the air jet when the maximum velocity (135 m/s) is reached. At the same time, the cornea reaches maximum concavity.

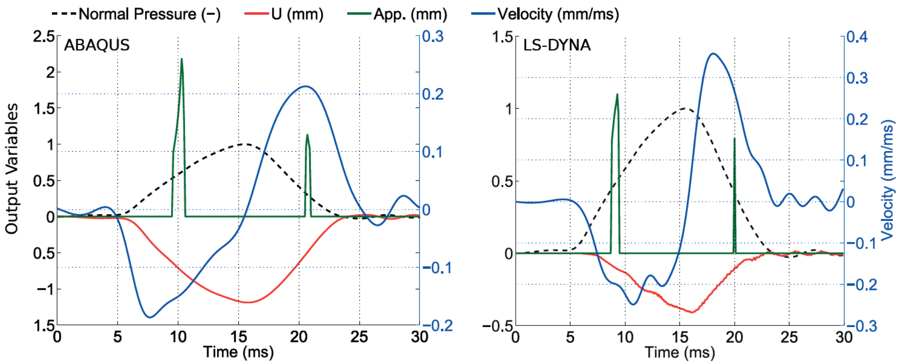

Fig. 3. Displacement and velocity of the apex of the cornea, and corneal applanation with and without humors. From 0 to 30 ms, both models are pressurized and stabilized at the IOP, after an air jet that lasted 25 ms.

tribution, and reaches the maximum value of 9.1 kPa, which is compatible with the theoretical value of 9.0 KPa.

The displacement experienced by the cornea is quite sensitive to the presence of humor in the model. If the simulation is performed without humor (using FSI and only structure analysis) with a constant IOP of 2 kPa, corneal displacement results five times greater (results not shown). If, on the contrary, a pure structural analysis is conducted, but allowing an increment of the cavity pressure with the deformation (fluid cavity feature in Abaqus), the maximum corneal displacement results three times greater with respect to the case of FSI with humors. These results indicate that humors are necessary in the model (Fig. 3).

4. Discussion and conclusions

NCT is gaining popularity as diagnosis tool in ophthalmology. A number of studies are considering this test as an alternative to characterize the mechanical behavior of corneal tissue.[3-5] However, in order to understand the contribution of the cornea to the mechanical response measured by the air jet, accurate simulations of the tests are required. Results from this study indicate that FSI simulations accounting for the presence of internal humors in the eye are required in order to accurately simulate the NCT test. Neglecting the humors and imposing a constant IOP during simulation lead to larger displacements of the cornea. In addition, these results indicate that most of the dynamic loading imposed by the air jet is absorbed by the humors, with minimal corneal contribution. Additional tests are required to study the sensitivity of the results (maximum corneal displacement) on the mechanical properties of the cornea and its thickness.

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