LED-based photoacoustic imaging of medical devices with carbon nanotube-polydimethylsiloxane composite coatings

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Abstract: Invasive medical devices such as needles and catheters can have low visibility with ultrasound imaging. Here, we demonstrate that visibility can be greatly improved using LED-based photoacoustic imaging in combination with optically absorbing nanocomposite coatings.

OCIS codes: (170.5120) Photoacoustic imaging; (170.7170) Ultrasound; (160.4236) Nanomaterials.

1. Introduction

Ultrasound (US) imaging is widely used for guiding minimally invasive procedures. These procedures include nerve blocks, tumor biopsies and central venous catheterisations. However, invasive medical devices can have poor ultrasonic visibility, which can lead to complications such as puncture of a critical structure or injection at an incorrect location [1].

Photoacoustic (PA) imaging has been used to visualise invasive metallic medical devices including needles [2] and brachytherapy seeds [3,4]. A promising aspect of this paradigm is that photoacoustic signals from metallic objects can be prominent relative to those of surrounding tissues. However, excitation light sources are often bulky, which is suboptimal from a clinical translation standpoint. A second challenge is that many medical devices are non-metallic and weakly optically absorbing, so that they may not be detectable with PA imaging.

In this study, a dual-modality PA and US system with compact light emitting diode (LED) arrays was used to image a needle and a catheter in biological tissue for the first time. To enhance PA visibility of a non-metallic epidural catheter, an elastomeric composite coating comprising multi-walled carbon nanotubes (MWCNTs) and polydimethylsiloxane (PDMS) was applied.

2. Materials and methods

The dual-modality LED-based PA and US imaging system (AcousticX, PreXion, Tokyo, Japan) [5] had a linear-array ultrasound imaging probe with 128 transducer elements, a central frequency of 9 MHz, and an inter-element spacing of 0.3 mm. It alternated between two modes: a conventional B-mode ultrasound imaging mode, and a photoacoustic imaging mode in which ultrasound was generated with photoacoustic excitation light. For the latter mode, pulsed excitation light was provided by two arrays of LEDs that were affixed on opposite sides of the imaging probe. Nominally, each array provided a pulse energy of 200 µJ at 850 nm over an illumination area of 50 mm × 7 mm on the sample surface; the maximum pulse repetition frequency was 4 kHz. Raw channel data from 128 channels were digitised simultaneously at 40 MS/s and images were reconstructed and displayed online at a frame rate of 6.25 Hz, with averaging performed over 384 repeated measurements.

To evaluate the feasibility of this system for visualising medical needles and catheters, two experiments were performed. In the first, a 14 gauge metal needle (Terumo) was inserted into chicken breast tissue. In the second, an epidural catheter (Smith Medical) was dip-coated with a custom elastomeric composite material comprising functionalised MWCNTs [6] integrated in PDMS [7]. The coating was applied to the exterior of the catheter, leaving the interior uncoated and unobstructed for fluid flow. After it had cured, the catheter was positioned between layers of chicken breast tissue. In both experiments, the medical devices were positioned within the ultrasound imaging plane.

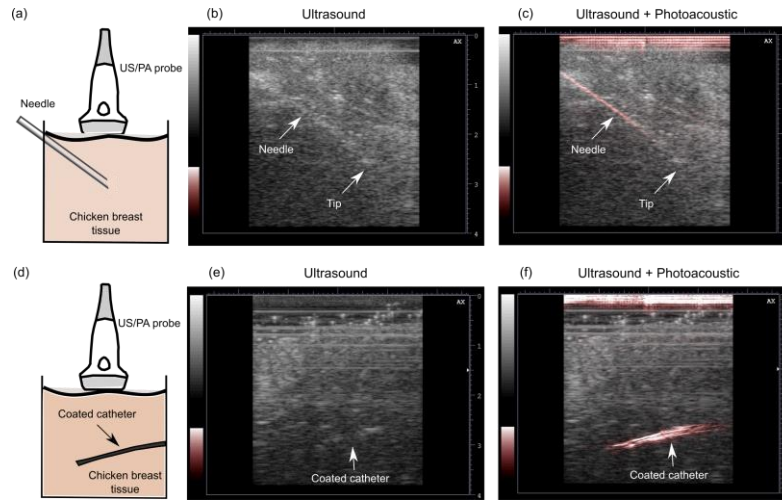## 3. Results and discussion

Figure 1. PA and US imaging of a needle [(a)-(c)] and a catheter with a MWCNT-PDMS composite coating [(d)-(f)] in chicken breast tissue. In overlays of the photoacoustic images on ultrasound images [(c),(f)], the medical devices are clearly visible, as compared with the ultrasound images alone [(b),(e)]. Both PA and US images are displayed with logarithmic compression. Vertical image scales: depth in centimetres.

With conventional US imaging, the needle was barely visible [Figure 1(b)]. With PA imaging, the needle shaft was clearly visible to a depth of approximately 20 mm [Figure 1(c)]. Likewise, the catheter with the MWCNT-PDMS coating was not visible on the US image [Figure 1(e)], but it was clearly visible with PA imaging [Figure 1(f)]. PA signals from the coated catheter were obtained at depths greater than 30 mm.

The maximum depth from which PA signals are obtained could be increased by delivering pulsed excitation light through the medical devices [4,8,9]. PA imaging provides information about the angle and shape of the medical device that is complementary to ultrasonic tracking methods, in which a miniature ultrasound sensor or transmitter within the medical device actively communicates with the external ultrasound probe [9-13].

Accurate and efficient visualisation of invasive medical devices such as catheters and needles is a long standing problem in US-guided procedures. This study demonstrated that pulsed excitation with compact LED arrays is sufficient to provide visualisation with PA imaging, and that catheters can be highly visible with PA imaging if they have an optically absorbing coating.

4. References

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