MEDICAL UNIVERSITY OF VIENNA

Forward-viewing photoacoustic laparoscope using all-optical ultrasound detection, flexible fiber bundles and fiber core targeted fast scanning

Qian Li, Stefan Preißer, Mikael T. Erkkilä, Richard Haindl, Harald Sattmann, Mengyang Liu, Rainer Leitgeb, Wolfgang Drexler

Center for Medical Physics and Biomedical Engineering, Medical University of Vienna

Objective

A key element for laparoscopy is the laparoscope and multiple advanced imaging techniques have been developed to enhance the performance of the standard camera-based white-light laparoscope. Photoacoustic imaging (PAI) is a hybrid imaging modality that uses laser-induced ultrasound to create a three-dimensional (3D) image of optical absorbing structures in the tissue. Compared with pure optical imaging methods, PAI can provide higher imaging depth as it relies on the excited ultrasound signal to form an image. In this study we developed a forward-imaging photoacoustic probe with the potential to enhance the imaging performance of traditional laparoscope for lesions characterized by angiogenesis due to the very high sensitivity of PAI to hemoglobin.

Material and Methods

A forward-viewing PAI probe is designed and fabricated. The 3D models and a picture of the probe are shown in Figure 1. The probe consists of a fiber connector, a customized micro-objective, a transparent all-optical Fabry-Perot (FP) transducer and a transducer mount. These components are assembled together within a stainless-steel outer sleeve with an outer diameter of 9 mm. An optical magnification power of -5 is achieved by the objective. The length of the whole probe is adjustable and is around 40 mm. A transparent all-optical ultrasound transducer (XARION Laser Acoustics GmbH) is customized for the probe. As shown in Figure 2, the sensor contains an FP cavity encapsulated by polymer foils. A detection laser with a central wavelength of 1550 nm is coupled into the cavity via a fiber and a 45º prism. The photoacoustic (PA) wave can be detected by the transducer through the induced density change by PA waves within the cavity. The transducer has a field of view (FOV) of 4.2×4.2 mm and an axial resolution of 220 μm, which is shown in Figure 2 by obtaining the full width at half maximum of the waveform from a 7 μm diameter carbon fiber.

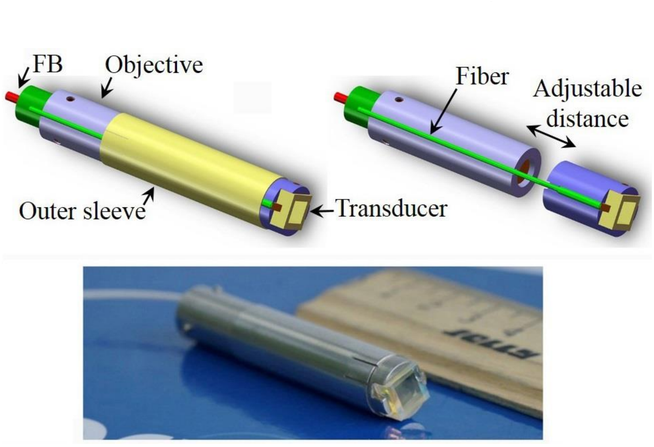

Figure 1. The forward-imaging PA probe

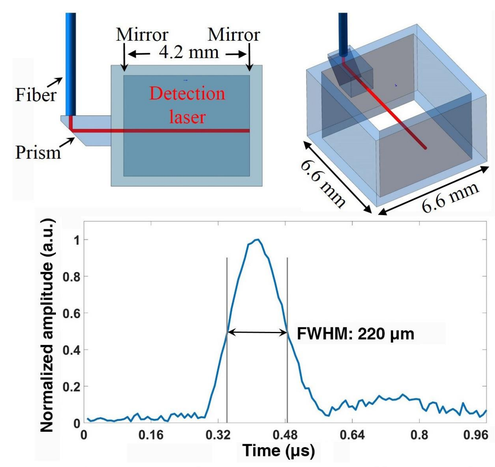

Figure 2. The transparent all-optical ultrasound transducer.

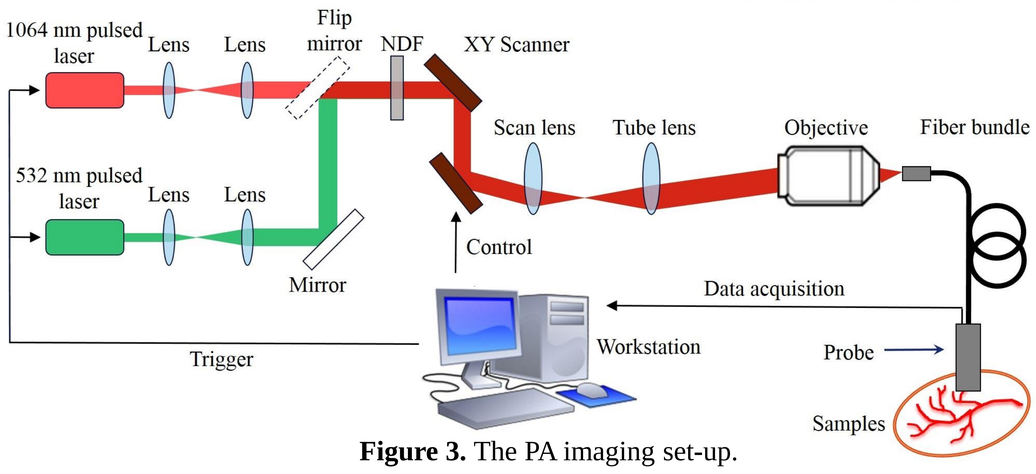

Figure 3. The PA imaging set-up.

To perform imaging using the custom designed PAI probe, a PAI system is set up and shown in Figure 3. Two solid-state pulsed lasers, one of 1064 nm wavelength (SPOT-10-500-1064, Elforlight) and the other one of 532 nm wavelength (SPOT-10-200-532, Elforlight), are used for imaging. A flip mirror is used to select one wavelength for PA excitation. A 2D galvanometer scanner (SCANcube III 10, SCANLAB GmbH) directs the beam to an objective (N10X-PF, 0.3 NA, Nikon) to be focused on the proximal end of a flexible fiber bundle (11.9 μm core-to-core distance, 18000 cores, SCHOTT North America). The light transmits through the fiber bundle (FB) to the probe for imaging.

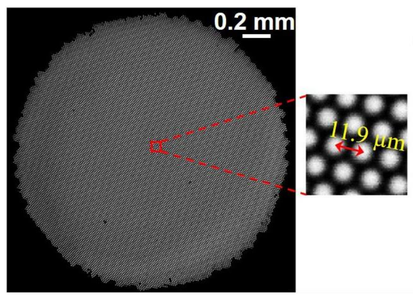

Figure 4. FB surface image.

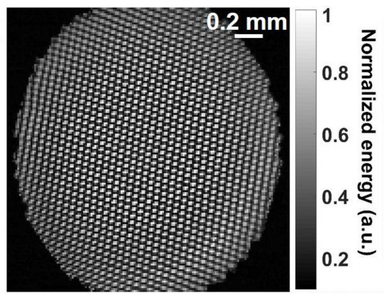

Figure 5. Pixelated FOV energy distribution

A well-known problem with imaging using FB is the pixilation effect caused by the fact that the inter-core materials of FB does not transmit light. Here the pixilation effect is demonstrated in Figure 5 with the pixelated FOV energy distribution created by a raster scanning (RS) on the proximal side of FB.

To remove the pixilation effect, a new scanning method, termed as fiber-core targeted scanning (FCTS) is developed to sequentially deliver the laser pulses into individual fiber cores without sacrificing the scan speed. Like RS, FCTS scans one row of cores after another. However, FCTS utilizes the image field correction function of the galvanometer system to dynamically adjust the scan speed to compensate for the deviation of core positions based on a mapping between scanner outputs and core positions. Compared with Figure 5, FCTS can create a very uniform FOV energy distribution, as shown in Figure 6.

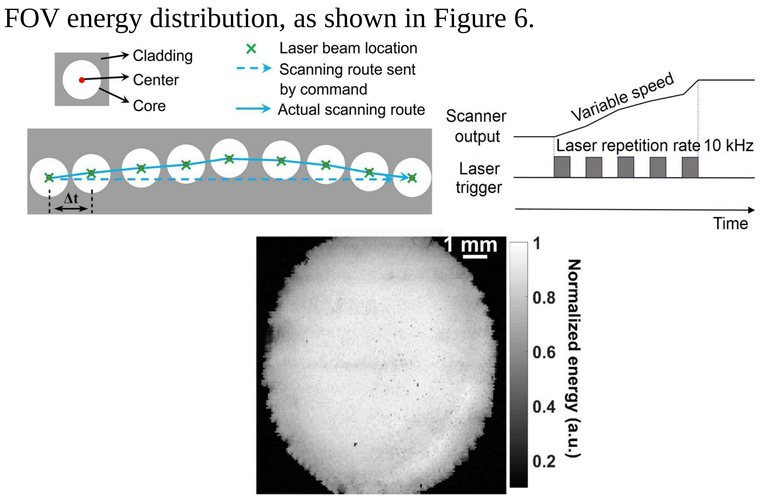

Figure 6. Principle of FCTS and FOV energy distribution created using FCTS.

Results

We first compared the imaging using RS and FCTS. As shown in Figure 7, either for the imaging of a hair knot or mouse blood vessels, with RS obvious pixilation artifacts can be observed while FCTS removes the artifacts due to a much more homogeneous FOV energy distribution. FCTS not only removes the pixilation artifacts but is also able to image more blood vessels than RS, as pointed out with white arrows in Figure 7. This is because hemoglobin has low optical absorption at 1064 nm wavelength, thus only FCTS can deliver enough energy to induce detectable PA signals due to higher transmission efficiency of FCTS. Because of this higher optical efficiency, the imaging contrast achieved by FCTS is also higher than RS.

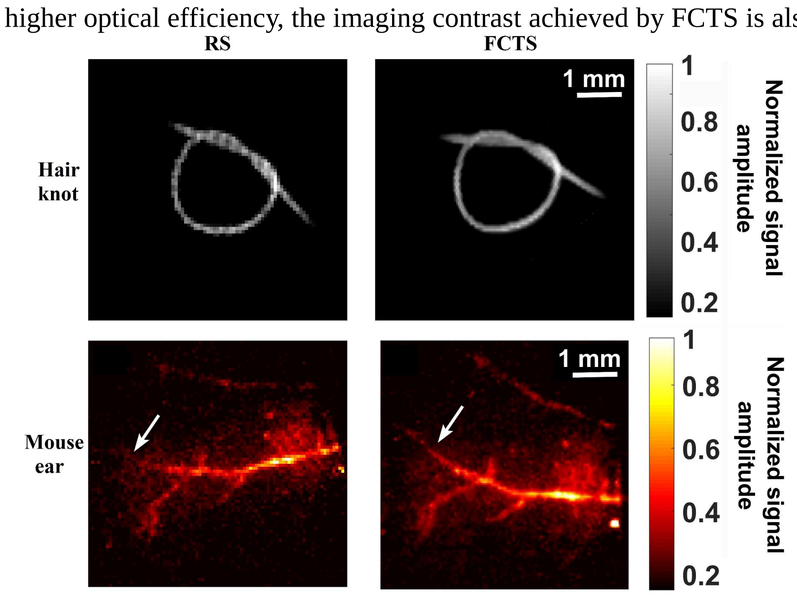

Figure 7. Principle of FCTS and FOV energy distribution created using FCTS.

An area on a foot of a healthy human volunteer, as shown in Figure 8, is imaged using the probe. Figure 8 first shows the imaging result as a depth-coded image. Major blood vessels marked as V1 to V4 can be clearly identified. Above these major blood vessels, PA sources with a depth from 0.05 to 0.5 mm are widely scattered within FOV, which are most likely generated by melanin inside the skin. By doing a maximum amplitude projection from a depth range of 0.5 to 2.5 mm, an image with much higher contrast for the major blood vessels can be seen in Figure 8. A MAP image projected along the X-Z planes is also shown in Figure 8.

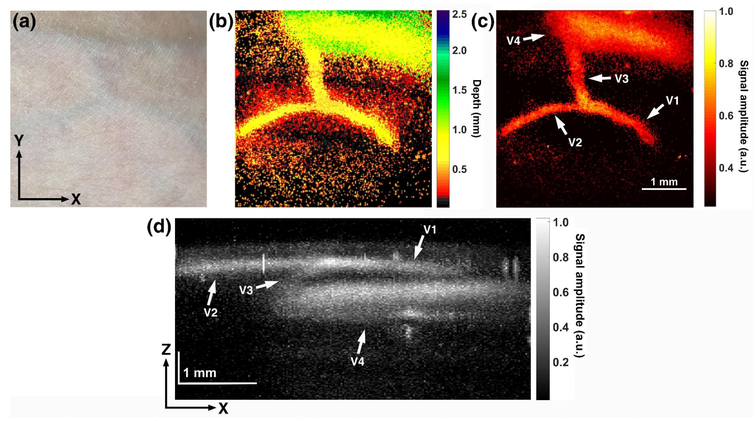

Figure 8. Imaging of the human skin using the probe.

Conclusion

In summary, we present a novel forward-viewing laparoscopic PAI probe based on flexible imaging fiber bundles, all-optical transducers and fast fiber core targeted scanning at the proximal end. It is demonstrated that the proposed probe can achieve high-resolution and high-contrast imaging of vasculatures in a series of *ex vivo* and *in vivo* studies. Therefore, the proposed forward-viewing PAI probe can be potentially a valuable laparoscopic imaging tool for lesion detection and surgery guiding by providing high-resolution, high-contrast, 3D vascular features.