In vivo endoscopic multifunctional optical coherence tomography imaging of lungs periphery before and after bronchial thermoplasty

Margherita Vaselli[1], *Fabio* Feroldi[1], *Joy* Willemse[1], *Maximilian G.O.* Graefe[1], *Dirck* van Iperen[1], *Annika W.M.* Goorsenberg[1], *Peter I.* Bonta[1], *Jouke T.* Annema[1], and *Johannes F.* de Boer[1]

[1]Department of Physics and Astronomy, LaserLab Amsterdam, VU University Amsterdam, the Netherlands

Abstract. We demonstrate the use of a motorized distal scanning endoscope to acquire *in vivo* data in lungs of severe-asthma patients before and after an asthma treatment procedure called bronchial thermoplasty. Conventional optical coherence tomography (OCT) intensity images and polarisation sensitive OCT images were extracted from the acquired data. PS-OCT endoscopy allowing the visualization and segmentation of airway smooth muscle layer - which plays a key role in bronchoconstriction during asthma attacks - showed its potential as means to evaluate the effectiveness of bronchial thermoplasty.

1 Introduction

Over the past 20 years OCT has been widely adopted in ophthalmology, cardiology and gastroenterology. Its adoption in interventional pulmonology has been slower, this can be attributed to the lack of commercially available OCT endoscopes suitable for lungs imaging. In this study we present *in vivo* images of airways at the periphery of the lungs, performed in a severe asthma patient before and after undergoing a recently-developed asthma treatment procedure called bronchial thermoplasty (BT) [1]. Imaging of lung tissue has been performed with a distally scanning catheter connected to a multifunctional OCT system. OCT intensity images, attenuation coefficient (AC) images, and polarisation sensitive OCT (PS-OCT) images showing both phase retardation, optic axis uniformity (OAxU) and optic axis (OA) orientation were extracted from the data. In particular optic axis orientation was used to segment the airway smooth muscle (ASM) layer, which is remodelled by BT therapy.

2 Methods

2.1 Imaging system

PS-OCT is an extension of conventional OCT that besides performing structural imaging of tissue allows to image sample birefringence, from which specific information about the tissue can be extracted [2]. The schematic of our endoscopic PS-OCT system is shown in fig. 1.a. Light emitted from a swept source laser is split into the two arms of a Mach-Zehnder interferometer. In the sample arm a polarisation delay unit (PDU) creates two depth-encoded polarisation states. A circulator (C) redirects the light to the endoscope; the backscattered light in the sample arm is then interfering with the reference arm light in a polarisation diversity detection module (PDDM), which separates the lights into orthogonal polarisation components on separate balanced detectors.

2.2 Endoscope

Imaging the airways periphery was possible through an in-house built endoscope, inserted in the lungs through the working channel of a standard bronchoscope. The distal scanning catheter we developed (fig. 1.b) is a motorized endoscope with a 1.35 mm diameter that allows to scan circumferentially the airways at 52 fps B-scan rate. The reliability of the micromotor placed at the tip of the catheter was improved by doubling the windings of the coil around the micromagnet to two. In order to provide clinicians with a cost effective imaging tool for research studies, the endoscope was designed and constructed to be reused several times.

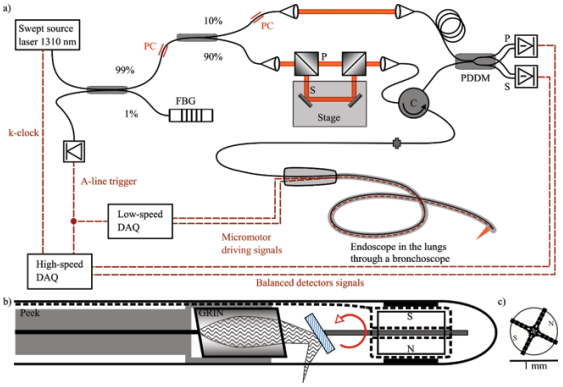

Fig. 1. a) Schematic of the PS-OCT system. b) Schematic of the OCT endoscope

* Corresponding author: m.vaselli@vu.nl

2.3 Intensity and PS-OCT images

On top of conventional OCT intensity images, the data acquired *in-vivo* in human lungs of a severe asthma patient were used to extract images based on the depth-resolved attenuation coefficient (AC) of tissue. AC images have been realized exploiting the algorithm developed by Vermeer *et al*. [3], which makes use of chromatic dispersion corrected and roll-off compensated intensity OCT images in linear scale. The attenuation coefficient of each depth location was estimated by dividing the intensity of each depth pixel by the sum of the intensities of the pixels underneath. Intensity based OCT images have a resolution and a depth of penetration sufficient to image the ASM, however backscattered light from ASM does not provide sufficient contrast to distinguish it from surroundings layers. Since ASM is arranged in fiber-like structure, it exhibits form birefringence, that can be highlighted by PS-OCT. In this study, birefringence properties have been extracted, adopting the Mueller-Stokes formalism, by using an algorithm developed by Villiger in 2016 [4]. Output of this method is a 3D vector: the birefringence vector γ, whose magnitude ρ corresponds to the amount of retardation induced by the sample and its direction $[\eta,v,\mu]$ represents the orientation of the sample optic axis (OA) in a Poincare sphere representation. OA shows consistent orientation throughout the sample if the fibers are oriented along the same direction. We also introduced a simple metric that evaluates the spatial uniformity of the sample OA: the optic axis uniformity OAxU [5].

$$OAxU = \sqrt{\langle\eta\rangle^2 + \langle v\rangle^2 + \langle\mu\rangle^2} \qquad (1)$$

OAxU is particularly useful to highlight areas of a sample with similar birefringence characteristics.

3 Results

Intensity based OCT images acquired at the periphery of the lungs in a patient affected by severe asthma are shown in fig. 2.

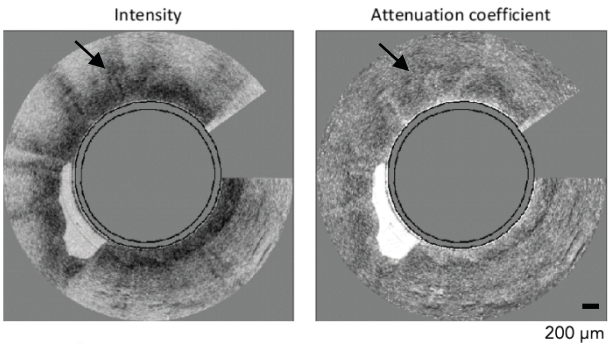

Fig. 2. Cross section frame from a distal location along the pullback. Intensity OCT B-scan and corresponding AC image.

AC images results to provide superior contrast of the lung airways compared to intensity images. In particular, epithelial folds (indicated with a black arrow in fig. 2) are better visualized in the AC images.

PS-OCT images highlighted the presence of several layers in the airway wall; in particular OA orientation and OAxU were used to delineate in the airway lumen the smooth muscle layer. Tissue layers characterized by high optic axis uniformity show high intensity signal in OAxU images (fig. 3); different orientations of these layers are then represented in different colours in OA images.

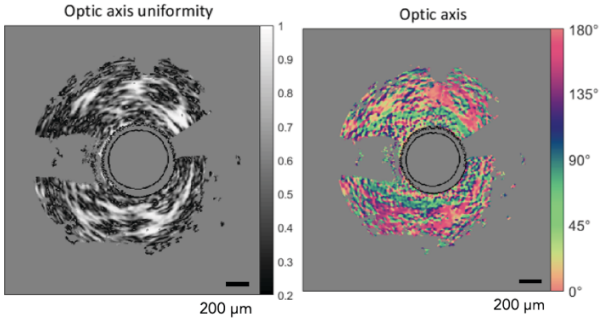

Fig. 3. Cross section frame from a proximal location along the pullback. OAxU B-scan and corresponding OA image.

Knowing ASM is made of consistently oriented fibers located within 100µm from the lumen surface, it was possible to discern this layer from other birefringent structures and segment it. Segmentation of the ASM layer allowed us to compare its thickness before and after BT treatment. Fig. 4 shows a 3D image of the segmented ASM acquired pulling back the catheter from a distal to a proximal location in the same lung segment before and after BT. As can be seen from fig. 4, the thickness of ASM after BT is reduced in the proximal area of the pullback, which corresponds with the area mainly treated by BT.

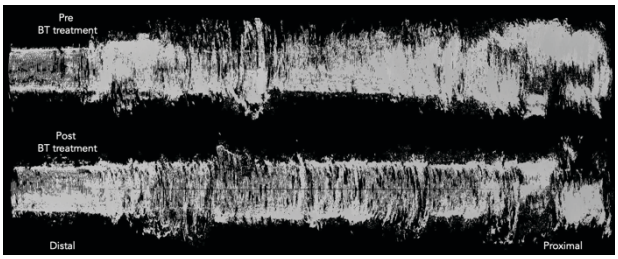

Fig. 4. 3D image of segmented ASM acquired during pullback.

References

1. G. Cox, et al., AJRCCM, **173**, p. 965-969, (2006)
2. J. Li, et al., Optics Express, **23**, p. 3390-3402, (2015)
3. K.A. Vermeer, et al., BOE, **5**, p. 322-337, (2014)
4. M. Villiger, et al., Scientific Reports, **6,** (2016).
5. J. Willemse, et al., Optics Letters, **44,** p. 3893-3896, (2019)