Delft University of Technology

Seeing from a new angle
design of a sideways-looking fiber-optic probe to advance spine surgery

Losch, Merle S.; Dankelman, Jenny; Hendriks, Benno H.W.

DOI
10.1117/12.3000959

Publication date
2024

Document Version
Final published version

Published in
Advanced Biomedical and Clinical Diagnostic and Surgical Guidance Systems XXII

Citation (APA)
Losch, M. S., Dankelman, J., & Hendriks, B. H. W. (2024). Seeing from a new angle: design of a sideways-looking fiber-optic probe to advance spine surgery. In C. Boudoux, & J. W. Tunnell (Eds.), *Advanced Biomedical and Clinical Diagnostic and Surgical Guidance Systems XXII* Article 1283109 (Progress in Biomedical Optics and Imaging - Proceedings of SPIE; Vol. 12831). SPIE. https://doi.org/10.1117/12.3000959

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.
For technical reasons the number of authors shown on this cover page is limited to a maximum of 10.

Seeing from a new angle: design of a sideways-looking fiber-optic probe to advance spine surgery

Merle S. Losch[a], Jenny Dankelman[a], and Benno H. W. Hendriks[a,b]

[a]Department of Biomechanical Engineering, Faculty of Mechanical Engineering, Delft University of Technology; Mekelweg 2, Delft, The Netherlands
[b]Image Guided Therapy and Ultrasound Devices and System Department, Philips Research, Royal Philips NV; High Tech Campus, Eindhoven, The Netherlands

ABSTRACT

Our research highlights the potential of Diffuse Reflectance Spectroscopy (DRS) in detecting cortical breaches during pedicle screw placement. We propose a sideways-looking fiber-optic probe, integrating diffuse light emission with both forward and sideways light collection. Experiments on an optical tissue phantom validate the probe's potential to distinguish bone tissues and provide real-time guidance for spine surgery. Our findings prove that DRS with diffuse emission can detect perpendicular breaches, and demonstrate how the integration of a 45° slanted fiber coated with gold enables parallel breach detection, advancing spine surgery by allowing for accurate pedicle screw placement.

Keywords: Diffuse Reflectance Spectroscopy, spine surgery, breach detection, fiber optics, probe design

1. INTRODUCTION

As the global population ages, a surge in degenerative diseases affecting the spine is seen.[1] This demographic shift has led to an increasing demand for spinal fusion surgery,[2,3] as medical intervention is often needed for pain relief. Through spinal fusion, the structural integrity of the spinal column is restored with an assembly of metal rods and screws typically placed through the pedicles. The placement of pedicle screws is a sensitive procedure that requires high accuracy given that even minor deviations in screw trajectory can cause serious injury to the delicate osseous, neural and vascular structures.

Various guidance systems have therefore been developed, including the use of intraoperative fluoroscopy, computer-assisted navigation, and robotic-assisted surgery.[4] While these existing methods have been helpful in improving the accuracy of pedicle screw placement, the associated additional cost hinders their widespread adoption and prevents access to this technology for many surgeons and healthcare facilities.

Tissue sensing offers a potential solution to this challenge, as it allows to detect changes in the physical properties of the surrounding tissue with relatively simple instrumentation. Earlier studies have shown the integration of optical fibers into medical devices, enabling spectral tissue sensing.[5–7] Specifically, DRS has demonstrated great potential in distinguishing different types of tissues, including bone,[8,9] providing insights into tissue composition and structure. By probing the region ahead of the pedicle screw during insertion, DRS could provide real-time tissue feedback, enabling surgeons to monitor the trajectory of the screw to avoid cortical breaches. However, current forward-looking approaches fail to exploit the potential of DRS for generating directional tissue feedback. Concretely, enabling sideways-directed DRS measurements could provide spine surgeons with guidance for the accurate placement of pedicle screws.

Through design of the distal end of a fiber-optic medical device, the light path is determined, which offers potential to control the angular distribution of light, and to emit and collect light off axis to allow for sideways-directed DRS measurements.[10] Emitting light diffusely into the tissue through a diffuser tip will increase the illuminated volume.[11] To cover the full range of impending cortical breaches whilst keeping the complexity of the probe low and minimizing the amount of fibers used, the probed volume can be manipulated with obliquely

---

Send correspondence to M.S.L.: m.s.losch@tudelft.nl

Advanced Biomedical and Clinical Diagnostic and Surgical Guidance Systems XXII, edited by
Caroline Boudoux, James W. Tunnell, Proc. of SPIE Vol. 12831, 1283109
© 2024 SPIE · 1605-7422 · doi: 10.1117/12.3000959

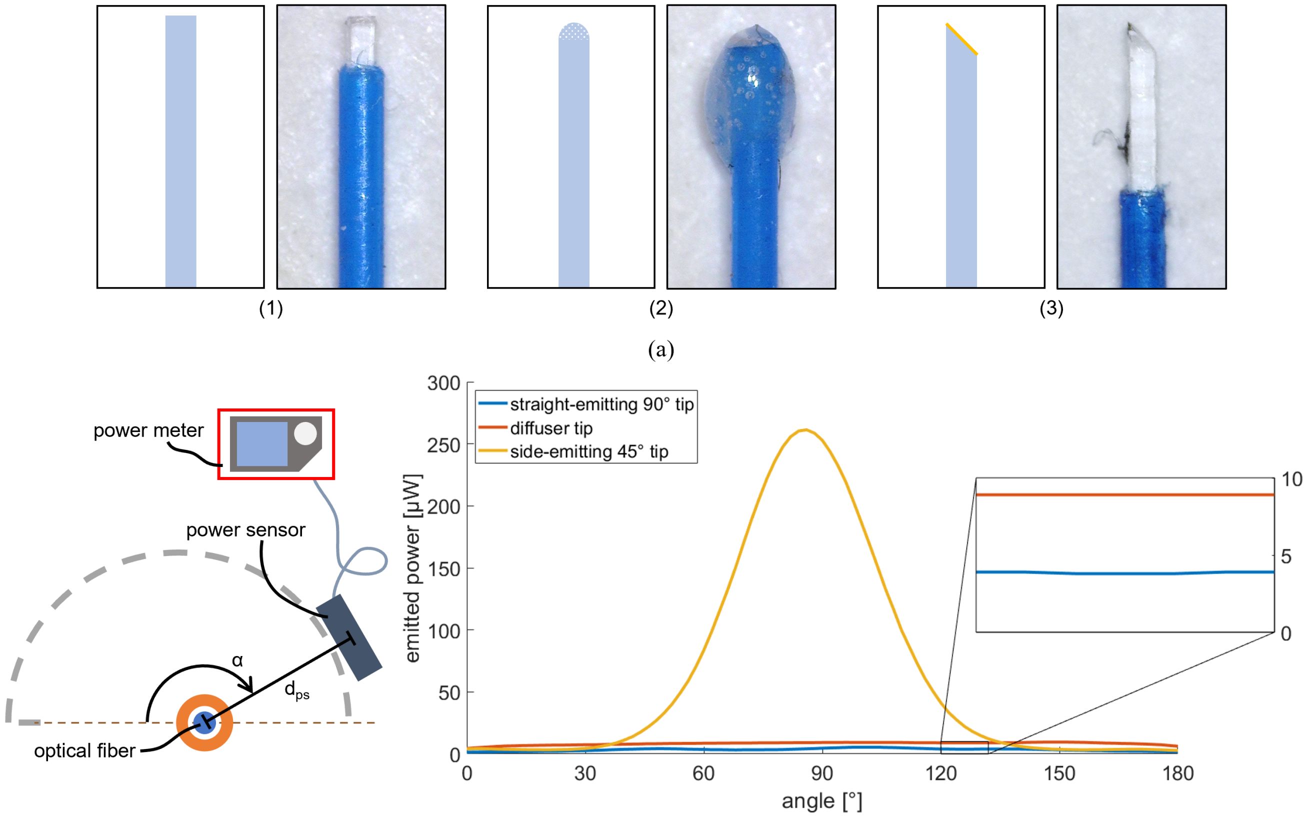
oriented collecting fibers.[12] Collecting light both along the device axis ("forward") as well as perpendicularly ("sideways") allows to examine the tissue ahead of and lateral to the probe tip to avoid both perpendicular and parallel breaches. To overcome spatial constraints for fiber angulation in medical devices, sideways collection is enabled by slanted optical fibers, which can be coated with silver or gold to maximize the collected intensity.[13]

This paper presents the design of a sideways-looking probe incorporating optical fibers with modified tips to provide directional feedback on tissue optical properties during spine surgery. Validation experiments on an optical tissue phantom prove the probe's capabilities for distinguishing bone tissues, demonstrating how it can contribute to improved pedicle screw placement accuracy.

2. MATERIALS AND METHODS

Optical fiber characterization Three different fiber tips for installation in the probe were manufactured by modifying 200 μm core diameter optical fibers with numerical aperture (NA) = 0.22 (M25L02, Thorlabs Inc., Newton (NJ), USA), see Fig. 1(a): (1) forward-emitting 90° tip (2) diffuser tip (3) sideways-emitting 45° tip with gold coating. The forward-emitting fiber is a standard terminated fiber with a 90° polished end surface. The diffuser tip was created from 10% barium sulfate (Acros Organics B.V.B.A., Geel, Belgium) dissolved in NIR-transparent optical adhesive (NOA68, Norland Products Inc., Jamesburg (NJ), USA). The sideways-emitting fiber features a polished surface with a 45° slant coated with gold through sputter deposition.

The fibers were connected to a tungsten halogen broadband light source (SLS201L, Thorlabs Inc., Newton (NJ), USA), and their angular emission was examined by placing an optical power sensor (S132C, Thorlabs Inc.,



(b) (c)

Figure 1: (a) Illustration and microscopic image of the three different fiber tips that were examined: (1) forward-emitting 90° tip (2) diffuser tip (3) sideways-emitting 45° tip with gold coating. (b) Setup of the optical fiber characterization (top view). (c) Angular emission of the optical fibers.

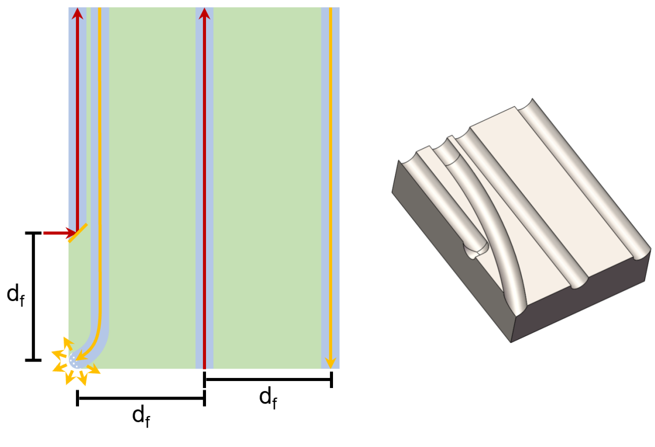
Newton (NJ), USA) at a distance of $d_{ps} = 20$ mm and rotating it 180° around the fiber tip in $\Delta\alpha = 2°$ steps. The power sensor was read out with a power meter (PM100D, Thorlabs Inc., Newton (NJ), USA) at $\lambda = 1310$ nm. The setup is illustrated in Fig. 1(b).

While the sideways emission of the forward-emitting 90° tip is, as anticipated, very low, Fig. 1(c) shows that the diffuser tip achieves almost threefold increase of sideways emission that is uniform over all angles α. The sideways-emitting 45° tip shows a Gaussian profile with a peak in emission around $\alpha = 90°$ that decays towards the edges to the same low value as the forward-emitting fiber, confirming that light can be steered sideways very precisely through a slanted, gold-coated optical fiber.

Prototype and instrumentation A probe was designed that houses three optical fibers for diffuse light emission and forward and sideways light collection at $d_f = 1.4$ mm distance each. The prototype is extended with a second, forward light-emitting fiber at $d_f = 1.4$ mm distance to the forward light-collecting fiber for conventional parallel DRS. The probe layout is illustrated in Fig. 2(a).

A prototype measuring 3 mm x 4 mm x 1 mm was manufactured from stainless steel, see Fig. 2(b). Either of the light emitting fibers can be connected to a tungsten halogen broadband light source with an integrated shutter (HAL-S, Avantes, Apeldoorn, The Netherlands). Either of the light collecting fibers can be connected to a NIR spectrometer with an InGaAs detector (S330-2 NIR, HORIBA Scientific, Piscataway (NJ), USA) to collect light at 255 distinct wavelengths between 839.65 nm and 1724.27 nm. The system is controlled using Philips custom-developed software and was calibrated prior to the experiments positioning the optical probe perpendicular to a Spectralon white reference standard (WS-1-SL, Labsphere Inc., North Sutton, NH, USA) at a distance of 3.2 mm.

Optical tissue phantom Vertebrae are composite structures comprising a hard outer shell from cortical bone that surrounds the inner matrix of spongy cancellous bone, see Fig. 3. The probe was validated on a two-layered optical tissue phantom consisting of a bottom layer simulating cortical bone made from water, NaCl (Groupe Salins, Clichy, France), 15% gelatin (250 bloom porcine gelatin powder, Dr. Oetker, Bielefeld, Germany), barium sulfate (Acros Organics B.V.B.A., Geel, Belgium), and sodium benzoate (Natural Spices B.V., Mijdrecht, The



(a) (b)

Figure 2: (a) Illustration of the probe layout encompassing three optical fibers for diffuse light emission and forward and sideways light collection, extended with a fourth optical fiber for forward light emission for conventional parallel DRS. (b) Illustration of the prototype with space for four optical fibers (dimensions: 3 mm x 4 mm x 1 mm).

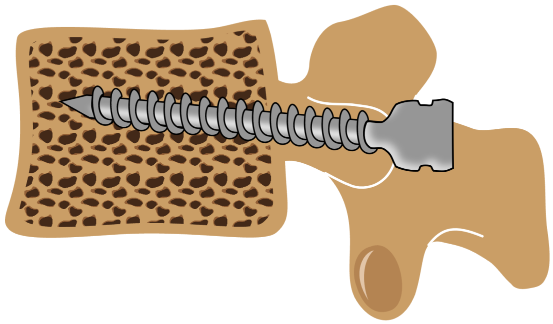
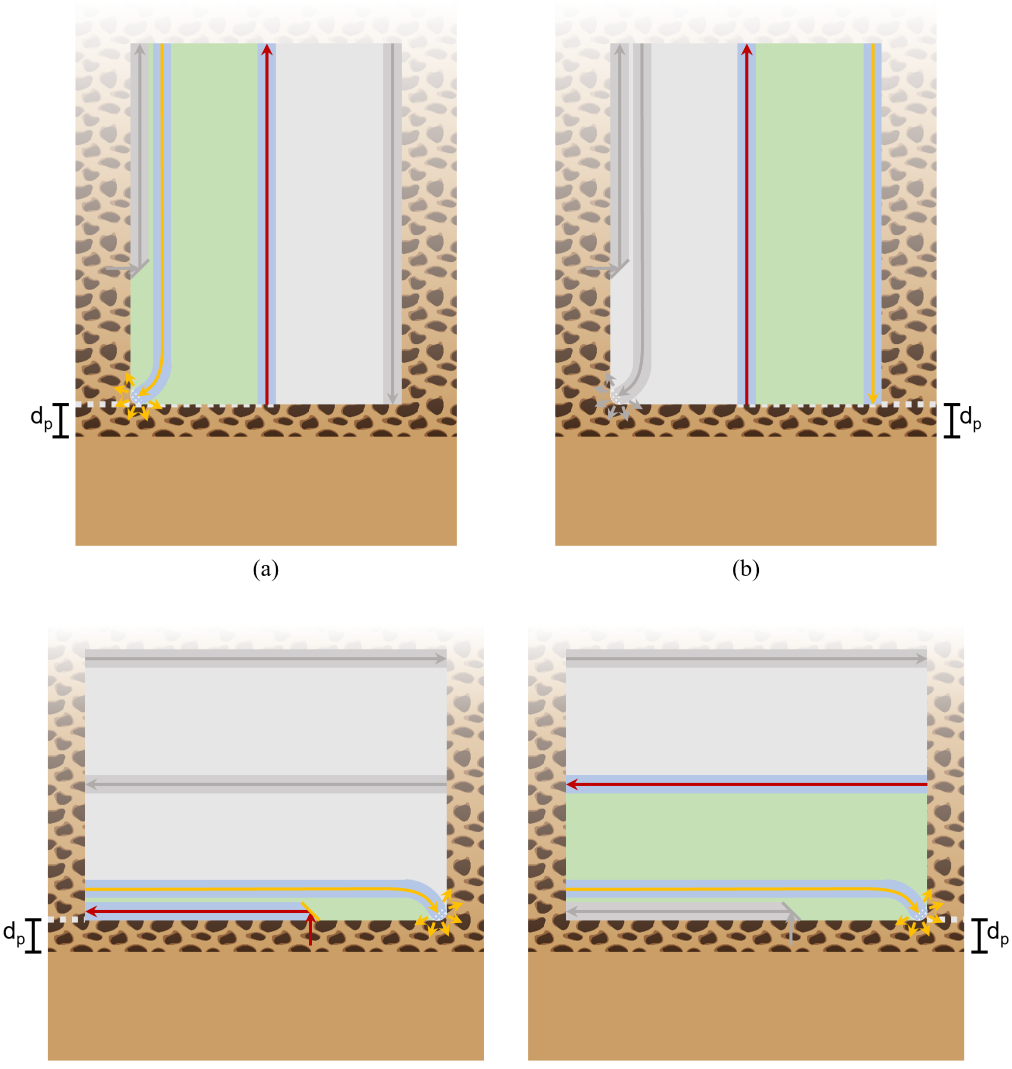


Figure 3: Illustration of a pedicle screw placed inside the vertebra (sagittal view).



(a) (b) (c) (d)

Figure 4: Illustration of the breach experiments on the two-layered optical tissue phantom in (a)-(b) perpendicular orientation (c)-(d) parallel orientation.

Netherlands), and a top layer simulating cancellous bone made from pure coconut milk with 19% fat (Thai Agri Foods Public Company Limited, Bang Sao Thong, Thailand).[12]

Breach experiments In the initial set of experiments, the probe's forward sensing capabilities were tested in a perpendicular breach scenario. The probe was oriented perpendicular to the interface of the two phantom layers and mounted onto a manual 25 mm linear translation stage equipped with an optical stage position encoder (Thorlabs Inc., Newton, NJ, USA). The diffuse light-emitting fiber was connected to the light source, and the forward light-collecting fiber was connected to the spectrometer. The fiber configuration is illustrated in Fig. 4(a). At various distances to the interface of the two phantom layers d_p [mm] $\in \{0, 0.25, ..., 2.5\}$, ten diffuse reflectance spectra were measured in each case (integration time of 1000 ms), which subsequently were averaged, filtered using a third-order Savitzky-Golay filter (frame length of 11), and normalized to $\lambda_0 = 1211$ nm. This experiment was repeated three times at different points within the phantom. The entire process was repeated for the conventional parallel DRS configuration, where light was emitted through the forward light-emitting fiber as illustrated in Fig. 4(b).

In the subsequent set of experiments, the probe's sideways sensing capabilities were tested in a parallel breach scenario. The probe was mounted in parallel orientation to the interface of the two phantom layers. Light was emitted through the diffuser tip with the sideways light-collecting fiber connected to the spectrometer as illustrated in Fig. 4(c). The experimental steps from the first set of experiments were replicated, and this process was then repeated with light collection through the forward light-collecting fiber, see Fig. 4(d).

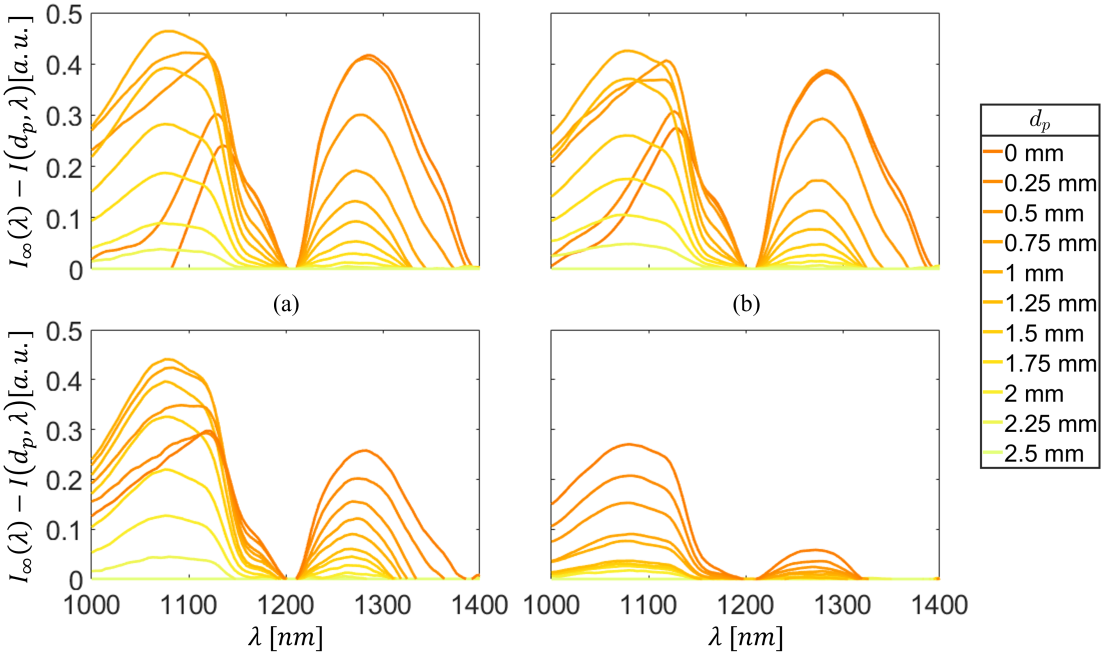
3. RESULTS

Fig. 5 presents typical plots of the normalized reflectance spectra that are encountered as the probe approaches the interface between the two phantom layers, simulating two different breach scenarios (perpendicular or parallel) with different fiber configurations. The spectra are plotted relative to the normalized reflectance spectrum of the pure cancellous bone-mimicking phantom ($d_p \to \infty$) for the respective fiber configuration, enabling the detection of changes in spectrum occuring along the pedicle screw trajectory in the wavelength range of 1000 nm to 1400 nm.

Approaching the cortical bone-mimicking phantom layer perpendicularly results in a gradual change in spectrum (yellow to orange). Spectra acquired at a set distance from the interface d_p with diffuse emission (Fig. 5(a)) are equivalent to those acquired with forward emission (Fig. 5(b)) in their shape and magnitude.

In the parallel breach scenario, a similar gradual spectrum change is observed. Spectra acquired with sideways light collection (Fig. 5(c)) are comparable in magnitude to those from the perpendicular breach scenario. With forward light collection (Fig. 5(d)), however, the first change in spectrum is noticeable only relatively close to the interface ($d_p = 1$ mm), and the total difference in intensity is decreased between the spectrum measured on the pure cancellous bone-mimicking phantom and the spectrum measured at the interface.

Fig. 6 provides a quantitative comparison of the different fiber configurations by illustrating the change in maximal intensity across all distances to the interface. When the interface is approached perpendicularly, the



(c) (d)

Figure 5: Normalized reflectance spectra ($\lambda_0 = 1211$ nm) for different distances to the interface relative to the normalized reflectance spectrum of the pure cancellous bone-mimicking phantom with (a) diffuse light emission and forward light collection, perpendicular breach (b) forward light emission and forward light collection (conventional parallel DRS), perpendicular breach (c) diffuse light emission and sideways light collection, parallel breach (d) diffuse light emission and forward light collection, parallel breach.

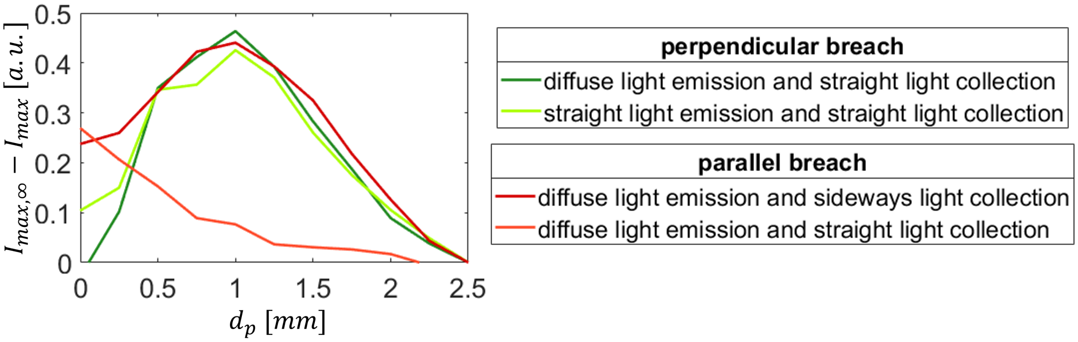


Figure 6: Normalized change in maximal intensity ($\lambda_0 = 1211$ nm) for different breach scenarios and fiber configurations.

maximal intensity increases consistently with comparable slopes and total increases in intensity for both tested fiber configurations. A slight decrease in maximal intensity is experienced at short distances to the interface ($d_p \leq 1$ mm).

Sideways light collection in a parallel breach scenario shows a very similar normalized change curve, yet with a slightly lower decrease close to the interface. In contrast, forward light collection during a parallel breach results in a notably lower curve, characterized by a flatter slope and lower maximal value. The maximal intensity only shows an increase very close to the interface ($d_p \leq 1$ mm), aligning with observations from Fig. 5(d).

4. DISCUSSION AND CONCLUSION

Our experimental findings emphasize the potential of DRS for detecting cortical breaches. The increase in intensity near the cortical boundary in Fig. 6 highlights the spectral differences between cancellous and cortical bone that can be leveraged for real-time tissue feedback. The spectral shape is also influenced by the differing scattering properties between the two phantom layers, and its gradual change is indicative of the combined scattering contributions from each layer. The decrease observed close to the interface of the two phantom layers* (Fig. 5(a)-(c)) may be attributed to a refractive index mismatch causing specular reflection.[12] This phenomenon is absent for forward light collection in a parallel breach scenario (Fig. 5(d)), where the detector is not facing the interface.

In a perpendicular breach scenario, diffuse emission does not impede breach detection, as shown by the similarity between spectra obtained with both diffuse and forward emission configurations (Fig. 5(a) and (b), Fig. 6). This suggests that DRS remains robust for perpendicular breach detection, irrespective of whether light is emitted to the tissue forward or diffusely. Really, diffuse emission may even facilitate sideways breach detection with a forward-collecting probe, though further investigation is required to demonstrate this correlation.

For parallel breaches, sideways light collection proves to be an important enhancement. While only minor changes in intensity are observed for forward light collection (Fig. 5(d)), sideways collection, on the other hand, demonstrates important spectral differences between cancellous and cortical bone (Fig. 5(c), Fig. 6) that match those obtained for perpendicular breach detection. This implies that diffuse emission with sideways collection provides comparable results to conventional parallel DRS. Thus, the combined approach of diffuse light emission and forward and sideways light collection offers promising potential for directional tissue feedback, thereby enhancing the clinical applicability of DRS in spine surgical guidance.

Limitations

During the optical fiber characterization, we focused solely on side emission, making it challenging to precisely assess the quantity of light emitted in all directions, particularly forward. However, after proving that the diffuser tip increases sideways emission compared to a forward-emitting 90° tip, our optical tissue phantom experiments confirmed that the diffuser tip illuminates tissue in a way that enables both forward and sideways light collection.

---

*The exact distance at which it occurs will depend on the calibration for d_p.

The use of scattering particles to create the diffuser tip introduces a trade-off. Adding insufficient scattering particles may result in excessive forward emission, while an abundance of scattering particles may lead to increased backscattering into the fiber. Although our initial attempt with 10% barium sulfate appeared effective, the diffuser's performance can be optimized by exploring a range of concentrations.

Practical challenges in potential development of a DRS probe for spine surgery include the need for a white reference standard to allow for consecutive, or ideally simultaneous, calibration of both DRS systems (forward and sideways). Additionally, a mechanism to switch between inputs from both collecting fibers is essential for surgeons to determine whether a breach is impending ahead of or lateral to the probe.

Finally, while our current design incorporates a fourth optical fiber for conventional parallel DRS, our experimental findings proved its dispensability. Future miniaturization efforts could render the probe suitable for cervical vertebrae, expanding the area of potential applications.

Conclusion

DRS has the potential to enhance pedicle screw placement by detecting cortical breaches without compromising its ability to identify perpendicular breaches when incorporating diffuse emission. To address parallel breaches, integrating a 45° slanted fiber for lateral light collection proves effective. Combining diffuse light emission with both forward and sideways light collection not only maintains the possibility to detect perpendicular breaches but also extends its application to scenarios involving (virtually) parallel breaches. Overall, these advancements broaden the practicality of DRS for pedicle screw placement, strengthening its potential for surgical guidance.

ACKNOWLEDGMENTS

The authors very much appreciate the valuable support in manufacturing the fiber tips and prototype provided by David Jager at DEMO of Delft University of Technology.

This research was supported by Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO-TTW 17553).

REFERENCES

[1] Modic, M. T. and Ross, J. S., "Lumbar degenerative disk disease," *Radiology* **245**(1), 43–61 (2007).

[2] Kobayashi, K., Sato, K., Kato, F., Kanemura, T., Yoshihara, H., Sakai, Y., Shinjo, R., Ohara, T., Yagi, H., Matsubara, Y., et al., "Trends in the numbers of spine surgeries and spine surgeons over the past 15 years," *Nagoya Journal of Medical Science* **84**(1), 155 (2022).

[3] Grotle, M., Småstuen, M. C., Fjeld, O., Grøvle, L., Helgeland, J., Storheim, K., Solberg, T. K., and Zwart, J.-A., "Lumbar spine surgery across 15 years: trends, complications and reoperations in a longitudinal observational study from norway," *BMJ open* **9**(8), e028743 (2019).

[4] Bourgeois, A. C., Faulkner, A. R., Pasciak, A. S., and Bradley, Y. C., "The evolution of image-guided lumbosacral spine surgery," *Annals of Translational Medicine* **3**(5) (2015).

[5] Utzinger, U. and Richards-Kortum, R. R., "Fiber optic probes for biomedical optical spectroscopy," *Journal of biomedical optics* **8**(1), 121–147 (2003).

[6] Fisher, M. A., Birkmeyer, P., Hawkins, J. R., Herard, K., and Upal, A., "Smart pedicle tool."

[7] Losch, M. S., Heintz, J. D., Edström, E., Elmi-Terander, A., Dankelman, J., and Hendriks, B. H. W., "Fiber-optic pedicle probes to advance spine surgery through diffuse reflectance spectroscopy," *Bioengineering* **11**(1) (2024).

[8] Burström, G., Swamy, A., Spliethoff, J. W., Reich, C., Babic, D., Hendriks, B. H., Skulason, H., Persson, O., Terander, A. E., and Edström, E., "Diffuse reflectance spectroscopy accurately identifies the pre-cortical zone to avoid impending pedicle screw breach in spinal fixation surgery," *Biomedical Optics Express* **10**(11), 5905–5920 (2019).

[9] Swamy, A., Burström, G., Spliethoff, J. W., Babic, D., Reich, C., Groen, J., Edström, E., Terander, A. E., Racadio, J. M., Dankelman, J., and Hendriks, B. H., "Diffuse reflectance spectroscopy, a potential optical sensing technology for the detection of cortical breaches during spinal screw placement," *Journal of biomedical optics* **24**(1), 017002 (2019).

[10] Losch, M. S., Kardux, F., Dankelman, J., and Hendriks, B. H., "Steering light in fiber-optic medical devices: a patent review," *Expert Review of Medical Devices* **19**(3), 259–271 (2022).

[11] Williams, J. A., Clements, D. J., Pearson, G. J., and Wilson, M., "Method and apparatus for filling a dental root canal," (Dec. 11 2007). US Patent 7,306,459.

[12] Losch, M. S., Kardux, F., Dankelman, J., and Hendriks, B. H., "Diffuse reflectance spectroscopy of the spine: improved breach detection with angulated fibers," *Biomedical Optics Express* **14**(2), 739–750 (2023).

[13] Green, A. D., Ehrlich, K., Tye, C. S., Maybin, J. A., and Tanner, M. G., "Fibre optic probes for endoscopic measurement of uterine hypoxia," in [*Diffuse Optical Spectroscopy and Imaging IX*], **12628**, 190–195, SPIE (2023).