Corvis ST biomarkers in healthy and keratoconus eyes: clinical and numerical evaluation

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Abstract

Non-Contact Tonometry (NCT) is a diagnostic tool intended to characterize corneal biomechanics in vivo. In order to analyze the response of the corneal tissue behavior, a numerical model could be of great help. This work aims to validate an in-silico NCT by comparing the clinical biomarkers of four patients to the numerical results of the same patient-specific simulations.

Introduction

Keratoconus (KC) is a corneal disease characterized by a region of high curvature and reduced thickness[1]. Understanding the biomechanical properties of the healthy and diseased region is significant to diagnose this pathology in time. Non-contact tonometry (NCT) (Corvis ST® [2]) is a non-invasive diagnostic tool intended to characterize corneal biomechanics in vivo by applying a defined air pulse to the cornea. During the test, the cornea deforms inward and then recovers to its original shape. The deformation depends on the interaction between the air pressure, the intraocular pressure (IOP), the thickness, and the biomechanical properties of the tissues involved. To detect the mechanical properties of the healthy and diseased cornea, a finite element method (FEM) is necessary. The best numerical approach to model the procedure is the Fluid-Structure Interaction (FSI) simulation [3] in which the structural governing equations of the eye are coupled with the fluid equations of the air. This work presents four patient-specific simulations of two healthy and two keratoconus corneas subjected to Corvis ST. The clinical biomarkers are compared with the numerical outputs to validate the procedure.

Materials and Methods

All the simulations are carried out using a 14 core Intel i9-10940X (3.30GHz) processor with the finite-element solver LS-Dyna R 13.0 (LSTC, Livermore CA, USA). The structural part is solved through the implicit structural solver, whereas the air is solved using the implicit ICFD solver.

Patient-specific corneal model

The finite element corneal models are constructed based on data retrieved by *Pentacam*® [4]. Pentacam is a tomographer which creates an elevation map and a pachymetry map (corneal thickness measured in microns). The elevation map represents the anterior surface of the cornea through a point cloud; by subtracting point to point the pachymetry data from the elevation data, the posterior point cloud data can be achieved. Then, through the software ANSA Pre Processor v22.01 (BETA CAE Systems, Switzerland) a surface fitting is performed, and the corneal geometry is obtained. Each geometry is then linked to an idealized limbo and sclera with idealized dimensions taken from the literature [3]. The cornea and the limbus are modelled as anisotropic nearly incompressible hyperelastic materials while the sclera is modelled as isotropic. The humours are modelled as incompressible fluids pressurized at a spatially homogenous intraocular pressure (IOP). Initially, the zero-pressure configuration of each eye is computed following an iterative algorithm. Then, a positive input flow rate is imposed on the fluid cavities to reach the patient-specific IOP.

Fluid-Structure Interaction simulation

The inlet Gaussian air puff velocity of the Corvis ST® (maximum of 120 ms during a period of 20 ms) is imposed at a nozzle 11 mm distant from the corneal apex. Zero pressure is imposed as an outlet boundary condition. The air is modelled as an incompressible fluid whose density and dynamic viscosity are $\rho = 1.25$ kg/m^3 and $\mu = 1.8 \cdot 10^{-5}$ Pa·s, respectively. A turbulence model based on a variational multiscale approach is assumed.

Results and Discussion

The results of the corneal reconstructions for two patients are reported in Fig. 1. The axial curvature and the thickness of the cornea computed by Pentacam are compared to the same parameters of the reconstructed model. The axial curvature is computed following equation 1 as reported in the Pentacam manual.

$$\mathbf{K(dpt)} = \frac{\mathbf{1{,}3375-1}}{\mathbf{r_{ANTERIOR}}} \cdot \mathbf{1000} \qquad [1]$$

In healthy patients, the curvature is almost constant all over the surface and the thickness varies from 550 µm at the centre of the cornea to 800 µm at the periphery. In keratoconus patients, a region in which the curvature is higher can be identified. Moreover, the thickness corresponding to the keratoconus region is lower reaching 450 µm. The FEM models reproduce correctly the geometrical clinical data. The air puff velocity streamlines for one patient are depicted in Fig. 2.a. One of the advantages of the numerical simulation is the possibility to analyse the 3D response of the cornea rather than only the equatorial plane (Fig 2.b) like the clinical evaluation of Corvis ST. The main biomarkers inferred from Corvis ST are compared in the four cases; an example is shown in Fig 2.c, where the comparison between the clinical deflection amplitude and the numerical displacement of the apex is shown. The congruability of three biomarkers in the four cases demonstrates that the simulations proposed can be used for further analysis regarding the corneal biomechanics.

Conclusions

The validation of patient-specific FSI simulations to model NCT have shown very promising results and constitute a fundamental step to find accurately the corneal tissue properties of both healthy and pathological eyes.

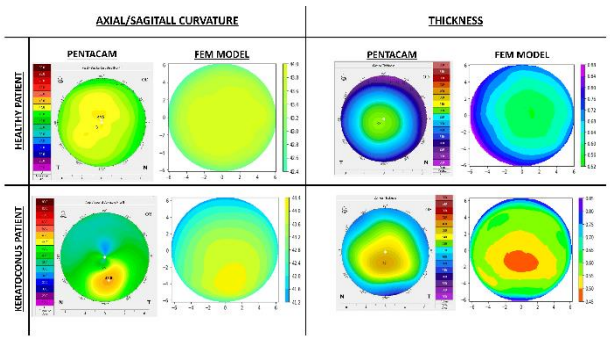

Fig 1: Comparison of curvature and thickness in the clinical data and the reconstructed FEM model. Results for one healthy and one KC patients are presented.

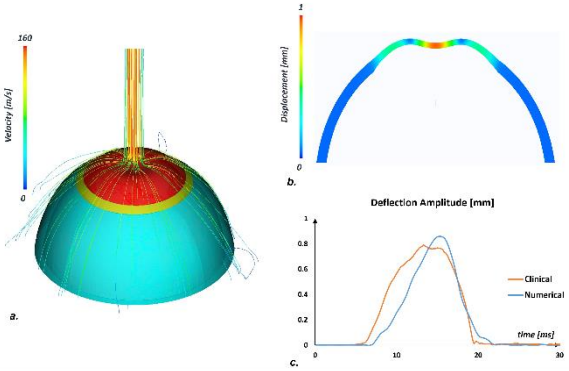

Fig 2: (a) Air velocity streamlines in the instant of highest concavity (HC) of the eye. (b) equatorial section of the eye in the instant of HC. (c) clinical and numerical evaluation of deflection amplitude for an healthy patient.

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