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Real-Time Three-Dimensional Imaging of Larynx Using a Swept-Source Optical Coherence Tomography (SS-OCT) System Consisting of a GRIN Lens Rod-Based Probe and a High Speed VCSEL Laser Source

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Abstract: We have developed an office-based laryngeal OCT imaging system for analyzing the cross-sectional anatomy in awake patients. Real-time in vivo imaging of human vocal cords and native vibrations of vocal folds are demonstrated.

Introduction

The vocal fold is a complex layered structure that has spatially varying mechanical properties. These layers vibrate with intake of air that leads to phonation, a process responsible for generating multiple harmonics and speech. There is a wide array of diseases such as benign (cysts, polyps), premalignant (dysplasia) and malignant lesions that involve sub-epithelial regions of the vocal fold. A biopsy under general anesthesia is required to histologically differentiate the above-mentioned lesions. Examining this microanatomy of vocal folds, specifically during phonation, may facilitate better understanding of vocal fold mechanics and aid in reliable diagnosis of vocal fold pathology without necessitating biopsies. Thus far, in vivo functional imaging has been restricted to stroboscopy or high speed digital imaging, and both imaging modalities are only capable of providing information about the superficial layer of tissue. Therefore, there is a growing need for more reliable and effective imaging modalities.

Optical Coherence Tomography (OCT) is an imaging modality capable of producing high-resolution cross-sectional images of living tissue. OCT has been extensively used in ophthalmology, but in the fields of head, neck and airway, OCT is still an investigational technology. It has been used for imaging early cancers and dysplastic changes along the mucosal lining. Several laryngeal OCT imaging studies have been conducted, but in all cases imaging was carried out under anesthesia [1]. OCT generally requires sedation and surgical endoscopy as it is a contact or near contact imaging modality. Developing an office-based system has been a long-term goal for various research groups [2, 3]. Office-based imaging has still been a challenge due to inadequate fields of view, limited imaging range, differences in anatomical geometry and inability to compensate for test subject’s head and examiner’s hand motion.

In this study, we developed an office-based system for cross-sectional imaging of vocal folds using an OCT system that comprised of a Vertical-Cavity Surface Emitting Laser (VCSEL) source with a larger lateral scanning range. This source addresses many of the issues faced by conventional OCT and other office-based systems. In healthy awake volunteers, we demonstrated: 1) real-time, cross-sectional structure of both true and false vocal folds, and 2) native vibration of the folds.

System and Methods

The SS-OCT system (Fig. 1) consisted of a 1310nm center wavelength 200kHz VCSEL swept source, and the output light was split 99:1. In the sample arm, a wavelength division multiplexer (WDM) was used to combine a 635 nm aiming laser beam with the 1310nm sample beam before the laryngeal scanner setup. The laryngeal setup (Fig. 2) consisted of a fiber collimator and an achromatic doublet focusing lens, a 2-axis galvo mirrors, a gradient index (GRIN) lens rod, and a 45-degree reflector. The aforementioned combined sample beam and aiming laser beam were sent through the WDM to the fiber collimator. This collimated output beam was subsequently focused and directed towards the proximal end of the GRIN lens rod. The focusing sample beam was then scanned by the 2-axis galvo and translated to the distal end of the 1 pitch GRIN lens rod, where the beam was reflected 90 degrees downward by the 45-degree reflector. The fiber collimator and achromatic doublet subassembly could be adjusted to tune the focal plane position of the sample beam to accommodate for anatomical differences between test subjects. For this study, a fixed frame size of 1000 a-lines was selected to achieve a frame rate of 200Hz. Simultaneous OCT and conventional video images were captured using a 90° rigid laryngoscope in tandem (Fig. 2). A nominal working distance (~6 cm) of the probe is selected to have a lateral resolution < 100 um and a confocal parameter of 6.4 mm, which covers more than half of the 12 mm imaging range of the VCSEL laser. The maximum lateral scanning range of the probe at 6 cm is approximately 8.4 mm, and imaging an area of 15 mm by 15 mm can be performed in about 1 second. The operator was able to see the region of the vocal fold scanned with the aid of an aiming beam. Audio and video data was recorded during phonation. The audio information was extracted and the fundamental frequency was analyzed in MATLAB.

Fig. 1 Laryngeal Scanner Setup

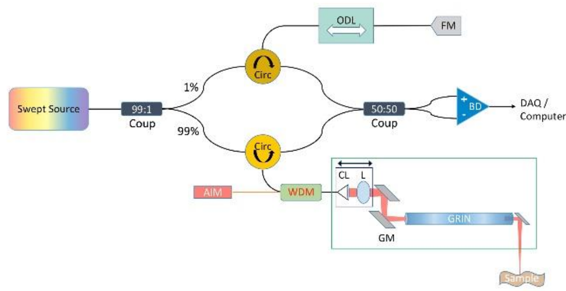

Fig. 2 Optical System Setup

Results

A montage of B-scan images (Fig. 3) of the subject phonating at approximately 250 Hz show the phasic movement of the true vocal folds. Fig. 3A and 3B show the effect of positive air pressure built during vocal fold closure. Fig. 3C to Fig. 3F illustrate vocal fold free margin movement during the release of the air pulse due to pressure build up. Fig. 3G to Fig. 3J show that lower pressure at the end of air pulse resulted in closure of vocal folds and allowed another air pressure column to build up, concluding the vibratory cycle. A nominal working distance (~6 cm) of the probe is selected to have a lateral resolution < 100 um and a confocal parameter of 6.4 mm, which covers more than half of the 12 mm imaging range of the VCSEL laser. The maximum lateral scanning range of the probe at 6 cm is approximately 8.4 mm, and imaging an area of 15 mm by 15 mm can be performed in about 1 second.

Conclusion

OCT is a high resolution, high-speed panaromic imaging modality with distinct advantages over conventional imaging techniques like CT, MRI and ultrasound imaging. The analysis of structural information of the vocal folds reveals specific sub-epithelial tissue layers as well as their movements relative to each other. This mode of imaging shows great potential to significantly impact clinical practices by providing patients with more reliable and economical preoperative consultations when encountering lesions of the larynx.

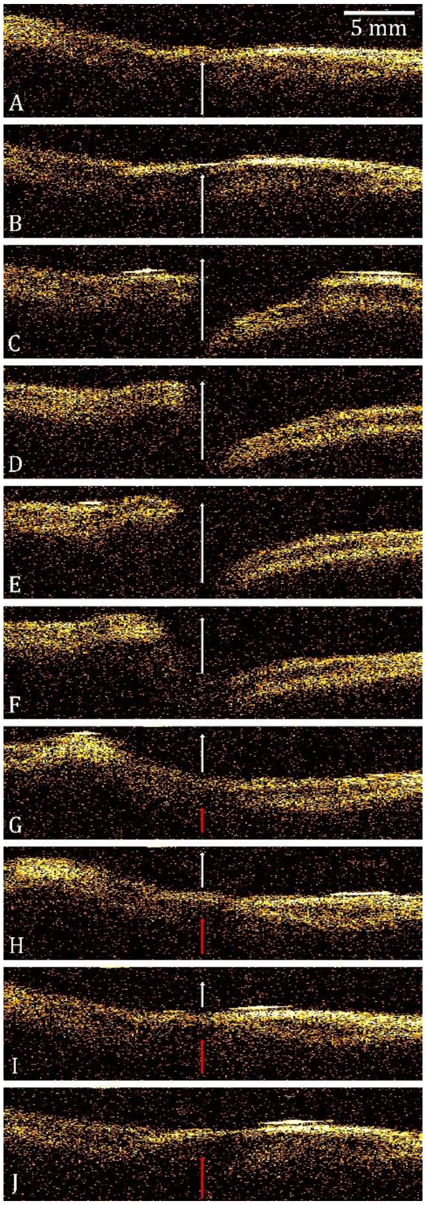

Fig. 3 Vocal Fold Vibratory Cycle

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