Non Contact Tonometry: a Fluid Structure Interaction study

Elena Redaelli[1], Benedetta Fantaci[1], Jorge Grasa[1], Giulia Luraghi[2], José Félix Rodriguez Matas[2]

[1] Applied Mechanics and Bioengineering (AMB)
Instituto de Investigación en Ingeniería de Aragón (I3A)
Universidad de Zaragoza, Mariano Esquillor s/n, 50018, Zaragoza, Spain.
Tel. +34-976762707, e-mail: elena.redaelli@*unizar.es*
[2]Politecnico di Milano, Italy

Abstract

Non Contact Tonometry is a clinical tool that records the displacement of the corneal surface caused by the application of an airflow. The measurements are not true representatives of corneal properties, but they are related. The proposed analysis simulates the test on an eye model to isolate the mechanical properties and establish clinical decisions.

Introduction

The cornea is the primary refractive surface of the eye, responsible for approximately ⅔ of its optical power [1]. The corneal shape is the result of the equilibrium between its *mechanical stiffness*, *intraocular pressure* (IOP), and the *external forces* acting upon it. An imbalance between these parameters can produce ocular pathologies which seriously affect patient sight. Consequently, it is important to understand how ocular factors are related to pathologies in order to improve treatments [2]. The Non Contact Tonometry (CorvisST) is a diagnostic tool that aims at determining the IOP and characterizing the mechanical properties of the corneal tissue by applying a short high velocity air-jet to the tissue. A deeper understanding of the process is required to translate the results of the test into clinical data. From a modelling perspective, the best numerical approach to reproduce the procedure is the Fluid Structure Interaction (FSI) modelling [3]. This work presents a FSI analysis to virtually apply an air-jet to a 3D averaged eye model.

Materials and Methods

In the first part of the study, the explicit finite element solver LS-DYNA (ANSYS) is employed to carry out simulations to set the parameters of the eye, the biomechanical properties of the structural part. The fluids involved are two: the humors, which are analyzed through a Lagrangian approach, and the air surrounding the eye, studied through an ALE approach. The Non Contact Tonometry is reproduced by means of a two way Fluid Structure Interaction simulation through the implicit ICFD solver in LS-DYNA (ANSYS).

Model of the Eye

The 3D model of the eye includes the cornea, the limbo, the sclera, the crystalline lens, the Zinn's Zonule, and the vitreous and aqueous humor (Fig. 1a). The model is axisymmetric about the optical axis, thus only one quarter of the globe is examined in order to reduce the computational costs. The geometry is obtained from averaged anatomic measures; all the parts are meshed with hexahedral solid elements. Axial displacements and rotations are restrained at the bottom surface of the sclera and at the axis of symmetry. The lens and the Zinn's Zonule are modelled with a linear elastic material, the sclera with an isotropic hyperelastic material, while the limbo and the cornea with anisotropic hyperelastic materials. The cornea is made of two families of collagen fibers perpendicular to each other; the limbo is made of one circumferential family of fibers. The direction of the fibers is included in the simulation by means of a Matlab code. The humors are modeled as Newtonian fluids embedded inside the ocular cavity at an intraocular pressure of 15 mmHg. At a first step, it is necessary to find the zero-pressure configuration of the eye, the geometry associated with the absence of IOP. An iterative Matlab algorithm that updates the nodal coordinates and the direction of the collagen fibers is employed. Starting from the zero-pressure configuration, a uniform load of 15 mmHg is applied to the structure of the eye with a ramp curve. When the structure is loaded, a contact between the structure and the humor is activated so that the structure transfers the pressure to the fluid inside the cavity.

Non Contact Tonometry simulation

The air surrounding the eye is modelled as an incompressible fluid (Fig. 1b); the air-jet is simulated imposing a velocity waveform to the air as the inlet boundary condition. The velocity waveform reaches 120 m/s in 15 ms and then returns to zero velocity in

10 ms. Zero pressure is imposed as the outflow condition and a variational multiscale based turbulent flow model is used for the simulation.

Results

The Non Contact Tonometry monitors the bidirectional deformation of the cornea through two applanation points during loading (the cornea deforms inwardly) and unloading[1]. At the first applanation point, the pressure of the air on the corneal surface (P1) is recorded. Figure 2a shows that the maximum pressure at the first applanation point is in the part of the air in contact with the center of the cornea. When the first applanation point is reached, the inlet velocity starts decreasing, simulating the deactivation of the air-jet. The contour of the air velocity at the first applanation point is plotted in figure 2b. The same quantities can be calculated at the second applanation point, during the unloading phase. In particular, with the pressure at the second applanation point (P2), the Corneal Hysteresis (CH) can be calculated: CH = P2-P1. The CH gives information about the dissipation of energy of the corneal tissue during the loading/unloading response, thus the viscoelastic properties of the cornea. The variation of the intraocular pressure (IOP) during the test and the maximum apical corneal displacement depend on the biomechanical properties of the tissues. Figures 3a and 3b show these two quantities at the first applanation point. While the pressure in the aqueous humor varies during the test, the pressure in the vitreous humor is not influenced due to the stiffness of the lens and the muscles. The maximum apical corneal displacement is reached in the center of the cornea.

Conclusions

The development of a strong FSI tool amenable to model coupled structures and fluid can be useful to correlate the results of the Non Contact Tonometry test to the biomechanical properties of the cornea. With the proposed simulation, it is possible to vary the mechanical stiffness of each tissue of the eye studying the influence that each parameter has on the results of the test. Moreover, the eye can be modelled with different intraocular pressures in order to study the effect of the IOP on the Non Contact Tonometry. In a second step, the properties of the corneal tissue can be determined through an optimisation process by numerically reproducing the deformation of the cornea.

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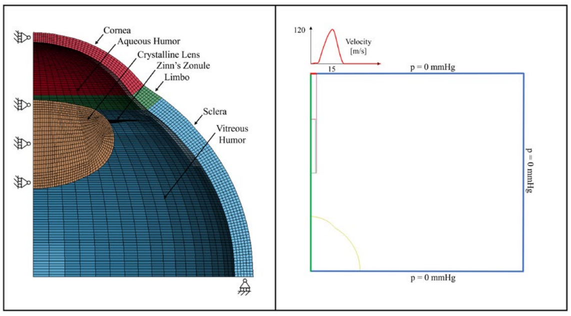

Figure 1: (a) Eye model geometry and boundary conditions. (b) Fluid domain and boundary conditions.

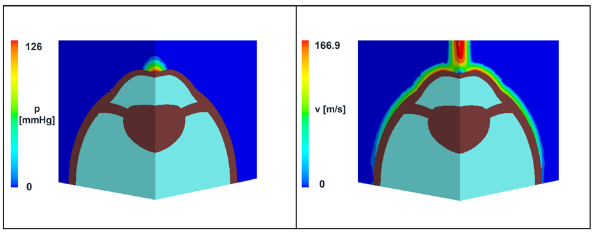

Figure 2: (a) Air pressure in mmHg at the first applanation point. (b) Air velocity in m/s at the first applanation point.

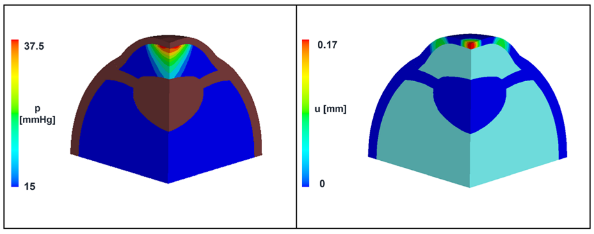

Figure 3: (a) IOP in mmHg at the first applanation point. (b) Maximum apical corneal displacement at the first applanation point.