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Theoretical and numerical analysis of the corneal air puff test

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ABSTRACT

Ocular analyzers are used in the current clinical practice to estimate, by means of a rapid air jet, the intraocular pressure and other eye's parameters. In this study, we model the biomechanical response of the human cornea to the dynamic test with two approaches. In the first approach, the corneal system undergoing the air puff test is regarded as a harmonic oscillator. In the second approach, we use patient-specific geometries and the finite element method to simulate the dynamic test on surgically treated corneas. In spite of the different levels of approximation, the qualitative response of the two models is very similar, and the most meaningful results of both models are not significantly affected by the inclusion of viscosity of the corneal material in the dynamic analysis. Finite element calculations reproduce the observed snap-through of the corneal shell, including two applanate configurations, and compare well with in vivo images provided by ocular analyzers, suggesting that the mechanical response of the cornea to the air puff test is actually driven only by the elasticity of the stromal tissue. These observations agree with the dynamic characteristics of the test, since the frequency of the air puff impulse is several orders of magnitude larger than the reciprocal of any reasonable relaxation time for the material, downplaying the role of viscosity during the fast snap-through phase.

1. Introduction

The cornea, the external convex–concave spherical lens of the eye, has the main functions to deviate the light rays onto the retina and to protect the delicate interior components of the eye. The spherical shape of the cornea is maintained by the action of the intraocular pressure (IOP), whose physiological range is 12–20 mmHg.

High IOP values are in general associated to pathological situations, such as glaucoma (Farandos et al., 2015). Early detection and monitoring of glaucoma require frequent IOP measurements through a specific device called tonometer. The tonometer applies a pressure on a delimited area of the external surface of the cornea, and IOP measurements are taken when a particular configuration is reached. Most tonometers commonly used in the clinical practice are based on static contact between instrument and cornea. Among static tonometers, the so-called Goldmann tonometer (GT) is considered to be the standard. When the tonometer's head, in contact with the cornea, detects the applanation of the portion of the corneal surface, it returns an estimate of the IOP (Goldmann and Schmidt, 1957). Like all non-invasive methods, the GT is inherently imprecise. Moreover, its measurements are based on the assumption that the effects of the corneal rigidity and the effects due to the presence of the tear film cancel out. But this is not always the case, especially if the cornea has been

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reprofiled by laser ablation refractive surgery (Chihara, 2008).

Drawbacks of static tonometry have been outwitted by the recent development of dynamic tonometers based on high speed camera imaging, such as the Ocular Response Analyzer (ORA; Reichert, Inc., Buffalo, NY), and the CorVis ST (CorVis ST; Oculus Optikgerate GmbH, Wetzlar, Germany). These advanced optical instruments use a rapid single air jet to modify visibly and temporarily the corneal shape. During the air puff test, the cornea snaps from its original convex shape to a locally concave shape, passing through two configurations characterized by an applanate zone. Applanation times and other shapes of the cornea during the test are used to compute a number of different parameters, expected to have some relevance in the biomechanical behavior of the cornea. Regrettably, none of them is clearly understood, because they cannot be related directly to the material properties of the cornea, nor to the eye's IOP (Martinez de la Casa et al., 2006; Piñero and Alcón, 2014). Some of the parameters supplied by the ORA have gained a certain level of popularity, in particular the corneal hysteresis (CH), defined as the difference between the pressures of a symmetric internal supply air plenum curve at the times of the two applanations (Luce, 2005). In general, the value of the second applanation pressure is smaller than the first applanation pressure, and the pressure drop roughly correlates to a sort of corneal "strength". According to the manufacturer, CH is an assessment of the cornea's ability to absorb and dissipate energy. This theory has been supported by some authors, which interpreted CH as an indicator of viscous and elastic properties of the cornea (Glass et al., 2008).

The dynamic features of the air puff test have been analyzed in recent studies. A numerical interpretation of the air puff test in dynamic terms, based on a simple one degree-of-freedom model, has been proposed in Han et al. (2014). Finite element models of the test, that account for the fluid-dynamics of the air jet, have been presented in axis-symmetric setting (Kling et al., 2014), using a pressure space–time profile obtained by combining preliminary CFD calculations and air jet pressure measurements taken during the test; and in fully tridimensional setting (Ariza-Gracia et al., 2015; Sinha Roy et al., 2015), using a CFD approach to account for the fluid–solid interaction between the air jet and the anterior surface of the cornea. Along this line, the main goal of this study is to understand whether the behavior of the cornea during the air puff test is driven by elasticity or there is an important contribution of material viscosity. Additionally, we want to understand how geometrical changes due to corneal laser refractive surgery may affect the results of the test.

We analyze the behavior of the corneal system undergoing the air puff test by using two different approaches, which differ in terms of conceptual complexity and amount of delivered results. In the first simplified approach, we approximate the corneal shell as a one-degree-of-freedom (1DOF) dynamic system, with the aim of understanding the fundamental physics underlying the air puff test. The simplicity of the model, characterized by a mass, a spring, and a dashpot, leads to an analytical solution that allows to identify the main aspects of the process and the relevance of the parameters governing the air puff test. In particular, the displacement and velocity of the mass are obtained in closed-form, and the results are useful to distinguish the effects of viscosity and elasticity, as conceived in mechanics of materials. The second approach is based on a fully tridimensional geometrically patient-specific finite element model of the human cornea (PSFE), reconstructed from digital data acquired on healthy patients through a corneal topographer (Sirius CSO, Scandicci, Italy). The PSFE model allows us to simulate accurately the response of the cornea to the air puff tests. In the limits of the current technology, the PSFE model has been proved to be reliable and predictive in quasi-static simulations (Sánchez et al., 2014; Simonini and Pandolfi, 2015). Our results agree with the experimental data provided by clinical ocular instruments.

The two models, albeit far apart in accuracy and apparently weakly correlated, compare reasonably well in terms of qualitative response, and agree in revealing the dominant aspects of the mechanics of the air puff test. The reason that moved us to analyze the simplified 1DOF model is the intuition that the mechanical response of the cornea's material to the air puff test is primarily—at least in the loading phase, i.e., when the air pressure is applied—an undamped dynamic phenomenon, where time scales are not long enough to activate time-dependent effects in the cornea's materials. The significance of the 1DOF model and its correlation to the sophisticated PSFE model can be grasped by comparing the first natural frequency of cornea and filling fluid system with the frequency of the air puff jet. As it will be shown later, the closeness of the two frequencies suggests that the process is dominated by dynamics, thus inertia effects prevail over other time dependent aspects. We can verify this intuitive idea using a 1DOF system, and assess qualitatively the influence of inertia and damping.

The paper is organized as follows. In Section 2.1 we describe the output of two ocular instruments used to perform the air puff test on human corneas. In Section 2.2 we describe the 1DOF model and in Section 2.3 the PSFE model, both used to simulate the air puff test. Results of the numerical investigations are collected in Section 3. In Section 4 we compare numerical and experimental results (taken from the literature) on air puff tests and discuss the possibility to use the test for the characterization of the corneal material properties.

2. The air puff test and the numerical models

2.1. Clinical ocular instruments for air puff tests

We refer to air puff tests carried out with two common clinical optical instruments. The sudden pulse exerted by these instruments causes the inwards motion of the cornea, which passes through an applanation, and successively snaps into a slight concavity. When the air pulse pressure decreases, the elastic corneal tissue recovers the original configuration, passing through a second applanation. Some instrument provides the time history of the jet air pressure and of a light signal intensity reflected by the corneal anterior surface, from where it is possible to derive information on the deformative state of the cornea.