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Enhancing photoacoustic visualization of medical devices with elastomeric nanocomposite coatings

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ABSTRACT

Ultrasound (US) imaging is widely used for guiding minimally invasive procedures. However, with this modality, there can be poor visibility of interventional medical devices such as catheters and needles due to back-reflections outside the imaging aperture and low echogenicity. Photoacoustic (PA) imaging has shown promise with visualising bare metallic needles. In this study, we demonstrate the feasibility of a light emitting diode (LED)-based PA and US dual-modality imaging system for imaging metallic needles and polymeric medical catheters in biological tissue. Four medical devices were imaged with the system: two 20-gauge spinal needles with and without a multi-walled carbon nanotube / polydimethylsiloxane (MWCNT/PDMS) composite coating, and two 18-gauge epidural catheters with and without the MWCNT/PDMS composite coating. These devices were sequentially inserted into layers of chicken breast tissue within the US imaging plane. Interleaved PA and US imaging was performed during insertions of the needle and catheter. With US imaging, the uncoated needle had very poor visibility at an insertion angle of 45^{o}. With PA imaging, the uncoated needle was not visible, but its coated counterpart was clearly visualised up to depths of 35 mm. Likewise, both catheters were not visible with US imaging. The uncoated catheter was not visible on PA images, but its coated counterpart was clearly visualised up to depths of 35 mm. We conclude that the highly absorbing CNT/PDMS composite coating conferred excellent visibility for medical devices with the LED-based PA imaging system and that it is promising for translation in minimally invasive procedures.

Keywords: Photoacoustic imaging, Ultrasound imaging, LED, Nanocomposite coatings, Minimally invasive procedures

INTRODUCTION

Accurate visualisation of interventional devices is critically important during minimally invasive procedures, such as nerve blocks, tumour biopsies, central venous catheterisations and percutaneous umbilical blood sampling. US imaging is widely used for guiding minimally invasive procedures. However, ultrasonic visualisation of interventional medical devices such as surgical needles and catheters can be challenging when they are inserted at large angles and depths. Additionally, during in-plane needle insertions, needles and catheters readily deviate from the US imaging plane so that their distal ends are invisible; during out-of-plane insertions, the needle shaft can be misinterpreted as the needle tip when the it intersects the imaging plane. Loss of visibility of interventional devices can lead to life-threatening complications, such as stroke resulting from inadvertent intravascular injections of particulate steroids [1].

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Photoacoustic (PA) imaging is a novel imaging modality that is based on ultrasound generation by optical absorption of pulsed or modulated light [2]. PA signals can be acquired using clinical linear array ultrasound (US) imaging probes to obtain naturally co-registered PA and US images that provide complementary functional, molecular and structural information of tissue with high spatial resolution. In addition to tissue imaging, these dual-modality PA/US imaging systems have also shown promise to improve the visibility of metallic medical devices including needles [3] and brachytherapy seeds [4,5]. Here, the image contrast originates from intrinsic optical absorption of the medical devices, which can be much higher than that of the surrounding tissues. However, many medical devices are non-metallic and have poor visibility with PA imaging. Another challenge from a clinical translation standpoint is that many conventional excitation light sources for PA imaging are bulky and expensive.

In this study, a light emitting diode (LED)-based PA and US imaging system was used to image medical needles and catheters that were inserted in biological tissue for the first time. An elastomeric composite coating comprising multi-walled carbon nanotubes (MWCNTs) and polydimethylsiloxane (PDMS) was used to enhance PA visibility of a non-metallic epidural catheter.

MATERIALS AND METHODS

1.1 LED-based PA and US imaging system

The dual-modality LED-based PA and US imaging system (AcousticX, CYBERDYNE Inc, Tokyo, Japan) [6] was based on a linear-array US probe. This probe had 128 transducer elements with a central frequency of 9 MHz, and an inter-element spacing of 0.3 mm. The system alternated between two imaging modes: a plane wave B-mode US imaging mode, and a PA imaging mode. For PA imaging, pulsed excitation light was provided by two arrays of LEDs that were affixed on opposite sides of the imaging probe to illuminate an area of 50 mm × 7 mm on the sample surface. Each array provided a pulse energy of 200 μJ at 850 nm, with a maximum pulse repetition frequency of 4 kHz. The pulse duration was tunable over the range of 30 ns to 100 ns. For both PA and US imaging modes, raw channel data from 128 channels were digitized simultaneously at 40 MS/s and 20 MS/s, respectively. PA and US images were reconstructed using an in-built GPU-based Fourier-domain reconstruction algorithm and displayed online at a frame rate of 6.25 Hz, with averaging performed over 384 image frames.

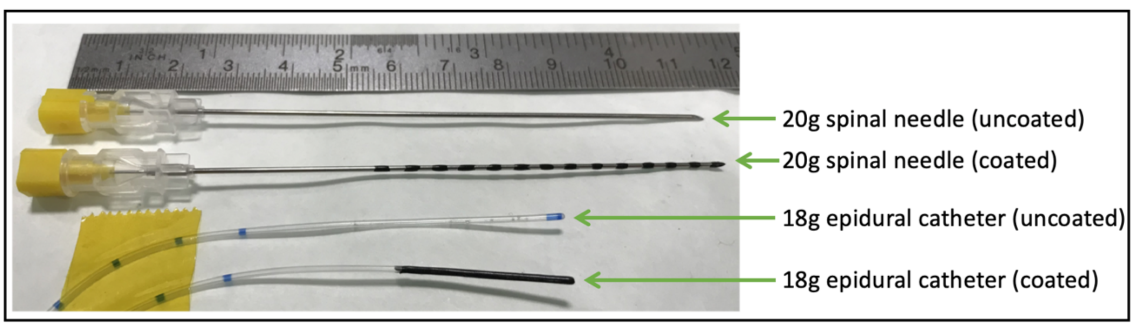

Figure 1. Photograph of the imaged needles and catheters. Two of them are coated with a multi-walled carbon nanotube / polydimethylsiloxane (MWCNT/PDMS) composite.

1.2 Coating medical needles and catheters

The MWCNT composite was fabricated using previously-described methods [7,8], with functionalized MWCNTs integrated into uncured PDMS [7]. This composite was applied to the exterior of a 20-gauge spinal needle (Terumo, Surrey, UK) and an epidural catheter (Smith Medical, Minneapolis, United States) and subsequently cured, leaving the interior uncoated and unobstructed for fluid flow. With the needle, the coating was applied in 14 regions spanning approximately 2 mm, with gaps of a similar size. With the catheter, the coating was continuous across a length of approximately 3 cm (Figure 1).

1.3 PA and US imaging

Two sets of experiments with the dual-modality LED-based PA and US imaging system were performed. In the first, the uncoated and coated needles were separately inserted into layers of chicken breast tissue at an angle of 45^{o}. In the second, the uncoated and coated catheters were sequentially placed between layers of chicken breast tissue, at shallow angles. In both experiments, the medical devices were positioned within the ultrasound imaging plane.

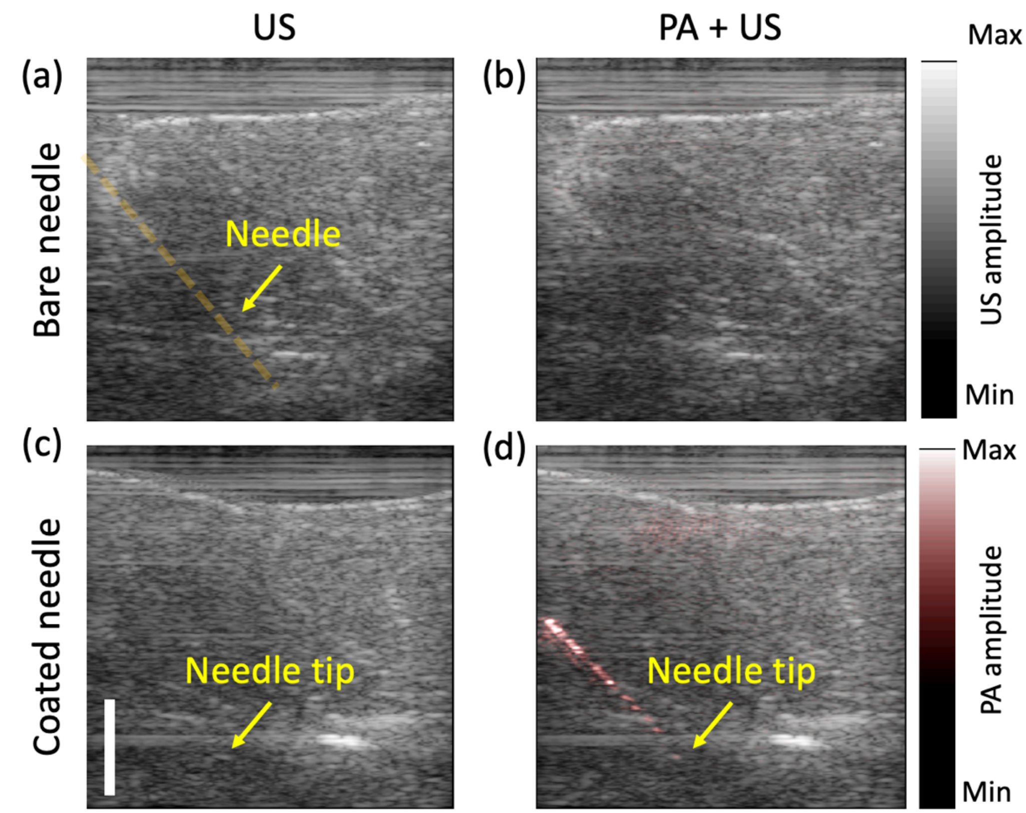

Figure 2. Photoacoustic (PA) and ultrasound (US) imaging of a 20-gauge spinal needle without (a-b) and with (c-d) a multi-walled carbon nanotube- polydimethylsiloxane (MWCNT/PDMS) composite coating. In (a), the location of the needle is indicated with a dashed yellow line. The image region that corresponded to the depth range of 0 to 5 mm, where there was water used for ultrasonic coupling, was cropped. Scale bar: 1 cm. Images are displayed in a logarithmic scale with dynamic ranges of 45 dB and 60 dB for PA and US images, respectively.

RESULTS AND DISCUSSION

With conventional US imaging, both the uncoated and coated needles were not visible [Figure 2(a,c)]. With PA imaging, the uncoated needle was also not visible, but the needle coated with the MWCNT/PDMS composite could clearly be visualized at depths down to 35 mm [Figure 2(b,d)]. Likewise, both the uncoated catheter and coated catheters were not visible on the US images [Figure 3(a,c)]. The uncoated catheter was also not visible with PA imaging. With the coating, the catheter was visible with PA imaging at depths up to 35 mm [Figure 3(b,d)].

This study provided a preliminary indication that optically absorbing coatings can be used to enhance visibility of medical devices with PA imaging. The MWCNT/PDMS composite is advantageous in this context as the MWCNTs confer high optical absorption, and the PDMS host material has a high thermal expansion coefficient to improve the efficiency of PA signal generation [7]. One limitation of this method for visualizing medical devices is that PA signals generated from proximal regions of the needle or catheter could be misinterpreted as originating from the distal ends. To overcome this limitation, 3D PA/US imaging could be used. Alternatively, direct visualization could be combined with ultrasonic tracking, where a miniature ultrasound sensor or transmitter is integrated within the cannula of the medical device to actively communicate with the external ultrasound probe, so that the tip of the medical device can be unambiguously identified [9-15]. To further extend the depth from which molecular and functional information of tissue could be obtained with PA imaging, excitation light could be delivered through the medical devices via an embedded optical fiber [4,16-18].

From a clinical translation standpoint, it is promising that PA signals could be obtained at clinically relevant depths of over 3 cm using LEDs as excitation light sources, and that co-registered US images can be obtained in real-time. The combination of medical device visualization using optically absorbing coatings and a compact, dual-modality PA/US system is promising for improving guidance of a wide range of minimally invasive procedures.

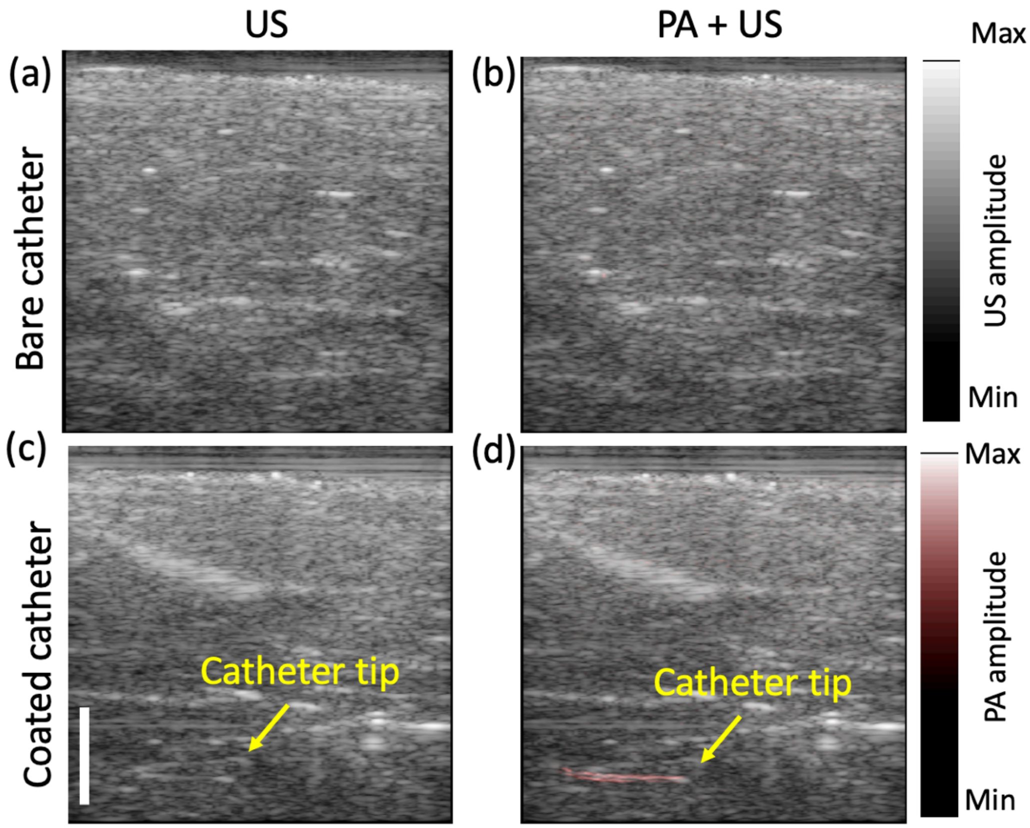

Figure 3. Photoacoustic (PA) and ultrasound (US) imaging of an 18-gauge epidural catheter with (c-d) and without (a-b) a multi-walled carbon nanotubes (MWCNT)s - polydimethylsiloxane (PDMS) composite coating. The image region that corresponded to the depth range of 0 to 5 mm, where there was water used for ultrasonic coupling, was cropped. Scale bar: 1 cm. Images are displayed in a logarithmic scale with dynamic ranges of 45 dB and 60 dB for PA and US images, respectively.

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REFERENCES

[1] Rathmell J. P., Benzon H.T., Dreyfuss P., Huntoon M., Wallace M., Baker R., Riew K.D., Rosenquist R.W., Aprill C., Rost N.S., Buvanendran A., "Safeguards to prevent neurologic complications after epidural steroid injections: consensus opinions from a multidisciplinary working group and national organizations," Anesthesiology 122(5), 974-984 (2015).

[2] Beard P., "Biomedical photoacoustic imaging," Interface Focus 1(4), 602-31 (2011).

[3] Su J.L., Karpiouk A.B., Wang B., Emelianov S.Y., "Photoacoustic imaging of clinical metal needles in tissue," J. Biomed. Opt.. 15(2), 021309 (2010).

[4] Bell M.A., Kuo N.P., Song D.Y., Kang J.U., Boctor E.M., "In vivo visualization of prostate brachytherapy seeds with photoacoustic imaging," J. Biomed. Opt.19(12), 12601 (2014).

[5] Singh M.K.A., Parameshwarappa V., Hendriksen E., Steenbergen W., Manohar S., "Photoacoustic-guided focused ultrasound for accurate visualization of brachytherapy seeds with the photoacoustic needle," J. Biomed. Opt. 21(12), 120501 (2016).

[6] Xia W., Singh M.K.A., Maneas E., Sato N., Shigeta Y., Agano T., Ourselin S., West S.J., Desjardins A.E., "Handheld Real-Time LED-Based Photoacoustic and Ultrasound Imaging System for Accurate Visualization of Clinical Metal Needles and Superficial Vasculature to Guide Minimally Invasive Procedures," Sensors, 18(5) (2018).

[7] Colchester R.J., Mosse C.A., Bhachu D.S., Bear J.C., Carmalt C.J., Parkin I.P., Treeby B.E., Papakonstantinou I., Desjardins A.E., "Laser-generated ultrasound with optical fibres using functionalised carbon nanotube composite coatings," Appl. Phys. Lett. 104(17), 173502 (2014).

[8] Noimark S., Colchester R.J., Poduval R.K., Maneas E., Alles E.J., Zhao T., Zhang E.Z., Ashworth M., Tsolaki E., Chester A.H., Latif N., "Polydimethylsiloxane composites for optical ultrasound generation and multimodality imaging," Adv. Func. Mater. 28(9), 1704919 (2018).

[9] Xia W., Noimark S., Ourselin S., West S.J., Finlay M.C., David A.L., Desjardins A.E., "Ultrasonic needle tracking with a fibre-optic ultrasound transmitter for guidance of minimally invasive fetal surgery," International Conference on Medical Image Computing and Computer-Assisted Intervention, 637-645 (2017).

[10] Guo X., Kang H.J., Etienne-Cummings R., Boctor E.M,. "Active ultrasound pattern injection system (AUSPIS) for interventional tool guidance," PloS One. 9(10), e104262 (2014).

[11] Xia W., Mari J.M., West S.J., Ginsberg Y., David A.L., Ourselin S., Desjardins A.E., "In-plane ultrasonic needle tracking using a fiber-optic hydrophone," Med. Phys. 42(10), 5983-91 (2015).

[12] Xia W., Ginsberg Y., West S.J., Nikitichev D.I., Ourselin S., David A.L., Desjardins A.E., "Coded excitation ultrasonic needle tracking: An *in vivo* study, " Med. Phys. 43(7), 40, 65-73 (2016).

[13] Xia W., West S.J., Finlay M.C., Mari J.M., Ourselin S., David A.L., Desjardins A.E., "Looking beyond the imaging plane: 3D needle tracking with a linear array ultrasound probe," Sci. Rep. 7(1), 3674 (2017).

[14] Xia W., West S.J., Mari J.M., Ourselin S., David A.L., Desjardins A.E., "3D ultrasonic needle tracking with a 1.5 D transducer array for guidance of fetal interventions," MICCAI, 353-361 (2016).

[15] Xia W., West S.J., Finlay M.C., Pratt R., Mathews S., Mari J.M., Ourselin S., David A.L., Desjardins A.E., "Three-dimensional ultrasonic needle tip tracking with a fiber-optic ultrasound receiver," JoVE 138 (2018).

[16] Xia W., Nikitichev D.I., Mari J.M., West S.J., Pratt R., David A.L., Ourselin S., Beard P.C., Desjardins A.E., "Performance characteristics of an interventional multispectral photoacoustic imaging system for guiding minimally invasive procedures," J. Biomed. Opt. 20(8), 086005 (2015).

[17] Mari J.M., Xia W., West S.J., Desjardins A.E., "Interventional multispectral photoacoustic imaging with a clinical ultrasound probe for discriminating nerves and tendons: an *ex vivo* pilot study," J. Biomed. Opt. 20(11), 110503 (2015).

[18] Xia W., Maneas E., Nikitichev D.I., Mosse C.A., dos Santos G.S., Vercauteren T., David A.L., Deprest J., Ourselin S., Beard P.C., Desjardins A.E., "Interventional photoacoustic imaging of the human placenta with ultrasonic tracking for minimally invasive fetal surgeries," MICCAI, 371-378 (2015).