Real-Time Tissue Differentiation Using Fiber Optic Sensing in Laser Catheters[1]

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1 Background

Tissue-aware surgical smart tools [1] could increase the safety and effectiveness of surgical procedures, especially for minimally invasive procedures that are poorly imaged and robotic surgery procedures that lack tactile feedback [2–4]. Tools equipped with tissue differentiation sensing could warn the surgeon of approaching danger in real-time, as well as verify procedural methods and results. Tissue sensing is currently also a weak link in the development of an accurate and safe closed loop robotic surgical procedure program.

Different electrical, mechanical, and optical properties of tissue have been used to image and have been explored in regards to their ability to distinguish tissue [3,5,6]. Using optical properties, however, may hold the greatest potential for embedding sensing at the tool-tip, as there are significant differences in the optical properties of tissues, and the use of optical fibers allows high-bandwidth, dense data to be transmitted from remote and confined surgical locations to a large processing unit.

We conducted experiments to assess the ability of a fiber optic sensor (FOS) to discriminate between different in vivo, in vitro environments. Using a porcine model and tissue phantoms, our tests demonstrated significant contrast between tissue contact and blood suspension, as well as the capability to distinguish between several different tissue types and provide a quantitative distance from the FOS tip to a surface.

2 Methods

An experimental probe system (Fig. 1) was designed to measure color intensities of different environments. The main system elements included a Leica KL1500 adjustable halogen light source, a fiber optic standard light guide (495 NE 7M, Karl Storz, Tuttlingen Germany), a universal serial bus (USB) digital microscope (Dr. Meter Model B003+ 300× magnification), and a Spectranetics SLS II Laser Sheath (14 Fr SLS SPNC Model #500-302) for Excimer laser ablation, which was modified by Spectranetics Corp. The modified laser sheath was made to have an optical fiber bundle at the distal tip that included four 150 micrometer return fibers (P.N. 7475-0042) (Fig. 1). Custom input and output couplers were 3D printed to functionally connect the Spectranetics laser sheath plug to the light guide and the output fibers to the USB microscope camera. A MotionFit Wireless SDK nine-axis inertial measurement unit (IMU) (Invensense MPU-9150) was used for absolute angle measurements at the tool-tip.

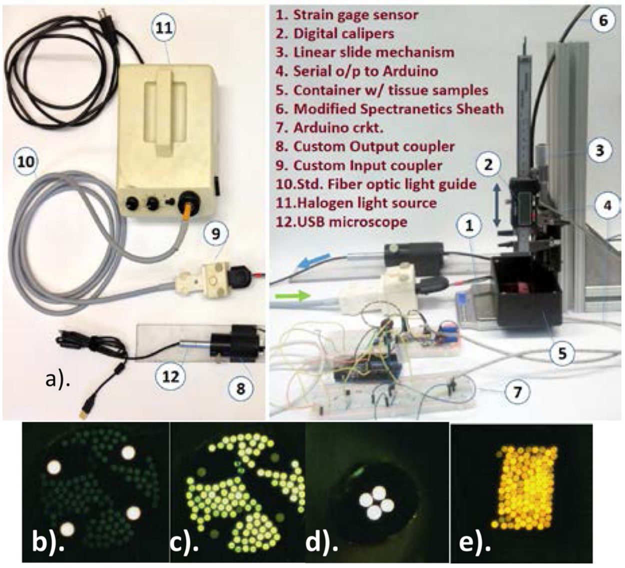

Fig. 1 (*a*) Experimental setup, (*b*) distal tool-tip with the return-input fibers, and (*c*) source fibers illuminated. (*d*) The proximal end of the illuminated four input fibers and (*e*) the source fibers inside the standard connector (fiber images provided by Spectranetics Corp.).

To evaluate the prototype's ability to distinguish tissue, testing was carried out in the visible heart lab at the University of Minnesota. The experiment was conducted in situ in the superior vena cava (SVC) as blood was pumped through the large vein via a syringe (Fig. 2). The distal tip of the FOS probe was placed at different tissue contact points in the excised block of porcine tissue. Video data were collected from the return optical fibers throughout the experiment, and these data streams were simultaneously captured and labeled in real-time using a modified SurgTrak [7] codebase at 30 Hz. MATLAB (Mathworks Corp., Natick, MA) was then used to extract red, green, and blue (RGB) masks from the video frames for color intensity analysis.

To evaluate the prototype's ability to measure the distance from its tip to tissue contact, a benchtop experiment was conducted with additional hardware and synthetic tissue phantoms suspended in porcine blood. A custom material testing stage (Fig. 1) was assembled to accurately measure the displacement and force as the tool-tip approached a tissue phantom in a blood environment. A microcontroller subroutine and logic-signal level change circuit were created to capture the output of the digital caliper (Neiko 01407A) mounted on a translation frame and transfer this data to a microcontroller (Arduino Uno). A custom instrumentation amplifier circuit with 30 Hz RC filtering was constructed to

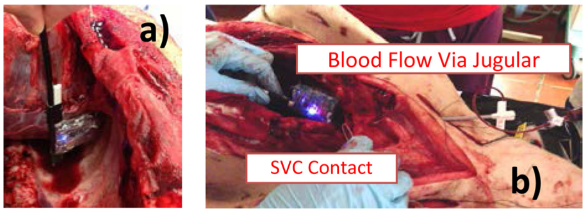

Fig. 2 (*a*) Footage of blood versus tissue experiment with the instrumented tool-tip vertically suspended and (*b*) the SVC identification experiment in blood flow. The IMU was used to determine contact angle (results of IMU data not shown).

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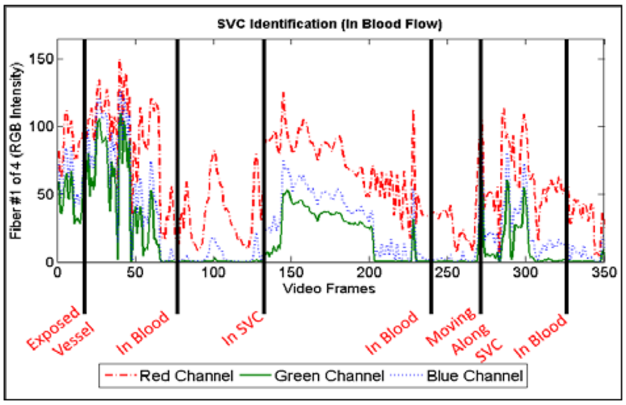

Fig. 3 Differentiation in optical properties between blood and tissue and SVC identification

capture the output of a weight scale strain gauge (AWS-SC-2KG Digital Scale) located below the experimental container, sensing probe force readings. This experiment utilized three phantom tissues: red silicone, yellow urethane, and a Simulab Corp. (Seattle, WA) bowel phantom. All materials were selected based on their ability to mimic different tissue colors. The phantoms were placed in a black, rectangular container located on the force scale and filled with porcine blood. The digital caliper was manually calibrated so that at 0 mm, the tool-tip initiates contact with the phantom. The fiber optic data were recorded in sync with the digital caliper and the strain gauge outputs, which were time-stamped via the microcontroller, recorded by PuTTY, and imported into MATLAB for analysis. This experiment was repeated at each of the halogen source's five analog intensity levels.

3 Results

To quantify and evaluate the tests, return fiber RGB intensities were collected from each optical fiber in each video frame. Data from one of the return fibers in the SVC identification experiment are shown in Fig. 3. SurgTrak labeled the video frames with the tissue type the fiber bundle tip was contacting via manual input during the experiment. These data also appear in Fig. 3.

The RGB data from the distance inference experiment were plotted against the displacement measured by the caliper. Figure 4 shows an example of these data from one optical fiber when testing the red silicone material at light intensity level 5 (Fig. 4).

4 Interpretation

The results of the SVC identification test (Fig. 3) show clear transitions in each color channel between blood and tissue contact, and between different tissue types. This demonstrates quantitative identification of tissue type in real-time, which is useful in imminent error detection and feedback during a surgical procedure.

The distance inference test results (Fig. 4) indicate that the FOS can detect imminent contact with tissue from a distance of 1 mm.

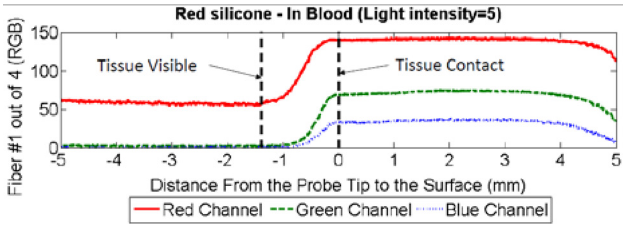

Fig. 4 The RGB data from a single fiber plotted against distance from tissue boundary shows tissue presence is detectable before contact with the tool-tip. Data from halogen intensity level 5.

Furthermore, as source intensity varied, the initial detection distance directly varied (not shown). This provides strong preliminary evidence that diffuse absorbance and transmittance (DAAT) characteristics can measure the distance to a tissue wall and sensitivity can be increased with higher light intensities.

The assessment of real-time optical properties via existing excimer laser sheath technology is feasible, even with rudimentary hardware, software, and data processing. Basic optical properties like color and DAAT characteristics were found to quantitatively discriminate contacted tissue types and proximity to contact. The positive results strongly motivate future research in FOS-based smart surgical tools.

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