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Potential of Laser Doppler Flowmetry in the Medical Needle Insertion Procedures

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***Abstract*— Medical needle insertion procedures possess the risk of life-threatening blood vessel rapture. Here we report a compact laser Doppler Flowmetry (LDF) based system that has a potential of blood vessel detection in the vicinity of the moving needle. The developed LDF system comprises two optical fibers inserted into the needle (the probe), a laser unit and a photodetector. The latter collects the signal produced by photons, scattered from the moving red blood cells that is further converted into perfusion value. Using LDF system, we have been able to detect the flow independently from the needle penetration angle, site or depth. Moreover, we showed that the blood vessel can be identified inside the tissue phantom while the probe is moving. Our results demonstrate that the developed LDF system is flexible and compatible with different types of needles and thus has a potential in the needle insertion procedures.**

I. Introduction

The risk of undesired blood vessel puncture exists in many medical procedures such as catheter installation for angiography and hemodialysis [1], commonly performed intravenous injections and cannulations [2], or even needle biopsy of intracranial tumor [3]. In needle intervention, rapture of the blood vessel may lead to serious complications the worst of which is the death of a patient. To avoid such issues, computer tomography (CT) or ultrasound are commonly used during procedure to image needle movement [4,5]. However, these systems are bulky and reduce the flexibility of intervention. Consequently, a compact and affordable device that allows blood vessel detection in front of the needle and can be used with any type of needle and procedure is highly desired.

Laser Doppler Flowmetry (LDF) has been implemented in clinical practice since 1981, when Bonner and Nossal have developed a model for laser Doppler measurements of blood flow in tissue becoming a standard for LDF measurements [6]. Based on this model, LDF has been investigated for static monitoring of skin [7,8], dental tissue [9] and brain [10] microcirculation. Moreover, commercial LDF devices for microvascular research are widely available for clinical use [11]. However, all LDF research and commercial studies are limited to static measurements of superficial and slow microcirculatory blood flow, not used for high velocity flows deep inside the tissue.

In this study, we evaluate the potential of LDF technology in blood vessel detection during needle insertion. We are particularly interested in insertion procedures when the needle probe is moving inside the tissue (Fig. 1). We employ sensor probe with two optical fibers integrated inside which is compatible with different types of needles for a variety of medical procedures. We validate the concept with tissue and blood mimicking phantoms. The rest of the paper is organized as follows: section II introduces the developed methodology and measurement system; section III reports the results including measurements limitations and phantom evaluation; section IV concludes the paper.

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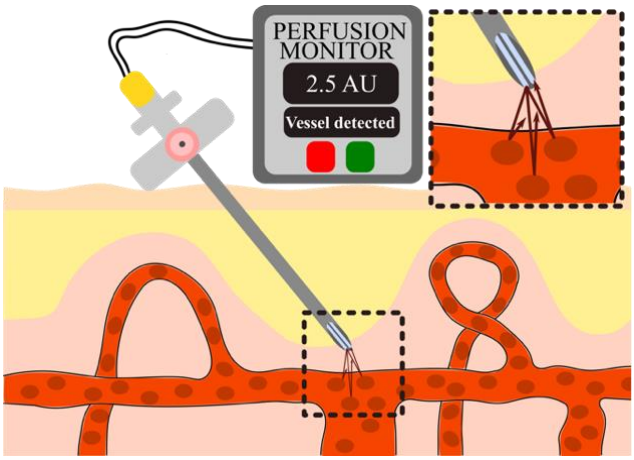

Figure 1. Concept of LDF measurement during needle insertion procedure. The needle probe with two integrated optical fibers is moving inside the tissue towards the blood vessel. The laser light is emitted from one fiber, scatters from the moving blood cells and is received by the second fiber. Perfusion monitoring software outputs the measurement results.

II. Methodology

A. Sensing Principle

The principle of LDF lies in the laser-tissue interaction [6,12]. When laser light of certain wavelength penetrates the tissue, part of the photons is scattered towards the detector due to tissue inhomogeneity and the blood flow. Scattering from the static tissue does not result in the frequency shift, while scattering by moving red blood cells (RBCs) shifts the frequencies of the photons. If the shifted photons are collected by a photodetector, frequency change in photocurrent can reveal the properties of the blood flow. In this study, we calculate the blood flow properties from the moments of power spectrum [6]:

$$M_i = \int f^i P(f) d(f) \quad (1)$$

where f is the frequency, $P(f)$ the power spectrum of the signal. Concentration of moving blood cells (CMBC) represents RBCs fraction in the tissue volume, proportional to the integral of the Doppler power spectrum density:

$$CMBC \propto M_0 \approx \int P(f) d(f) \quad (2)$$

Perfusion (Perf) is characterized by both concentration and velocity of the moving RBCs, and is proportional to the frequency-weighted Doppler power spectrum:

$$Perf \propto M_1 \approx CMBC \cdot \langle V \rangle \approx \int fP(f)d(f) \quad (3)$$

where V is velocity. Perfusion is a qualitative value and is thus expressed in arbitrary units (AU).

B. LDF System Architecture

To detect the blood vessels during insertion, the LDF system should satisfy the following requirements. First, the blood flow in the big blood vessels with the speed of 10-1200 mm/s [13] should be distinguishable from the microcirculation (0.3-10 mm/s [13]), widely present in all tissues. Second, the system should identify the vessel in front of the tip before touching the vessel wall to avoid unnecessary puncture. Thus, the detection depth should be sufficient in order to allow withdrawal of the probe during insertion. Last, for flexible procedure the operation range should not be limited by the angle or the site of the probe in relation to the blood vessel.

The LDF system for the insertion measurements should detect the blood flow through the tissue of a certain thickness to allow needle retraction before blood vessel penetration. To achieve this, the laser light should penetrate sufficiently through the skin, fat, blood and water. Some laser wavelengths are entirely absorbed by melanin in the skin, while other can penetrate through all tissues to some degree. Near infrared light in the range of 650-1350 nm is called "therapeutic window" in clinical applications due to its low absorption by melanin, hemoglobin or water [14]. In this study, a wavelength of 808 nm was used for its lowest attenuation by all tissue components [15].

Fig. 2 shows the schematic of the developed LDF system. The system comprises a sensor setup, a data acquisition unit and a PC for signal processing and output monitoring. The sensor setup consists of two optical fibers and a needle (the probe), power and signal cables, a laser unit and a photodetector. The laser unit is a custom built with exchangeable laser diode providing flexibility of the laser wavelength and power in comparison with commercial LDF systems, which are restricted to certain laser parameters.

The measurement probe comprises two optical fibers (200 µm diameter, numerical aperture of 0.39, M38L01, Thorlabs) glued together and inserted into the needle with inner diameter 0.41 mm (22G), providing 0.2 mm fibers

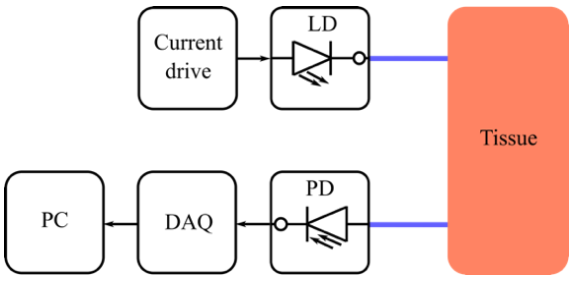

Figure 2. Schematic of the developed system. A current drive supplies power to a laser diode (LD) that transfers light to the tissue via a sending optical fiber. The scattered light is collected by a receiving fiber and sent to a photodetector (PD). The signal is processed by a DAQ and saved to a PC.

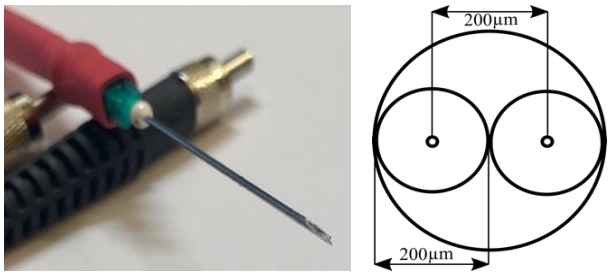

Figure 3. The measurement probe and the fibers inside the needle.

separation. Fig. 3 shows the schematic of fibers position inside the needle as well as a photo of the probe. The probe design allows using any needle with inner diameter larger than two diameters of optical fiber.

The laser light emitted from the laser diode (LD, 808 nm, LD808-SA100, Thorlabs) is transmitted through the sending optical fiber to the measurement probe and interacts with the tissue. The scattered and reflected light transfers via the receiving optical fiber to the photodetector (PD, PDA100A, Thorlabs), which converts optical signal into electrical output. A data acquisition device (DAQ, NI USB-6363, National Instruments) collects photodetector signal and sends it to the computer. The signal is displayed and recorded in real time with LabVIEW application, and post-processed using MATLAB.

C. Experimental Phantoms

To validate the developed LDF system, an experimental setup was built as shown in Fig. 4. It includes a transparent plastic tube (inner diameter: 0.5 mm, wall thickness: 0.25 mm) that mimics a blood vessel, a syringe (volume: 20 ml), semi-skimmed milk (1.5% fat, Valio) as a blood-mimicking fluid, and a syringe pump (PHD ULTRA 4400, Harvard Apparatus) for pushing the fluid through the tube and imitating the blood flow. A manual z-theta micromanipulation stage controls the position of the probe in vertical direction and rotation. Skin-simulating material was fabricated from milk (1.5% fat, Valio), red ink, and gelatin, where the plastic tube was placed into to mimic the blood vessel inside the tissue.

D. Experimental Conditions

The operation of the developed LDF system was evaluated by measuring the perfusion of the blood-mimicking flows with different velocities and particles concentrations. The velocities were varied in the range of 0 mm/s – 10 mm/s with 1 mm/s step. The concentration of the particles was adjusted by diluting milk fractions (25%, 50% and 75%) in water. The power spectrum and perfusion value reflect the response of the system to the flow velocity and concentration changes.

The limitations of the LDF system were assessed in terms of penetration depth, site and angle (Fig. 5). A manual microstage was used for positioning control. The penetration angle, at which the probe is placed in relation to the blood vessel, varies in ±30-90º range. The penetration site is defined by the portion of light that goes through the blood flow inside the vessel. When the probe is centered in relation to the vessel walls (site 1 in Fig. 5), all laser light

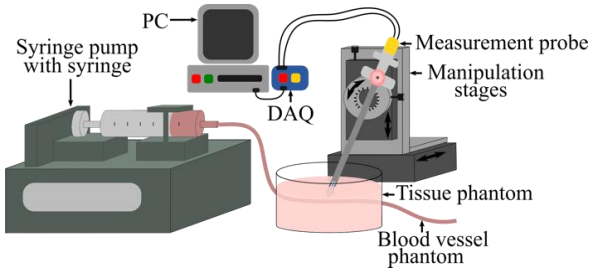

Figure 4. Experimental phantom comprised of a syringe pump with a syringe pushing blood mimicking liquid through the tube, tissue phantom, a probe mounted on a micromanipulation stage, a DAQ and a PC for signal processing.

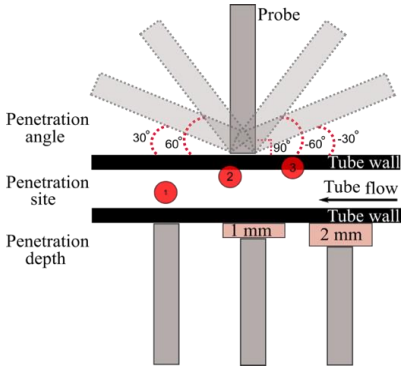

Figure 5. Schematic of the probe positions in relation to the tube and tube walls. Penetration angle with angle marks: 90º, ±60º, ±30º (top); different penetration site when the probe is perpendicular to the vessel: 1- light passing through the center of the blood flow, 2 – partially through the vessel side wall, and 3 – mostly through the vessel side wall (middle); penetration depth: 0, 1 and 2 mm tissue separation (bottom).

passes through the blood flow. If the light is not perfectly centered and passes partially through the side wall, misalignment of penetration site exists (sites 2 and 3 in Fig. 5). The penetration depth determines the thickness of the tissue between the probe and the blood vessel at which the blood flow detection is possible. Tissue of 1 and 2 mm thickness have been evaluated.

III. Results

A. LDF Measurement Results

To evaluate the LDF system, the blood-mimicking fluid was pumped through the plastic tube as shown in Fig. 4. The measured power spectra, corresponding to each flow velocity, are presented in Fig. 6a. The spectra are distinctly widening with increasing velocity. Blood flows with 1-10 mm/s velocities are clearly distinguishable. The variation of particles concentration in the flow affects photodetector's signal intensity and consequently the perfusion as predicted in (2,3) and shown in Fig. 6b. Thus, the system can differentiate between low (below 10 mm/s) and high (10-1200 mm/s) speed blood flows, fulfilling the first application requirement.

B. Evaluation of Measurement Limitations

In order to define operational limits of the system, perfusion measurements of the static fluid and 4 mm/s flow were compared. To evaluate the influence of the penetration angle between the probe and the tube, we vary the angle

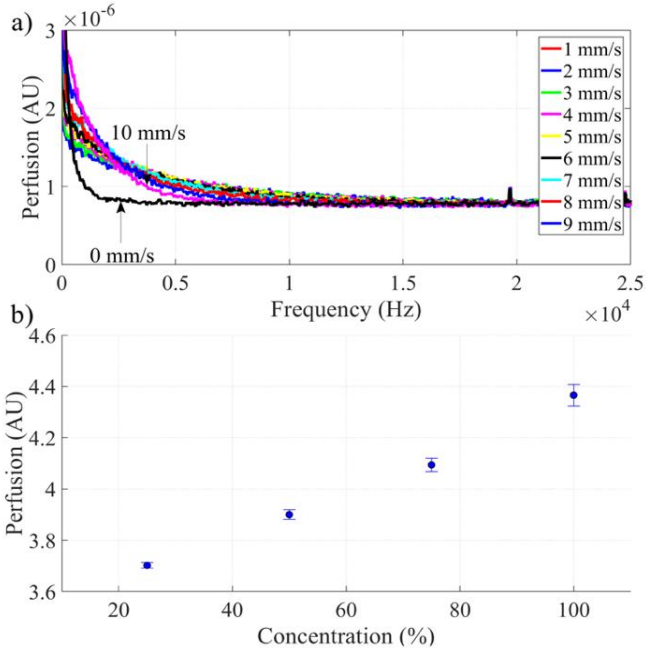

Figure 6. Measurement results of LDF evaluation experiments: the power spectra of LDF signals corresponding to 0-10 mm/s blood flow (a), the trend of perfusion increasing with increasing particles concentration of the flow (b). Error bars respresent standard deviation of 5 measurements.

from perpendicular position (90º) to ±30º, as shown in Fig. 7a. The signal intensity is at maximum at 90° as expected, and reduces with decreasing angle with its minimum value at ±30°. Fig. 7b indicates the penetration site evaluation results. The flow is clearly distinguishable when the laser penetrates the blood vessel-mimicking tube in the center between the walls (site 1), or when the probe is slightly misaligned and a small portion of light goes through the side wall of the vessel (site 2). However, the flow is unidentifiable if the penetration is mostly through the wall (site 3) because too little photons are scattered from the moving RBCs. Moreover, the maximum depth of penetration with effective detection in the current setup is 1 mm (Fig. 7c). With a thicker tissue-mimicking barrier between the probe and the tube, most of the light is absorbed leading to no detection.

C. Phantom Evaluation

In phantom evaluation, we tested the ability of the system to search the blood vessel based on the detection of the blood flow while moving the needle inside the tissue. The probe was inserted into the tissue-mimicking phantom and manipulated manually towards the tube with the flow.

As shown in Fig. 8a, the system outputs noise when the needle is moving, but the measurement stabilizes when the probe reaches the tube and the flow is detected. Further, the probe was directed and stabilized towards the blood vessel-mimicking tube, and the flow was initiated. Immediate increase of the perfusion demonstrates that the probe inside the phantom tissue can differentiate between the blood vessel and the actual blood flow (Fig. 8b). This shows that the LDF system is potentially applicable in the blood vessel detection applications.

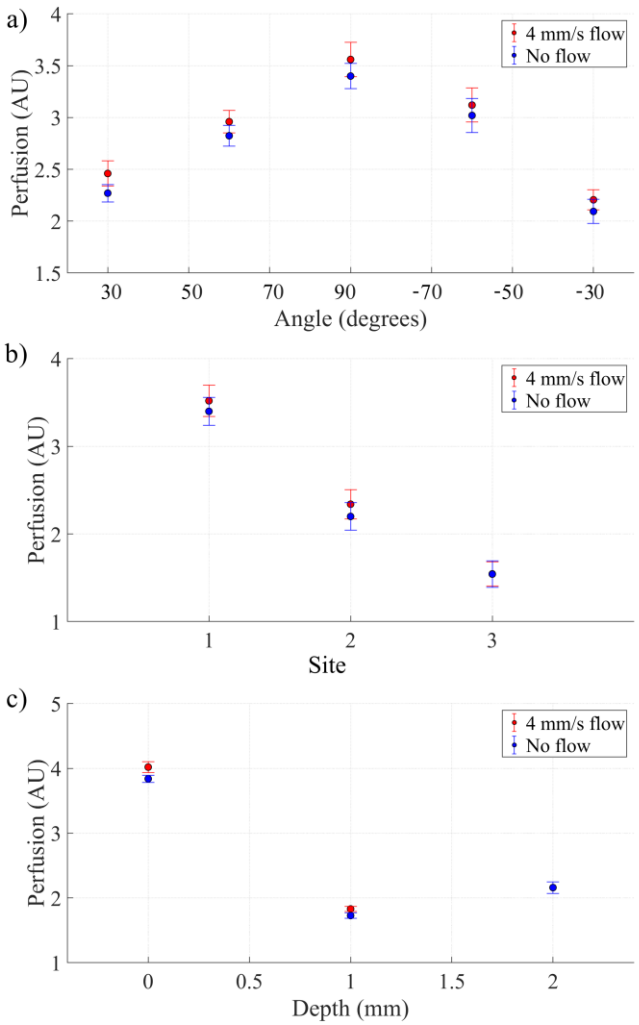

Figure 7. Measurement results of system limitations experiments: penetration angle (a), penetration site (b), and penetration depth (c). Error bars respresent standard deviation of 5 measurements.

IV. Conclusion

In this work, we have developed the blood vessel detection system based on LDF technology. The device consists of a laser and a detection unit with two optical fibers inside a needle probe. The architecture of the probe allows a variety of needle applications in medical interventions. The initial assessment shows that the system can detect the blood flow in the vicinity of the needle tip while moving inside the tissue. The penetration depth of 1 mm allows possible needle retraction if a blood vessel is detected in front of the probe. The blood flow is distinguishable if the needle is not perfectly aligned to the center of the blood vessel and at a probe-blood vessel angle of ±30-90°. These results show that the system is potentially applicable for the needle insertion procedures. Future work includes development of compact LD-PD setup for portability and flexibility, as well as experiments with real blood and tissue.

Acknowledgment

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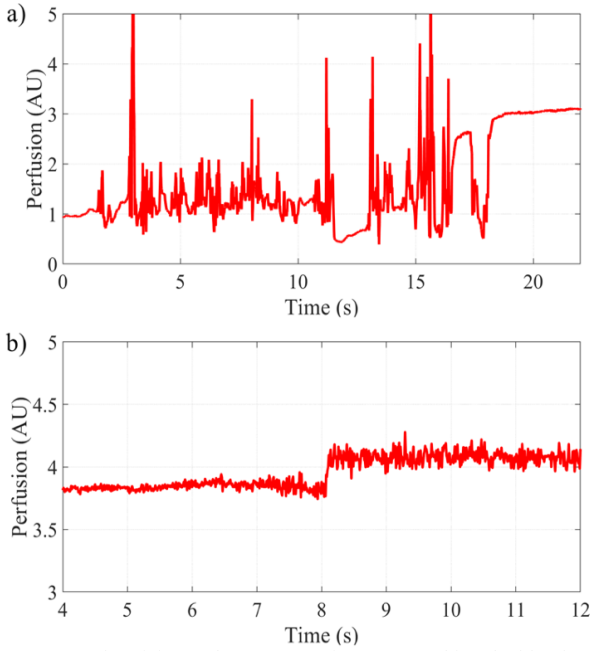

Figure 8. Results of tissue phantom experiments: searching the blood vessel inside the tissue (a), and confirming the blood flow detection (b).

References

[1] M.-C. Guilbert *et al.*, "Arterial trauma during central venous catheter insertion: Case series, review and proposed algorithm," *Journal of Vascular Surgery*, vol. 48, no. 4, pp. 918–925, 2008.

[2] C. Sahutoglu *et al.,* "A Venous Catheter Complication: Venous Perforation and Lung Injury," *Turkish Journal of Anesthesia and Reanimation*, vol. 42, no. 5, pp. 270–272, 2014.

[3] H. Malone *et al.,* "Complications Following Stereotactic Needle Biopsy of Intracranial Tumors," *World Neurosurgery*, vol. 84, no. 4, pp. 1084–1089, 2015.

[4] A. Seitel, *et al.*, "Computer-assisted trajectory planning for percutaneous needle insertions," *Medical Physics*, vol. 38, no. 6Part1, pp. 3246–3259, 2011.

[5] B. Saugel *et al.*, "Ultrasound-guided central venous catheter placement: first things first," *Critical Care*, vol. 21, no. 1, 2017.

[6] R. Bonner and R. Nossal, "Model for laser Doppler measurements of blood flow in tissue," *Applied Optics*, vol. 20, no. 12, p. 2097, 1981.

[7] D. Boggett, J. Blond, and P. Rolfe, "Laser doppler measurements of blood flow in skin tissue," *Journal of Biomedical Engineering*, vol. 7, no. 3, pp. 225–232, 1985.

[8] E. Figueiras *et al.*, "A new laser Doppler flowmeter prototype for depth dependent monitoring of skin microcirculation," *Review of Scientific Instruments*, vol. 83, no. 3, p. 034302, 2012.

[9] I. V. Fedosov *et al.* "Compact laser Doppler flowmeter for application in dentistry," *Saratov Fall Meeting 2004: Optical Technologies in Biophysics and Medicine VI*, 2005.

[10] E. Figueiras *et al.* , "Self-mixing microprobe for monitoring microvascular perfusion in rat brain," *Medical & Biological Engineering & Computing*, vol. 51, no. 1-2, pp. 103–112, 2012.

[11] E. Raposio *et al.*, "Transcutaneous oximetry and laser Doppler flowmetry values in patients with chronic skin ulcers treated with platelet rich plasma and stromal vascular fraction cells: a pilot study," *European Journal of Plastic Surgery*, vol. 41, no. 5, pp. 577–582, 2018.

[12] I. Fredriksson, "Model-based quantitative laser Doppler flowmetry in skin," Journal of Biomedical Optics, vol. 15, no. 5, p. 057002, 2010.

[13] S. S. Kenneth and M. Carol, "Anatomy and physiology: The unity of form and function", 1998.

[14] V. V. Tuchin and V. Tuchin, "Tissue optics: light scattering methods and instruments for medical diagnosis." (2007).

[15] R. Richards-Kortum and E. Sevick-Muraca, "Quantitative Optical Spectroscopy For Tissue Diagnosis," *Annual Review of Physical Chemistry*, vol. 47, no. 1, pp. 555–606, 1996.