A New Procedure to Estimate Patient-Specific Intraocular Pressure

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Abstract
Measuring Intraocular Pressure (IOP) is a critical field of research in ophthalmology. This work presents and energetic approach to study the Non Contact Tonometry based on the results of a Fluid Structure Interaction simulation. Then, combining these results with clinical images, a new method to estimate the IOP is proposed.

Introduction
Glaucoma, a leading cause of blindness worldwide, is primarily caused by elevated intraocular pressure (IOP)[1]. Accurate and reliable IOP measurements are the key to diagnosing the pathology in time and to provide for effective treatment strategies. Measuring IOP is also important for other eye conditions which can have serious consequences for vision and overall eye health. The currently available methods for measuring IOP include contact and non-contact tonometers (NCT), which estimate IOP based on the Imbert-Fick law. This law states that an external force applied to a sphere is equal to the pressure inside the sphere multiplied by the applanation area. Consequently, the estimation of IOP is based on the direct relationship with the time of initial applanation caused by an external load, that in the case of NCT is an air pulse. The deformation of the cornea during the tonometry is the result of the coupling between four factors: the IOP, the mechanical properties of the corneal tissue, the corneal thickness, and the external force applied [2], therefore basing the estimation of IOP on the time of first applanation can lead to inaccuracies and wrong evaluations. This work presents an energetic approach to studying non-contact tonometry and proposes a new methodology for estimating IOP without the influence of the geometrical and mechanical corneal factors.

Methods and Results

3D FSI analysis
A 3D Fluid Structure Interaction (FSI) simulation with a patient-specific geometry (detailed in [3]) is conducted to simulate the NCT (Fig. 1.a). The work of the IOP (internal) and of the air puff (external) are calculated on the anterior surface of the cornea based on the results of the FSI simulation. Then, a sensitivity analysis is carried out to evaluate the influence of IOP, mechanical properties of the corneal tissue and corneal thickness on the intersection between the two developed works. The work of the IOP initially is not zero because the pressurization involves deformation of the corneal anterior surface. When the corneal surface is impacted by the air puff, the deformation is in the opposite direction to that of the IOP, but in the same direction as the air puff pressure. Conversely, the work of the air puff increases during the impact while the work of the IOP decreases (Fig. 1.b). The point of equilibrium occurs when the work of the air puff and work of the IOP are equal, causing the deformation of the cornea to stop increasing. The equilibrium point does not coincide with the first applanation point. In fact, the analysis of the corneal velocity during Corvis ST examination from both healthy and keratoconic patients reveals that the first applanation point does not correspond to the instant of the highest velocity of the corneal apex. After the first applanation point, the corneal velocity continues to increase, indicating that the cornea is subjected to a positive acceleration and force. The sensitivity analysis reveals that the first intersection point between the curves varies with the IOP. However, when changing both the mechanical properties of the corneal tissue and the thickness of the eye, the equilibrium point does not change. The work of the IOP at the end of pressurization is linearly dependent on the IOP. In particular, by analysing the work of the IOP in different simulations with varying IOP we obtained a regression line of:

$$IOP\,[mmHg] = 262.56\,work_{IOP}[mJ] + 8.6761$$

with R^2=0.9794. Therefore, we can accurately estimate a patient's IOP by knowing the developed work at the end of pressurization.

2D CFD analysis and IOP estimation
A method to segment the clinical images of Corvis ST (a commercial NCT) is outlined and a function to

approximate the movement of the corneal anterior section is proposed based on the function in [4]. A 2D axisymmetric CFD simulation is conducted with a moving boundary describing the movement of the cornea segmented from the images (Fig. 1.c). The CFD simulation provided the pressure profile over the patient-specific corneal anterior surface depending on its deformation in time which has been used to calculate the total work of the air puff (Fig. 1.d). For the patient analysed, the maximum corneal velocity was measured at $7.93ms$, when the calculated work of the air puff was $0.0104mJ$. With the method described above, we obtained a value of IOP of $14.85mmHg$. The Corvis ST measured an IOP of $14mmHg$ for that patient.

Discussion and Conclusions

The cornea's deformation during the air puff, depends on the coupled effect of the IOP, corneal thickness, mechanical properties of the corneal tissue and air pressure; as a result, the equilibrium point may not necessarily coincide with an applanated cornea. In the instant of the highest velocity instead, the cornea is at equilibrium. Our energetic analysis considers the equilibrium of the anterior corneal surface at the intersection point between the work of the air puff and the work of the IOP. Since both works are calculated on the anterior corneal surface, the thickness of the eye is not considered and does not influence the equilibrium results. We conducted an analysis of the equilibrium in the radial component. As a result, the equilibrium is only dependent on the IOP. Since the thickness of the structure is negligible with respect to its surface, the mechanical properties of the cornea do not play a role in the equilibrium. The approach we propose has the potential to estimate the IOP excluding the influence of the thickness and mechanical properties of the corneal tissue.

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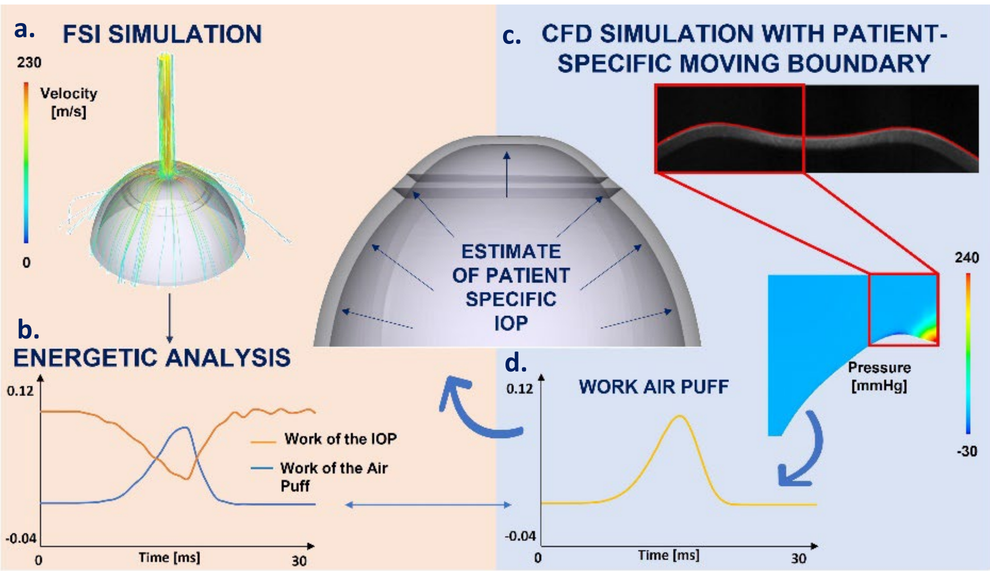

Figure 1: Methodology used to estimate the patient specific Intraocular Pressure (IOP).