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In-vivo office-based dynamic imaging of vocal cords in awake patients with swept-source optical coherence tomography

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Abstract
Optical coherence tomography (OCT) is an evolving noninvasive imaging modality and has been used to image the human larynx during surgical endoscopy. The design of a long GRIN lens based probe capable of capturing images of the human larynx by use of swept-source OCT during a typical office-based laryngoscopy examination is presented. *In vivo* OCT imaging of the human larynx is demonstrated with 40 fame/second. Dynamic vibration of the vocal folds is recorded to provide not only high-resolution cross-sectional tissue structures but also vibration parameters, such as the vibration frequency and magnitude of the vocal cord, which provide important information for clinical diagnosis and treatment, as well as in fundamental research of the voice. Office-based OCT is a promising imaging modality to study the larynx.

Introduction

Laryngeal carcinoma is the most common primary head and neck malignancy. The cardinal symptom of early laryngeal cancer is hoarseness, but because this complaint is relative innocuous, laryngeal cancer often goes undiagnosed for many months and referral to an otolaryngologist may be delayed up to nine months following the onset of symptoms. Accurate clinical diagnosis and treatment of early-stage laryngeal cancer based on the physical examination is extremely difficult and inaccurate. Conventional physical examination uses a laryngeal mirror, flexible fiber-optic or rigid laryngoscopes (with or without video/videostroboscopy) to achieve a two-dimensional view of the laryngeal structures. Although it is difficult to differentiate among the wide spectrum of diseases ranging from chronic laryngitis to pre-malignant and malignant lesions, which all mimic one another.

Lack of basement membrane integrity is the key feature of early invasive cancer. There is no reliable non-invasive, non-operative method available for surgeons to make a laryngeal cancer diagnosis without a biopsy. Using current while light flexible techniques, the endoscopic yield in terms of diagnostic sensitivity and specificity for diagnosing visible lesions in patients is very low.

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Biopsies of the vocal cord aimed at diagnosing cancer require a full-thickness excision of superficial epithelium, basement membrane and connective tissues. These biopsies may have a detrimental effect on patient's vocal cord vibration and ultimately lead to a permanent change in voice. Repeated biopsies are common in order to ascertain a definite diagnosis, and will bring even higher risks. The above difficulties demonstrate the huge need for improved noninvasive diagnostic technology, as well as improved abilities to determine margins and to perform definitive safe biopsies on patients with clinically suspected larynx malignancies.

Optical coherence tomography (OCT) is a noninvasive medical imaging method based on the principle of low-coherence interferometry [1]. It was developed to perform in vivo cross-sectional tomography imaging of tissue structure, composition, and physiological information with high imaging speed and resolution. It has become a powerful tool for medical diagnostics [2-4]. Recently we reported an office based laryngeal time-domain OCT imaging device [5]. A rigid laryngoscope serves as a platform to which a second device can be attached to perform simultaneous OCT imaging. However, the scanning mechanism was slow. A GRIN lens based probe was also developed for office-based laryngeal imaging with a speed of 8 frames/s with a spectral domain OCT system [6]. Since the device is cantilevered about 5-8 cm above the vocal cords, there is no need for anesthesia and there is no risk in with this approach. However, one of the biggest challenges for an office-based OCT laryngeal imaging is the movement of the patient's neck and physician's hand. The latter is further levered by the cantilevered design of the probe. The relative movements between the larynx and probe tip can easily exceed several millimeters, and shift the images outside the OCT imaging window (or A-scan imaging depth). Also, the working distance is different from patient to patient; physicians have to practice the ability to adjust the working distance while holding the probe steady. In-vivo imaging of the vocal folds in awake patients without anesthesia has not been reported in the literature.

In this paper, we demonstrate an office based laryngeal swept-source OCT imaging system. Fast laryngeal imaging of 40 frames/s is realized to greatly eliminate motion artifacts caused by tremor (<1Hz) between the patients and the probe. For the first time, in-vivo noninvasive imaging of the vocal folds in awake patient is reported. Furthermore, dynamic vibration of the vocal folds is recorded to provide not only the high-resolution cross-sectional tissue structures but also important vibration parameters, such as the vibration frequency and magnitude of the vocal cord, which may provide additional helpful information for diagnosis.

System setup and results

The schematic diagram of the fiber-based swept source OCT system is shown in Fig. 1. The output light from a swept light source at 1310 nm with a FWHM bandwidth of 100 nm and output power of 5 mW was split into reference and sample arms by a 1 × 2 coupler. The light source was operated at a sweeping rate of 20,000 Hz. The reference power was attenuated by an adjustable neutral density attenuator for maximum sensitivity. The GRIN lens based endoscope was connected to the sample arm with 80% power from the source. Two circulators were used in both reference and sample arms to redirect the back-reflected light to a 2x2 fiber coupler (50/50 split ratio) for balanced detection. Dispersion compensation is important to achieve high resolution. The dispersion can be measured with a mirror as a sample by constructing the complex representation of the spectral fringe pattern and correcting the phase as a function of the wave number [7]. The measured axial resolution of 8 μm was close to the theoretical axial resolution of 7.5 μm since the spectrum of the swept light source is nearly Gaussian shaped. The lateral resolution, which is determined by the endoscope's focus spot, was measured to be 15 μm.

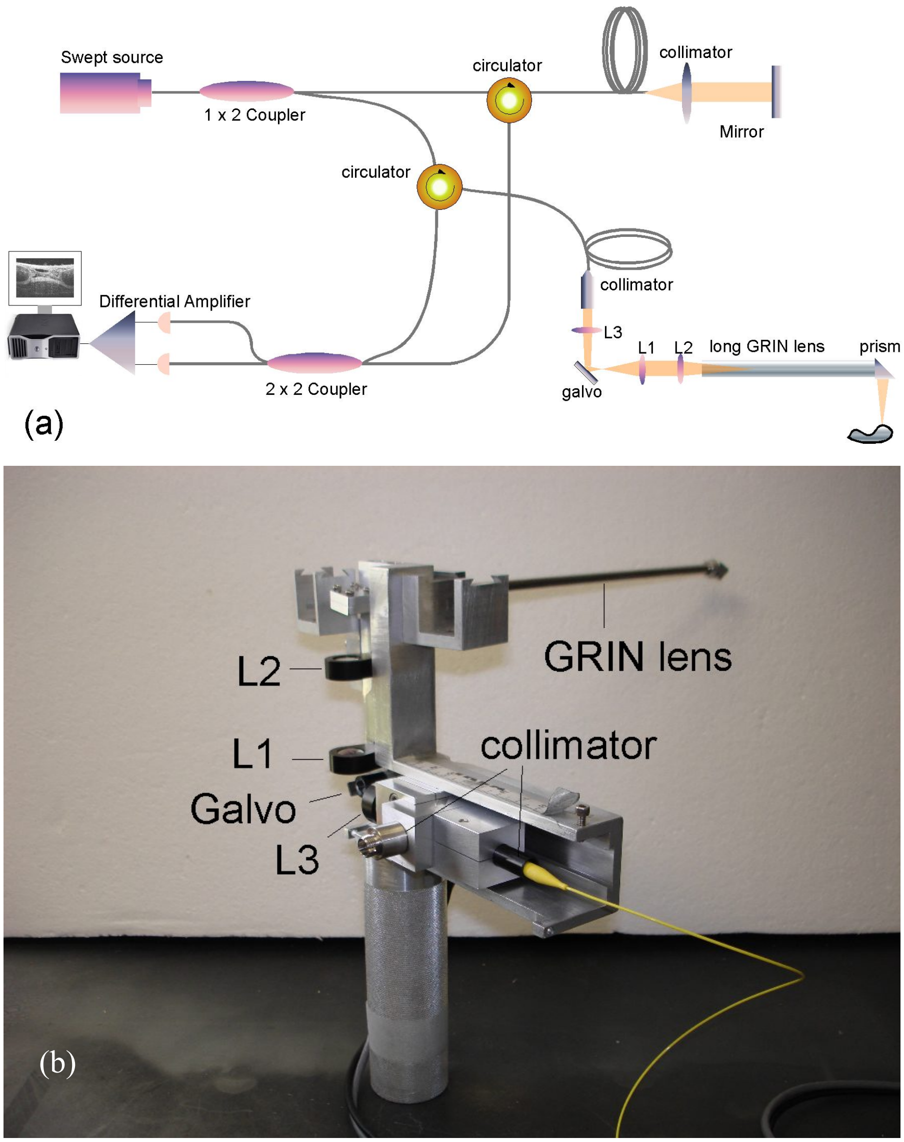

Fig. 1 (a) Schematic diagram of a GRIN lens rod based dynamic focusing swept-source OCT system; (b) design of the probe.

In laryngeal endoscopy, the depth of the larynx varies remarkably from patient to patient. Changing the optical path length of the reference arm to match a variable working distance is difficult. The most convenient solution is to maintain a constant optical delay in the sample arm while tuning the working distance to ensure that the sample beam is always focused into the vocal cord. The device must quickly adjust to image the larynx as it changes position within the pharynx. We use an enhanced version of a previously reported GRIN lens based probe [6] to fulfill constant-optical-delay dynamic focusing. A long GRIN (gradient index) lens used in this design can be considered as one pitch and an optical relay for visible wavelength. However, for 1310 nm wavelength, which is the center wavelength of the OCT light source, the GRIN lens is closed to one pitch but cannot be considered as an ideal optical relay any more, especially when the average working distance of the probe (or the beam coming out of the probe tip) reaches about 65 mm for laryngeal imaging. In order to achieve an ideal optical relay, the GRIN lens is used with a group of lenses L_1, L_2 to form a so-called optical-ballast within a $4f$ optical system. The composite $4f$ optical system has a magnification of one and can be considered as an optical relay, the optical delay of the focal point remains constant during adjustment of the working distance.

A carriage holds the OCT device and the endoscope together in a “double-barreled” configuration. In order to identify the scanning point (area) during an OCT examination, an aiming beam should be coupled into the system. Previously, a 2×1 coupler was used in the sample arm to couple a green aiming beam from a 532nm solid-state laser. However, in order to achieve the maximum sensitivity for OCT imaging, only a very small portion (<10%) of the green light was allowed for imaging, which was oftentimes not bright enough with the background incandescent lamp on for endoscope imaging. In our enhanced probe, a dichrioc mirror based design was used. The sample beam from the OCT system is collimated, passes through a dichroic mirror, a focusing lens L_3, and reflects 90° to the fixed lens group by a scanning galvo (Fig. 1b). The green beam is also coupled into the system through another channel of the dichroic mirror for aiming purpose. The fiber and the two collimators and focusing lens L_3 are assembled as one component and can be moved back and forth along the propagation direction for distance adjustment by the physician during the examination. Two customized prisms are attached at the proximal and distal tips of the GRIN lens for beam deflection. During the examination both of the dual-channel endoscope and OCT signals are digitized and displayed on a single monitor (Fig. 2).

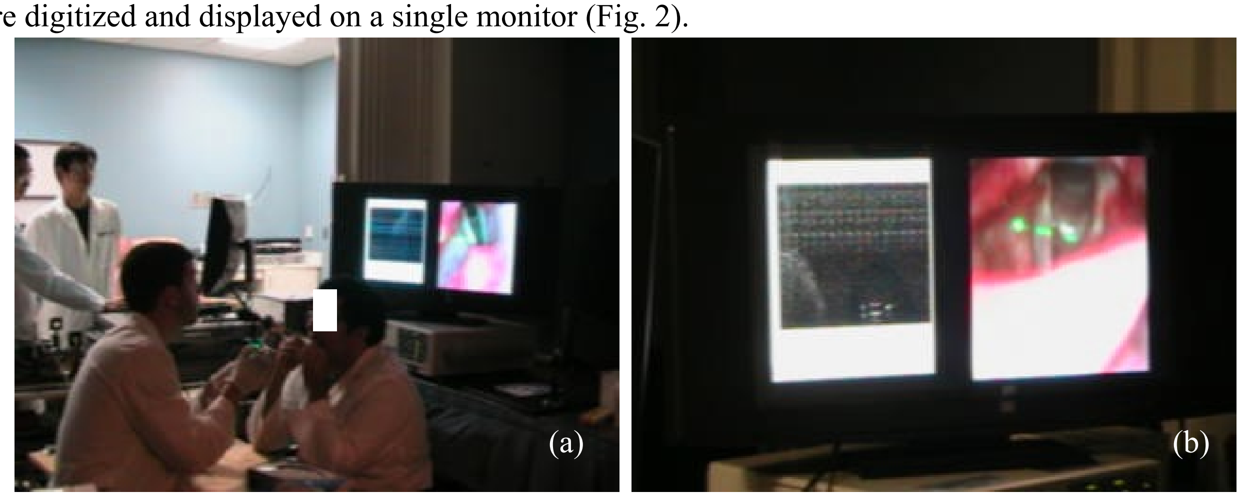

Fig. 2 (a) OCT probe attached to the laryngoscope for office based laryngoscopy examination; (b) Dual-channel endoscope and OCT signals shown in a monitor.

During the examination of vocal cord, the patient is asked to sit straight up and hold his tongue with a gauze during the procedure. The back of the throat may be sprayed with benzocaine 20% that numbs the mouth and throat to eliminate the gag reflex, prior to the imaging. Once we obtain a clear vision of the vocal cords as well a good position of the aiming beam, , the patient is asked, as with the conventional stroboscopic examination, to phonate, in order to produce different movements of and positions of the vocal cords. During the whole procedure we are recording both the OCT images as well as the laryngoscopic images. Figure 3(a) and 3(b) shows the cross-sectional images of vibrating vocal cords of a male and female volunteer during examination, respectively. The epithelium and basement membrane can be clearly identified. The image is comparable with images obtained in anesthetized patients during surgical endoscopy. In the tested chest vibration mode the frequency of the vocal cord is about 120 Hz for the male volunteer and about 200 Hz for the female volunteer. This is a perfect fit for the measured OCT images shown in Fig. 3. Since the OCT imaging speed is 40 frames per second, 3 cycles observed in Fig. 3(a) corresponds to ~120Hz frequency. While Fig. 3(b) contains up to 5 vibrations per cycles and corresponds to a vibration frequency of 200 Hz. The precise dynamic vibration amplitudes can also be measured based on the above OCT images. Since the total imaging depth in the above figures is 2.6mm, the estimated maximum vibration amplitudes in Fig. 3(a) is about 1.2mm and that in Fig. 3(b) is about 0.59mm.

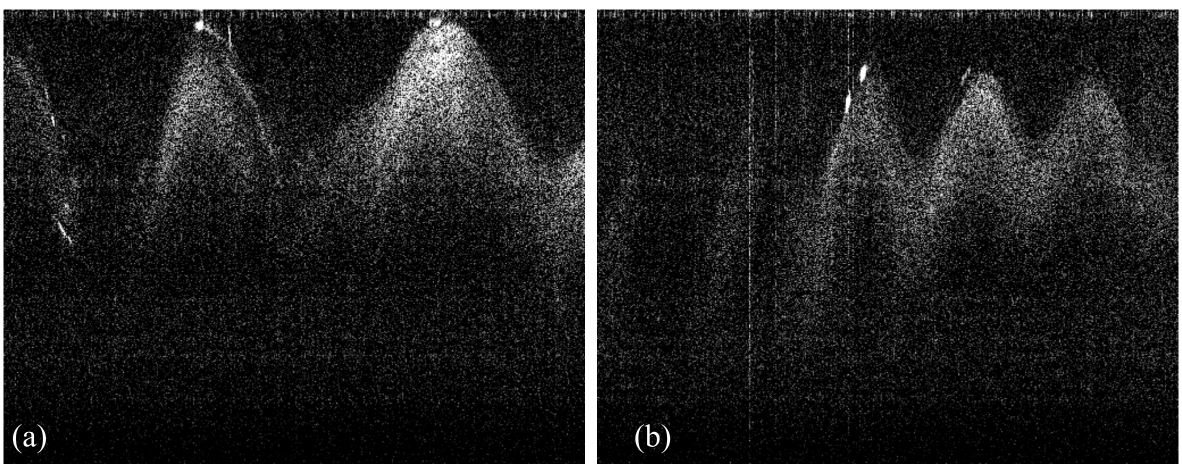

Fig. 3. Vibrating vocal cord with different frequencies: (a) ~120Hz and (b) ~200 Hz

Conclusion

In summary, we demonstrate video-rate *in-vivo* laryngeal imaging of 40 fps during a typical office based laryngoscopy examination with a swept-source OCT system. Dynamic vibration of the vocal folds is recorded to provide not only the high-resolution cross-sectional tissue structures but also important vibration parameters, such as the vibration frequency and magnitude of the vocal cord, which provide important information for clinical diagnosis and treatment as well as in fundamental research in voice. Office-based OCT is a promising new imaging modality to image the larynx.

Having the advantage of being performed without the need for general anesthesia or tissue removal. Office-based OCT has potential to guide surgical biopsies, direct therapy, and monitor disease.

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