Air puff-coupled multi-spot OCT
for assessment of asymmetries in corneal biomechanics

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ABSTRACT

The ability to perform multi-meridian, simultaneous OCT measurements of air-induced corneal deformation is expected to highly improve the accuracy of assessing corneal biomechanics. We propose a simplified method targeting 3-D deformation measurement that could be introduced to modern swept-source OCT systems. We utilize a spatial-depth-encoded multiplexing technique to provide a 9-spot measurement of the deformation. The method is promising for the assessment of corneal deformation asymmetries in the detection and diagnosis of corneal pathologies such as keratoconus. We present in detail the system and key requirements to provide simultaneous 9-spot deformation measurement. Finally, results on porcine eyes *ex vivo* and human eye *in vivo* are presented.

1. Introduction

Various non-contact methods, including Brillouin microscopy [1], shear-wave elastography [2], and measurements of air-induced macro corneal deformations, can be used to study corneal biomechanics and/or to estimate intraocular pressure. The latter approach is most advanced in terms of clinical *in vivo* evaluation. Clinicians have access to the commercial device (Corvis® ST, Oculus) that provides Scheimpflug camera-based measurements of air-induced corneal deformation at the central horizontal meridian. Assessment of normal and pathological corneal response was already reported for this technique [3]. In addition, Optical Coherence Tomography (OCT) has been combined with an air-puff stimulus [4], with demonstrated clinical usefulness [5-6].

Recently, OCT-based air-puff was improved by providing fast sequential imaging at multiple meridians [7]. With this approach, we were able to detect corneal deformation asymmetries not available to Corvis® ST. Obviously, one can achieve improved accuracy of deformation asymmetries assessment with more meridians measured in a simultaneous fashion.

Here, we present a simplified solution towards more monitoring points that can be implemented within an OCT system. Instead of a multiple-meridian approach, we proposed sparce 3D sampling. Careful analysis of FEM modeling results revealed that with only 9 points (Fig 1A) at which air-induced deformation is measured, one can estimate IOP and material stiffness (using central spot information), Also for pathologies such as keratoconus, it is possible to identify the cone location and the mechanical weakening within the cone (using remaining 8 spots).

2. Methods and results

The air puff-coupled multi-spot system (Fig. 1A) was first evaluated using FEM modeling of air-induced corneal deformation. We analyzed a number of corneal models with various central corneal thicknesses (450÷650 μm) and material stiffness (corresponding to ages of 10÷100 years). Additionally, keratoconus eye models with various cone centers (0÷1.5 mm from the apex) and radius (1÷2 mm) were included in the analysis. In total, 50 heathy and 600 keratoconus models were used. As an optimal, with best assessment of the deformation asymmetry, spot distribution we selected a 9-spot setup with one central spot to measure CCT and apex deformation, and 8 peripheral spots deposited at ~1.1 mm radius to probe the deformation asymmetry.

The deformation at each location can be detected with a separate OCT system for each spot, which is not cost-effective. We decided to utilize a modified spatial-depth-encoded multiplexing scheme [8], where all spatially distributed channels are acquired simultaneously. To allow separation of channels for effective analysis of deformations, appropriate optical path delays were added to each spot channel, so the corresponding images appear at different depths on the final OCT image. To enable a spatial-depth-encoded multiplexing scheme, we used a 1300 nm swept laser (SL131090 – 1300 nm, 100 kHz Sweep Rate, Thorlabs). OCT fringe signal was recorded using a high sampling rate digitizer (ATS9373 - 12 bit, 4 GS/s, Alazar Technologies Inc.) using a dual-edge sampling feature (doubling k-clock given imaging depth).

The hybrid sample arm consists of a cascade of 2x2 and 1x4 couplers) to provide optimal light delivery and coupling for a single interferometer design. Light from outputs of 1x4 couplers is collimated (F110APC-1310 - 1310 nm, f = 6.35 mm, NA = 0.37, Thorlabs) and guided onto an array of 5mm prism mirrors (Fig. 1C and E). All beams reflected from the mirror array converge at the back focal plane of the imaging lens (30 mm) to provide 8 imaging points at the cornea separated as described previously (Fig. 1A). The central spot is additionally used for patient alignment procedures (cross-scan OCT preview). The scanning pattern generated with a pair of galvo scanners is relayed using a 300 mm lenses telescope (Fig. 1B) through a cross-shaped opening in the mirror array custom mount (Fig. 1C).

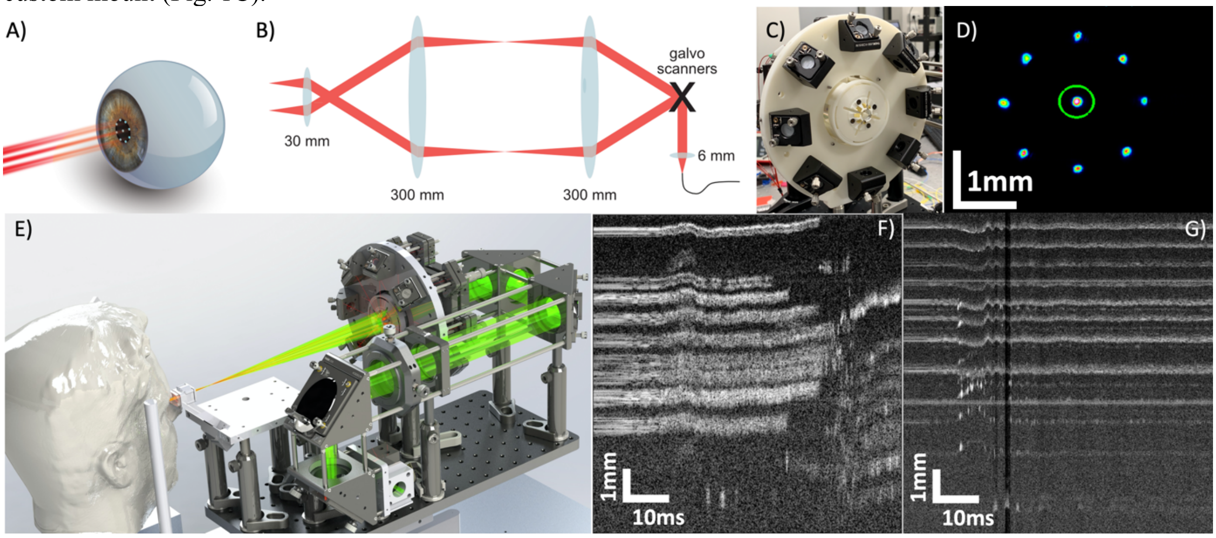

Fig. 3 A) 3D visualization of multi-spot air-puff measurement concept, B) Simplified schematic of central channel optics providing cross-preview for patient alignment, C) Photography of a 3D-printed mirror array mount with 5mm prism mirrors mounted and corner cube kinematic mounts for peripheral beams alignment visible, D) Spatial beams distribution measure with beam profiler CCD camera, E) 3D rendering of the quasi-3D air-puff imaging system, Example measurement on human eye in vivo (F) and eye phantom (G).

The alignment of all 9 spots of our multi-spot system is presented in (Fig. 4D). The average power at the sample was 1.2 mW for the central beam and 2.5 mW for all peripheral beams. Exemplary results of the deformation measured at all 9 spots simultaneously on human eye in vivo (Fig. 1F) and phantom eye (Fig. 1G) are also presented.

To conclude, we presented a novel method to advance the assessment of corneal biomechanics. Quasi-3D air-puff OCT enables measurement of corneal deformation asymmetries and can be a promising tool for detection and diagnosis of corneal pathologies as keratoconus. The optomechanical design of the system will be presented in detail and key requirements to provide simultaneous 9-spot probing of air-induced corneal dynamics will be discussed. Finally, quasi-3D measurements of porcine eyes ex vivo and human eye in vivo will be presented.

5. Acknowledgments

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreements No 779960, No 666295, and No 713694. Karnowski and Curatolo acknowledge the support from the Polish National Agency for Academic Exchange (PPN/PPO/2018/1/00082, ULAM/2020/1/00176).

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