Applications of the *ImTOPScanner* for the investigation of ocular biomechanical parameters

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Ocular biomechanics have gained increased interest in recent years. The material properties of the cornea and the sclera determine the eye´s shape and play an important role in several ocular pathologies. In keratoconus (KC), a progressive non-inflammatory disorder that results in thinning and protrusion of the cornea into a conical shape[1], corneal alterations are usually detected when the vision is already irreversibly affected. But the changes in the biomechanical properties take place before these morphological features occur[2]. For the more common eye condition myopia, which results from a mismatch between the focal length of the ocular components and the axial length of the eye, studies have shown an alteration of the scleral biomechanical properties in the equatorial and posterior scleral regions[3]. The ability to quantify biomechanical changes in the ocular tissue could enable earlier detection of disease progression, more individualized treatment options, and avoid irreversible vision loss, corneal transplants, or retinal detachment. Non-contact approaches that quantify biomechanical properties *in vivo* include Optical Coherence Elastography (OCE)[4-6], Brillouin microscopy[8], and air-puff deformation Scheimpflug imaging[9, 10]. Recently, Optical Coherence Tomography (OCT) devices have been coupled with air-puff excitation sources to capture deformation at the corneal apex or on the principal horizontal meridian[10-11].

We have recently presented the *ImTOPScanner*, a customised swept-source OCT system coupled with a quasi-collinear air-puff excitation, capable of acquiring dynamic corneal deformation on two meridians[13] (current set-up and example images are shown in fig. 1a). One advantage of the additional scanning meridian is that corneal deformation asymmetries, which are due to softer corneal regions below the corneal apex (typical in KC patients), can be detected more easily. Fig. 1b shows the currently investigated asymmetry parameters during deformation. In addition, the proposed system is highly flexible in terms of customizing the air-puff parameters and ocular alignment, so that it can be used additionally for analysing scleral biomechanics[14]. In both cases, the resulting deformation parameters provide advanced input data for Finite Element (FE) modeling inverse analyses to estimate a set of ocular material properties[15] (see fig. 1c). The system also functions in phase-sensitive mode, which allows detection of nano-scale displacements on the cornea. Using phase-sensitive OCT, we have implemented an advanced form of an OCT

vibrography[16] technique utilizing co-axial acoustic stimulation and OCT measurement with pre-compensation of acoustic frequency content and signal reconstruction in the Fourier domain.

Within this presentation, we will give an overview of the most recent results from a patient study on corneal biomechanics that include KC patients and healthy subjects, using the ImTOPScanner. We quantified deformation asymmetries (average asymmetries in displaced area, ADA, see fig. 1b) on two meridians, and present estimations of patient-specific corneal material properties from FE modelling (fig. 1c). We will further present first results of scleral deformation imaging, and discuss scleral deformation parameters and the estimated elastic modulus of different locations on the sclera. Finally, we will demonstrate the feasibility and reliability of the presented co-axial and acoustic pre-compensation approach for OCT vibrography studies of the cornea by measurement of the mechanical resonance modes of contact lenses and porcine corneas.

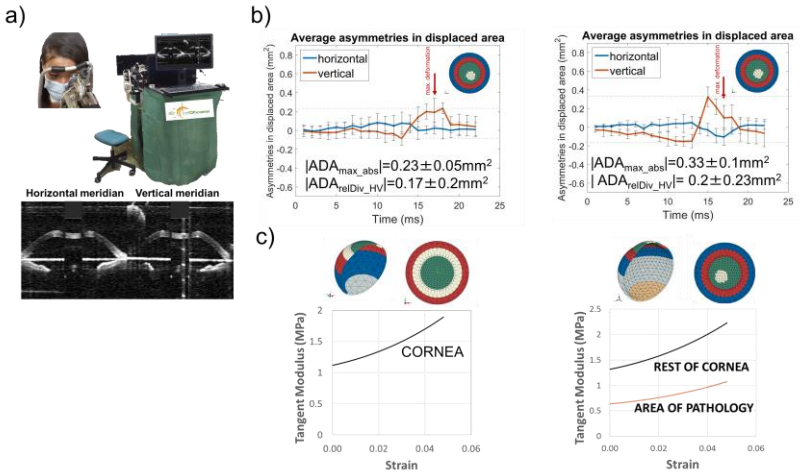

Figure 1. a) Set-up of the ImTopScanner device for patient use. Below an example-OCT image, showing the horizontal (left) and vertical (right) meridian during corneal air-puff deformation b) The average ADA for a KC patient. c) FE modeling inverse analysis for a healthy (left) and moderate KC (right) subject.

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[1]H. R. Vellara and D. V. Patel, *Clin. Exp. Optom*. **98**(1), 31–38 (2015)
[2]C. J. Roberts and W. J. Dupps, *J.Cataract Refractive Surg.* **40**(6), 991–998 (2014).
[3]J. R. Phillips, M. Khalaj, and N. A. McBrien, *IOVS*, 41, 2028–2034 (2000)
[4]K. Larin and D. D. Sampson, *Biomedical Optics Express,* 8.2, 1172-1202 (2017)
[5]Z. Jin et al., *Journal of biophotonics,* 13.8, e202000104 (2020)
[6]A. Ramier et al., *Scientific reports,* 10.1, 1-10 (2020)
[8]G. Scarcelli et al., *IOVS*, 53.1, 185-190 (2012)
[9]C.J. Roberts, et al., *Journal of refractive surgery,* 33.4, 266-273 (2017)
[10]A. Eliasy et al., *Frontiers in bioengineering and biotechnology* 7, 105 (2019)
[11]D. Alonso-Caneiro, et al., *Optics express,* 19.15, 14188-14199 (2011)
[12]C. Dorronsoro et al., *Biomedical Optics Express,* 3.3, 473-487 (2012)
[13]A. Curatolo et al., *Biomedical Optics Express,* 11(11), 6337–6355 (2020)
[14]D. Bronte-Ciriza et al., *Biomedical Optics Express* 12(10), pp.6341-6359 (2021)
[15]A. Elsheikh and D. Wang, *Comput. Methods Biomech. Biomed. Engin.* 10(2), 85–95 (2007)
[16]E. W. Chang et al., *Opt Lett*, vol. 37, no. 17, pp. 3678–3680 (2012)