Available online at www.sciencedirect.com
ScienceDirect
Comput. Methods Appl. Mech. Engrg. 340 (2018) 202–215
Computer methods in applied mechanics and engineering
www.elsevier.com/locate/cma

Fluid–structure simulation of a general non-contact tonometry. A required complexity?

Miguel Ángel Ariza-Gracia[a,e,*], Wei Wu[b], Begoña Calvo[a,c], Mauro Malvè[d], Philippe Büchler[e], José F. Rodriguez Matas[f]

[a] Aragón Institute of Engineering Research (i3A), Universidad de Zaragoza, Zaragoza, Spain
[b] Department of Mechanical Engineering University of Texas at San Antonio, San Antonio, TX, USA
[c] CIBER in Bioengineering, Biomaterials & Nanomedicne (CIBER-BBN), Spain
[d] Department of Mechanical Engineering, Universidad Pública de Navarra, Pamplona, Navarra, Spain
[e] Institute for Surgical Technology and Biomechanics (ISTB), Universität Bern, Bern, Switzerland
[f] LaBS, Department of Chemistry, Materials and Chemical Engineering "Giulio Natta", Politecnico di Milano, Milano, Italy

Received 1 March 2018; received in revised form 23 May 2018; accepted 24 May 2018
Available online 1 June 2018

Abstract

Understanding corneal biomechanics is important for applications regarding refractive surgery prediction outcomes and the study of pathologies affecting the cornea itself. In this regard, non-contact tonometry (NCT) is gaining interest as a non-invasive diagnostic tool in ophthalmology, and is becoming an alternative method to characterize corneal biomechanics in vivo. In general, identification of material parameters of the cornea from a NCT test relies on the inverse finite element method, for which an accurate and reliable modelization of the test is required. This study explores four different modeling strategies ranging from pure structural analysis up to a fluid–structure interaction model considering the air–cornea and humor–cornea interactions. The four approaches have been compared using clinical biomarkers commonly used in ophthalmology. Results from the simulations indicate the importance of considering the humors as fluids and the deformation of the cornea when determining the pressure applied by the air-jet during the test. Ignoring this two elements in the modeling lead to an overestimation of corneal displacement and therefore an overestimation of corneal stiffness when using the inverse finite element method.

Keywords: Corneal biomechanics; Dynamic simulations; Fluid–structure interaction simulations; Non-contact tonometry

1. Introduction

Elevated intraocular pressure (IOP) is responsible for the damage of the optical nerve. Prolonged exposition to this mechanical load leads to glaucoma and, eventually, to blindness. Since this degenerative process is generally asymptomatic, a number of devices have been developed to monitor the ocular pressure [1–3]. The first developed

* Corresponding author at: Aragón Institute of Engineering Research (i3A), Universidad de Zaragoza, Zaragoza, Spain.
E-mail addresses: mariza@unizar.es, miguel.ariza@istb.unibe.ch (M.Á. Ariza-Gracia).

https://doi.org/10.1016/j.cma.2018.05.031
0045-7825/

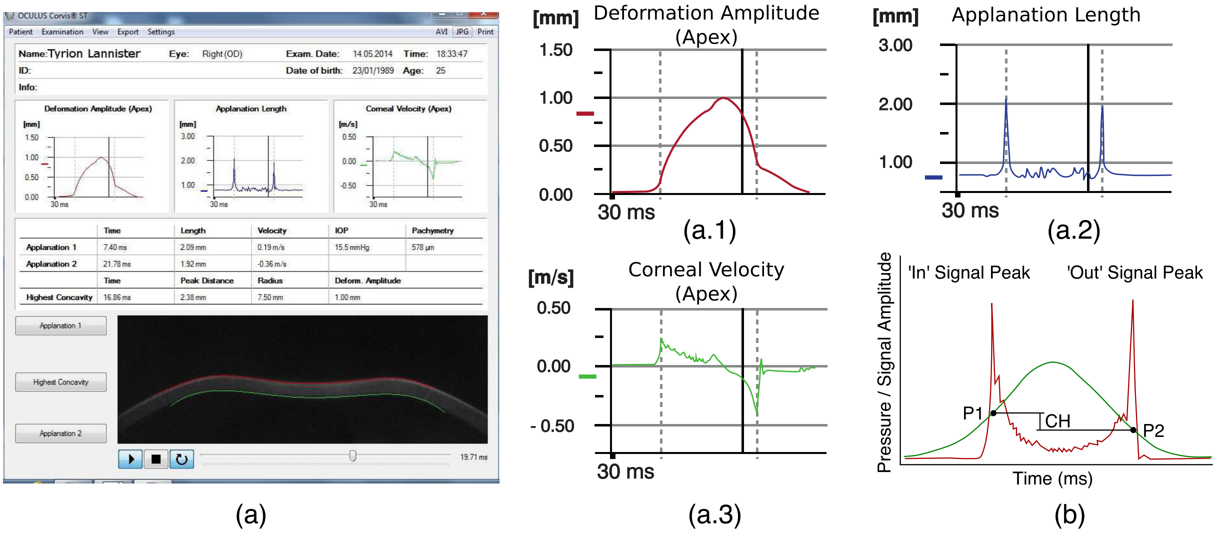

Fig. 1. Mechanical markers measured with non-contact tonometers: CorVis and Ocular Response Analyzer (ORA): (a) Capture of CorVis's Graphic User Interface. Based on medical imaging (corneal section in the bottom), different biomarkers are measured: (a.1) deformation amplitude, (a.2) applanation length and time, (a.3) corneal velocity. The deformation amplitude measures the displacement of the apex over time, the applanation length gives the greatest flattened area of the cornea when going inwards/outwards and the time at which they happened, and the corneal velocity gives the velocity of the apex over time; (b) Corneal Hysteresis (Orbscan) is the difference between the pressure measured at the first applanation (going inwards) and the second applanation (going outwards) ($CH = P_1 - P_2$).

devices measured the IOP by direct contact with the cornea e.g. the Goldman tonometer, whereas the new generation of non-contact tonometers (NTC), are able to measure the IOP without direct contact with the cornea. Non-contact tonometers rely on a short air pulse to induce a deformation of the cornea. During corneal deformation, a two-dimensional transversal slice is recorded using a Scheimpflug camera (see Fig. 1a) from which the IOP pressure is calculated. In addition to the estimation of the patient's IOP, these devices provide with additional mechanical markers derived from the evolution of the corneal curvature over the time of the test [4–6]. Some of these markers are: (i) the deformation amplitude (see in Fig. 1a.1), (ii) the first and second applanation times and lengths (see in Fig. 1a.2), (iii) the corneal speed (see in Fig. 1a.3), and (iv) the corneal hysteresis (see in Fig. 1b). These mechanical markers aim at being used to assess the result of a refractive surgery [7] or to evaluate the evolution of certain pathologies such as keratoconus [8].

The mechanical response of the ocular system during a NCT measurement is complex. The process relies on an air pulse of amplitude 5 to 8 times the physiological IOP, of the order of 15 mmHg, and duration of approximately 30 ms [4–6,9]. The mechanisms responsible for the load transfer from the air jet to the cornea are complicated as they depend on the patient's anatomy and position, the intraocular pressure, and the mechanical properties of the cornea among others. In addition, the fast corneal loading due to the air-puff induces a complex dynamic response of the eyeball. For these reasons, the measurement of the IOP for clinical use is not directly provided by a mechanistic analysis of the NCT test, but is determined indirectly through empirical correlations between the measured deformation profile of the cornea and known intraocular pressure measurements [10]. In addition, the mechanical markers currently obtained with this method lack of a direct physical interpretation and their use for the treatment of patients should be handled with care.

Despite of the limitations, non-contact tonometry is appealing to obtain a patient-specific characterization of the mechanical condition of the eye in vivo. However, a deeper understanding of the mechanisms, and their interactions, involved in the test is required in order to correctly translate these results to the clinic, or to instruct computational models used for planning refractive interventions.

Few studies have been performed to simulate a non contact tonometry test. To date, most studies have been limited to structural analysis considering the mechanical response of the cornea only, neglecting the internal structures in most cases, and ignoring the fluid–structure interaction of the air with the cornea during the test. Kling et al. [11] used two-dimensional CFD simulations with different corneal deformations to determine the pressure applied to the