Received: 2 March 2024 | Accepted: 14 June 2024
DOI: 10.1002/ame2.12469

ORIGINAL ARTICLE

Epidural pressure measurement using a fiber-optic sensor (proof-of-principle in vivo animal trial)

Susanne Barz[1] | Marvin Friedemann[2] | Sebastian Voigt[2] | Markus Melloh[3] | Thomas Barz[4]

[1]Department of Anaesthesiology, Intensive Care Medicine and Pain Therapy, Rostock University Medical Center, Universitätsmedizin Rostock, Rostock, Germany

[2]Chemnitz University of Technology, Chemnitz, Germany

[3]School of Public Health and Social Work, Queensland University of Technology, Brisbane, Queensland, Australia

[4]Orthopedic Department, University of Greifswald, Greifswald, Germany

Correspondence
Thomas Barz, Orthopedic Department, University of Greifswald, Fischstr. 1, Greifswald 17489, Germany.
Email: info@barz.online

Abstract

Background: An increase in epidural pressure around the stenosis has been observed in patients with lumbar spinal stenosis (LSS) with positive signs of sedimentation or redundant nerve roots. Further analysis of the pressure conditions in the stenotic area would be of great interest. We hypothesized that it would be possible to determine the physiological parameters of the epidural pulse wave and its course in pathological stenosis as a basis for objective identification of LSS based on pressure using a new measuring method with continuous spatial and temporal resolution.

Methods: We performed a single-case proof-of-principle in vivo animal trial and used a newly developed hybrid pressure-measurement probe with a fiber-tip Fabry–Pérot interferometer and several fiber Bragg gratings (FBG).

Results: With reproducible precision, we determined the mean epidural pressure to be 7.5 mmHg and the peak-to-peak value to be 4–5 mmHg. When analyzing the pressure measured by an FBG array, both the heart and respiratory rates can be precisely determined. This study was the first to measure the pulse wave velocity of the cerebrospinal fluid pressure wave as 0.97 m/s using the newly developed pressure probe. A simulated LSS was detected in real time and located exactly.

Conclusions: The developed fiber-optic pressure sensor probe enables a new objective measurement of epidural pressure. We confirmed our hypothesis that physiological parameters of the epidural pulse wave can be determined and that it is possible to identify an LSS.

KEYWORDS
animal, cerebrospinal fluid pressure, pulse wave velocity, spinal stenosis

1 | INTRODUCTION

Lumbar spinal stenosis (LSS) is a condition in which narrowing of the neural and vascular structures of the lumbar spine causes variable clinical symptoms such as back or lower extremity pain and fatigue, especially when walking or standing. If symptoms persist after conservative treatment or if there is a neurological deficit, surgical treatment is indicated.[1,2] Clinical signs of stenosis, such as pain or reduced functionality, possibly with evidence from a treadmill test, radiological evidence of narrowing,[3] or a positive sedimentation sign,[4] can indicate surgery.[5]

Because an increase in pressure in the area of the stenosis was found in patients with severe LSS with positive signs of sedimentation or redundant nerve roots, emphasized by other studies,[6–9] a further analysis of the pressure conditions in the area of the stenosis would be of great interest.

Cerebrospinal pressure waves result from complex interactions. Cerebral ventricles with the choroid plexus produce liquor, which is resorbed by meningeal arachnoid granulations and drained by nerve root outlets via the lymphatic system. Pressure is influenced by arterial and venous blood flow in the brain and separately in the spinal cord itself, by breathing and the volume of the abdominal cavity with feedback on the blood flow, and by the cross sections of the spinal cord in relation to the dural sac and the surrounding bony structures.[10–14] In humans, this forms a wave-shaped pressure curve with bidirectional cerebrospinal fluid movement[15,16] with an average pressure of ~9 mmHg in the supine position in the lumbar spine, measured using conventional piezoelectric pressure probes with similar intra- and epidural pressure.[12,15]

A human flow velocity of 3 cm/s can be determined in magnetic resonance tomography; however, measured values for the epidural and intradural pulse wave velocities are not yet available. A change in the human flow gradient of ~4.5 m/s was previously determined, which could correspond to the pulse wave velocity.[17]

The flow, pressure, and waveform of the flow and pressure curves vary with stenosis in the spinal canal.[4]

2 | METHODS

We hypothesized that it would be possible to determine the physiological parameters of the epidural pulse wave and its course in pathological stenosis using a new fiber-optic measurement method with continuous spatial and temporal resolution. Pressure and flow of the epidural pulse wave could be the basis for objective identification of LSS requiring surgery.

2.1 | Pressure probe

Fiber-optic sensors in the form of Fabry–Pérot interferometers (FPI) and fiber Bragg gratings (FBG) are suitable for many medical applications because of their simple operation, small structural size, signal linearity, sensor multiplexing ability, and electromagnetic compatibility.[18–20] They enable continuous spatial- and time-resolved measurements. Fiber-optic pressure-sensor catheters compensate for the disadvantages of conventional pressure-measurement systems.[21,22] We used a newly developed hybrid pressure-measurement probe with a fiber-tip Fabry–Pérot interferometer (FTFPI) and several pressure-sensitive FBGs (Figure 1).

FBGs are refractive-index modulations written on the core of a silica optical fiber, each of which reflects light at a characteristic wavelength. This allows the use of multiple intrinsic strain-, pressure-, and temperature-sensitive sensors along the optical fiber.[21] The measurement combines the registration of hydrostatic pressure using a membrane pressure sensor with the registration of dynamic pressure differences by radial compression of the fiber, causing a Bragg wavelength shift in different FBGs. Our probe prototype had the following specifications and dimensions: fiber diameter, 125 µm; material, fused silica; mantle diameter, 1.5 mm; and material, medical-grade silicone (Figure 2). The tip of the probe is a cylindrical pressure sensor chip consisting of a pressure-sensitive membrane manufactured using microelectromechanical system technology. The membrane deformation for absolute pressure measurement was detected using the implemented interferometer. Evaluation in the wavelength window of the FBG enabled the simultaneous spectral recording and evaluation of an FPI and several FBGs with one readout unit.

The detection rate for FBG is 200 Hz, and that for the absolute pressure sensor on the tip is 11 Hz. Because the FBG area is located outside the introducer in direct contact with the surrounding tissue, the influence of needle material on temperature and registration time must not be considered.[23]

A broadband light source with a continuous broadband spectrum in the infrared range emits an optical signal that is reflected by a wave-selective mirror and finally detected. If an external pressure on the plastic jacket deforms the glass fiber, light reflection changes.

The interference pattern and Bragg wavelength were read simultaneously using a specially designed FBG interrogator combined with a broadband light source, and conclusions can be drawn regarding the ambient pressure values.[19]

Pretesting on a dynamic vessel model resulted in high-pressure resolution with automated temperature compensation, if necessary, such that spatially and temporally resolved pressure wave curves could be derived in real time. The pretesting was verified in different media and different experimental setups for technical reliability and reliability of the data with high reproducibility.[24,25]

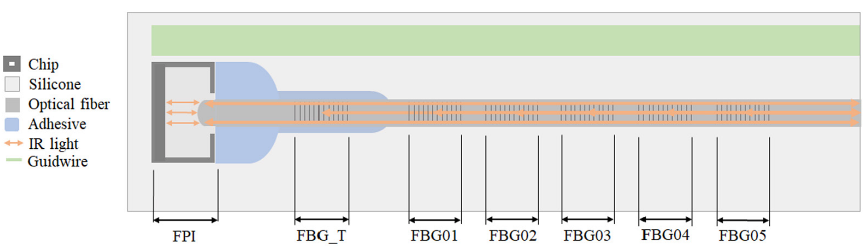

FIGURE 1 Schematic cross section of the sensitive area.

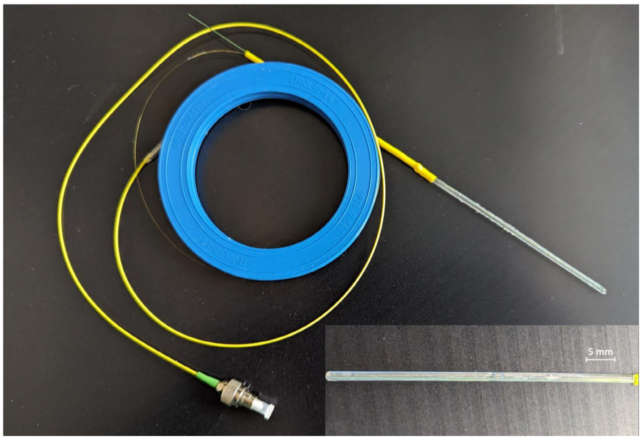

FIGURE 2 Image of the inserted probe.

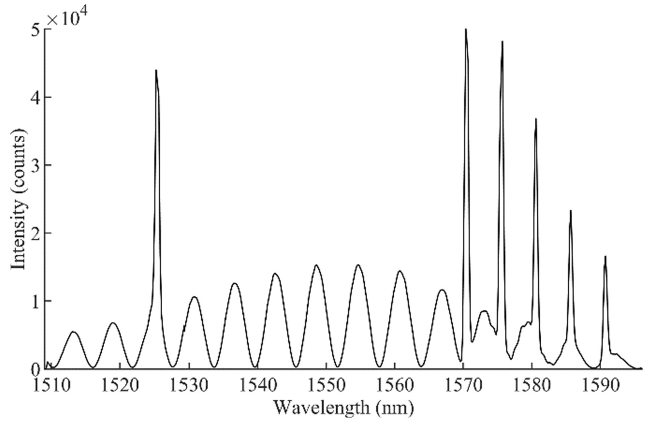

FIGURE 3 Optical spectrum of superposed FTFPI (fiber-tip Fabry–Pérot interferometer) and FBG (fiber Bragg grating) signals.

2.2 | Signal processing

The prototype of the evaluation unit consisted of a superluminescent diode (SLED) and a spectrometer (including optical components and an image sensor) and was designed for querying FBGs. Broadband light was coupled to a glass fiber. The SLED contained a circulator to transmit superimposed FTFPI and FBG signals to the spectrometer (Figure 3).

2.3 | Animal testing application

Preliminary tests on isolated organs were not planned because after the presentation of functionality in the simulators, the interaction between anatomy and physiological parameters in vivo is important.

Due to the complexity of the anatomy of the organs and associated questions as well as the organ dimensions and physiology of the organ systems, which are similar to those of humans, the pig model was found to be particularly suitable for this study.[26–28]

Considering the reliability of pretest measurements and the minimization of animal harm, we designed our study as a proof-of-concept investigation. Repeated measurements in animals would have no additional benefits for further human applications. Human surveys are more reasonable for basic scientific research and have already begun after ethical approval.

The large-animal experiment was examined and approved by Az. 42502-2-1617 FDG Landesverwaltungsamt Sachsen-Anhalt, Dessauer Straße 70, 06118 Halle (Saale).

2.4 | Surgical approach

Due to the design of the pressure probe prototype and its unequivocal positioning in the epidural space, the probe was inserted via L5 laminectomy (Figure 4).

The 50-kg domestic pig was given general anesthesia under monitored conditions and was subjected to a standard Caspar microsurgical approach with laminectomy L5 under image intensifier control until the dura was clearly visible. After probe insertion, the wound was closed to restore a normal situs. The pressure probe was repeatedly advanced cranially into the epidural space. Epidural pressure curves of all five pressure-sensitive FBGs were obtained continuously during the entire process.

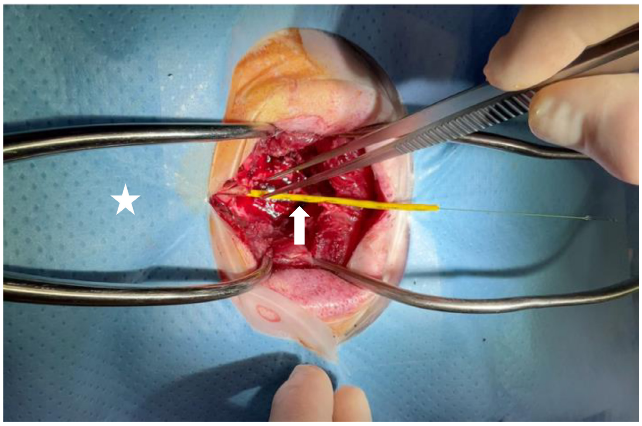

FIGURE 4 Surgical epidural insertion of the probe during in vivo trial (cranial, asterisk; interlaminar window, arrow).

We inserted a 15-mm kyphoplasty balloon (Medtronic, Minneapolis, MN, USA) in addition to the sensor probe up to the level of L4 and successively filled the balloon with a contrast medium (Iopamidol SOLUTRAST 250, Bracco, Milan, Italy) to simulate LSS under image intensifier control up to the maximum extent in the spinal canal (Figure 5). Measurements were performed 10 times with and without simulated stenosis with high reproducibility. We did not calculate repeatability because we used different prototypes.

3 | RESULTS

The calibration of the hybrid sensor resulted in a sensitivity of −5 pm/mmHg for the absolute pressure sensor and 0.75 pm/mmHg for the distributed sensors.

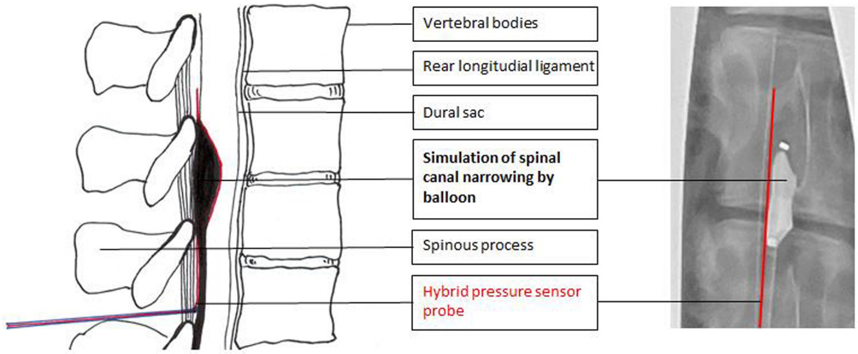

FIGURE 5 Anatomy of the spinal column with simulated LSS (lumbar spinal stenosis) under X-ray and sensor probe next to the balloon.

The FTFPI indicates the prevailing pressure level in the lumbar spinal canal. The figure shows the absolute pressure in the lumbar spinal canal of the test animal lying down, with a mean pressure of 7.5 mmHg and a peak-to-peak value of almost 4 mmHg (Figure 6).

The time- and space-resolved relative pressure distributions along the FBG array within a breath are shown in Figure 7. The raw data were smoothed using a moving average filter. Due to the high sample rate of the readout, this is possible without the loss of information.

An analysis of the pressure measured by the FBG array showed a heart rate of 84 beats per minute and a respiratory rate of 18 breaths per minute, which corresponded exactly to the heart and respiratory rates of the test animal documented in systemic monitoring. They were determined using peak detection algorithm in the time domain (Figure 7). This was done manually in the current dataset and verified by a transformation to frequency domain. In a future application wavelet filtering or Fast Fourier Transform-based algorithms can be used to determine these parameters. Pulse waves were generated by the pulsating liquid in the spinal canal, which is linked to the cardiovascular system, as described earlier.

The time delay between the heartbeat-induced pulse maxima on each FBG represented the movement of the pressure wave along the probe. An algorithm was used to detect all pulse wave maxima on each FBG (marked with "+" in the diagram). The pulse wave time delay between FBGs was reproducible for each heartbeat. The average pulse wave velocity was calculated by applying the time delay of the pulse wave peaks between the FBGs and the distance between FBG01 and FBG05. The increasing offset is the respiration-induced pressure variation of ~12 mmHg peak to peak per breath.

A pulse wave velocity of 0.97 m/s was determined.

After the normal epidural pressure in the lumbar spinal canal of the lying animal was measured, lumbar spinal canal stenosis was simulated by filling the canal with a kyphoplasty balloon.

Simultaneous measurements along all detection points provided an overview of the effect of the LSS on the absolute pressure and propagation of pulse waves. Wavelength data are shown in Figure 8.

The lower frequency still detectable by all FBGs corresponds to the respiratory rate.

The heart rate and respiration-dependent pulse waves and their changes at the level of the simulated stenosis can be clearly determined and are important parameters for the localization of

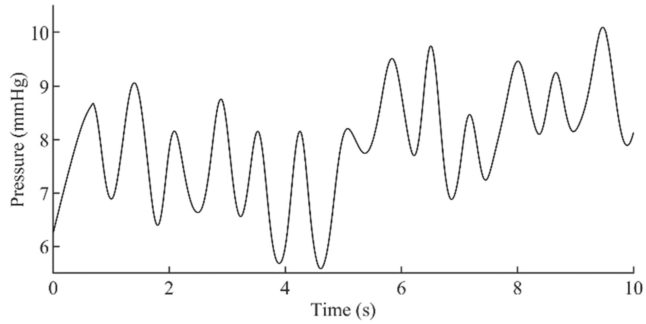

FIGURE 6 Range of epidural pressure and pulse waves in lumbar spinal canal without LSS (lumbar spinal stenosis) registered with FTFPI (fiber-tip Fabry–Pérot interferometer).

the stenosis. Coherent pulse waves corresponding to the heartbeat were no longer recognizable caudal to the FBG01. Consequently, the stenosis was immediately caudal to FBG01 and was detectable on the X-ray image.

The stenosis simulated by the insertion of the kyphoplasty balloon and its degree, determined by the filling volume of the kyphoplasty balloon, was detected in real time, with the pressure probe positioned along the simulated stenosis. Probe localization was confirmed by measuring the length of the X-ray-visible fiber from the tip under the image intensifier. In the future, probes for human applications would have vapor-deposited tantal markers.

4 | DISCUSSION

Pressure measurement plays a critical role in many areas of clinical practice by providing valuable diagnostic and monitoring information (e.g., blood pressure and intracerebral pressure).

In spinal surgery, examinations related to pressure are rare and mostly of a scientific nature, that is, for intradiscal pressure, with almost no clinical relevance.[29,30] This is due to the technical difficulty in measuring the pressure and the lack of a physiological basis that make the interpretation of pathological findings impossible. FBG-based probes were demonstrated to measure the decrease in pressure in the "loss of resistance method" for epidural puncture[31–33] but were up-to-date never used for epi- or intradural pressure measurement.

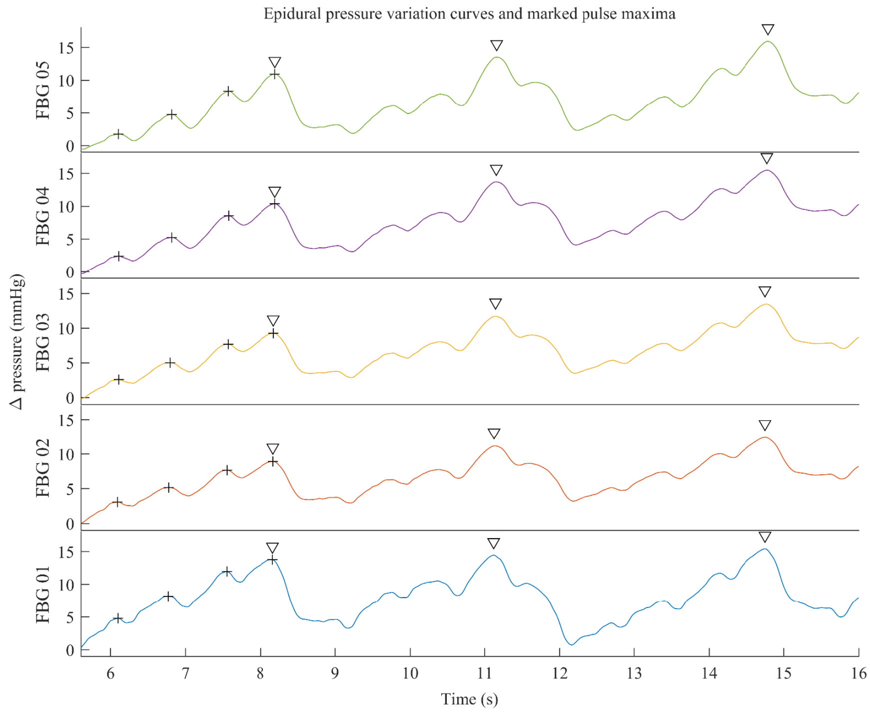

FIGURE 7 Detection of pulse wave and pulse wave velocity without stenosis. The base level shows pressure increase due to respiration during inspiration (crosses represent the amplitude produced by heart pulse wave, and triangles represent the amplitude of the superposed breath wave).

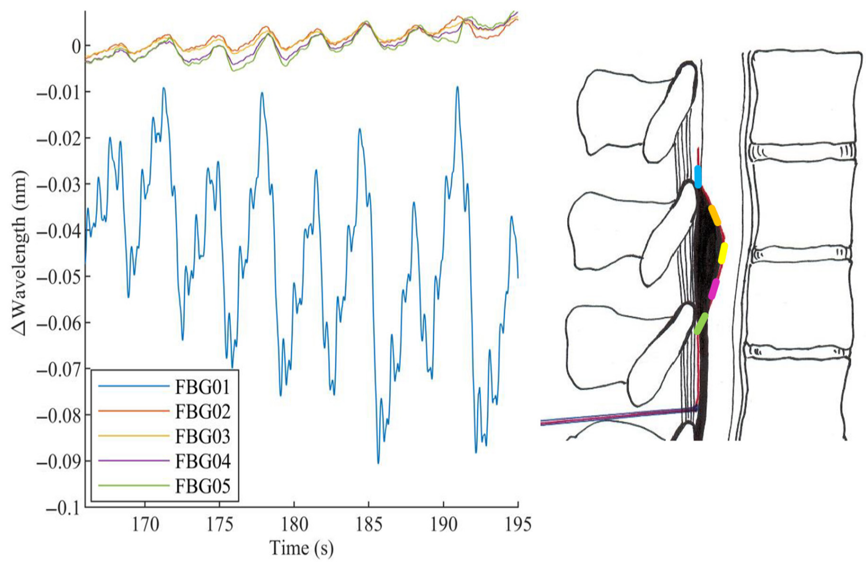

FIGURE 8 Demonstration of the relation between narrowing location (FBG01) and no-longer detectable pulse waves distal to the stenosis (FBG02–FBG05), with the pressure probe positioned along the simulated stenosis.

Takahashi et al.[34,35] highlighted the importance of intra- and epidural pressure in the development of LSS symptoms. Direct intraoperative epidural pressure measurement revealed a connection between increased intradural pressure[8] and the positive sedimentation sign[36] on sagittal magnetic resonance imaging (MRI) as a phenomenon of redundant nerve roots,[37,38] an indicator of surgery.

Recently, studies by Kheram et al. and Zipser et al.[7,9] and the interpretation of phase-contrast MRI measurements[6,39] have led to increased focus on the pressure in the spinal canal.

We confirmed our hypothesis that physiological parameters of the epidural pulse wave can be determined using this new measuring method and that it is possible to identify LSS. A weakness of our study is that we created an acute situation by mechanically triggering stenosis; therefore, we cannot conclude how pressure and flow would change in slowly developing LSS. Our previous investigation on epidural pressure using a conventional pressure probe showed no differences in epidural pressure as a function of the time of development of acute stenosis due to disc herniation or chronic stenosis due to degeneration.

Measurements were taken only in animals lying under general anesthesia. As further investigations are possible after approval and are more meaningful in humans, this proof of concept is the first step toward establishing the development of this novel probe.

The miniaturization of the FBG fiber and its combination with an FPTIF enables minimally invasive measurement of the pressure in the spinal canal at spatial and temporal resolution so that the pressure, flow, and pulse wave velocity as well as the characteristics of the time course of these parameters can be recorded in real time.

The prerequisites for a clinically reliable pressure measurement (accuracy, calibration, and signal artifact suppression) were met, resulting in a pressure resolution of 1 mmHg. Because the application of multiple FBGs of various lengths is possible, an unknown stenosis can be diagnosed over the entire predetermined length, that is, by introducing a probe with a 20-cm sensor length interlaminar at L5/S1 for investigation of the lumbar spine.

Because of the mechanical strength of fiberglass and silicone coating systems, their broad clinical application in the diagnosis and treatment of LSS is possible.

1. Preoperative application to determine clinically relevant stenoses different from other pathologies causing claudication and multilevel pathology for functional testing of different postures for stress testing on the treadmill or retroflexion test.
2. Intraoperative monitoring of sufficient decompression of the spinal canal in the cranial and caudal directions, especially during endoscopic procedures. Clinically, the perception of pulsatile phenomena in the dural sac is already used as a characteristic of sufficient decompression.

   In addition to neuromonitoring, pressure measurements can help to avoid excessive corrective maneuvers in scoliosis and profile realignment, particularly in minimally invasive procedures.
3. Postoperative monitoring for sudden detection of postoperative clinically relevant epidural hematomas, which are rare but often have serious clinical consequences.

Several questions must be answered before clinical application of this technique, particularly collection of data sets from individuals with and without various spinal diseases. Helpful might be a combination and extrapolation of real pressure data from MRT images. The next step is the semi-industrial production of the pressure-measuring probe at a price that allows for its wider use after Conformité Européenne testing and approval to collect basic physiological data, from which the limits of relevant pathologies in relation to clinical symptoms can be reliably derived. However, objective parameters can be used to determine whether decompression is necessary for LSS or not.

Because the longitudinal characteristics of pressure waves can be recorded for the first time with the help of a new type of pressure-measuring probe, progress is also possible in other medical areas, especially in cardiological and vascular diagnostics and in urological and gastroenterological diagnostics.

Derivation of the indication for surgery for LSS in the lumbar spine alone from measurements with the pressure probe is not expected because stenoses causing spinal claudication can also selectively affect the nerve roots in the neuroforamina and recessus. Segmental instability and alignment pathology result in additional aspects of surgical therapy. Therefore, the indication for spinal surgery remains a complex decision based on the background of an individual patient.

5 | CONCLUSIONS

The proposed fiber-optic pressure sensor probe might be a new objective measurement method for the assessment of LSS. The simultaneous evaluation of several measuring points enables the time- and location-resolved recording of the pressure distribution in real time.

The pulse wave measured in a feasibility study in a large animal experiment in the lumbar spinal canal without stenosis had an amplitude of ~4 mmHg. Values of up to 12 mmHg were obtained by superimposing the change in pressure synchronously with respiration. A pulse wave velocity of ~0.97 m/s was determined.

The LSS simulated by balloon dilatation was reliably localized and quantified in real time by changing the pulse-wave characteristics. Whether this technique has the potential to improve diagnostic accuracy for chronic stenosis and patient outcomes remains unclear.

AUTHOR CONTRIBUTIONS

Susanne Barz: animal trial, background data report, scientific writing. **Marvin Friedemann:** technical development and support, data analysis. **Sebastian Voigt:** technical plan, pressure sensor development, data analysis. **Markus Melloh:** background support concerning lumbar spinal stenosis. **Thomas Barz:** plan for animal trial, coordination.

ACKOWLEDGMENTS

None.

FUNDING INFORMATION

Authors received no funding.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

ETHICS STATEMENT

Animal experiment was examined and approved by Landesverwaltungsamt Sachsen-Anhalt, Dessauer Straße 70, 06118 Halle (Saale) (Az. 42502-2-1617 FDG) with consideration of directive 2010/63/EU of the European Parliament and of the Council of 22 September 2010 on the protection of animals used for scientific purposes.

ORCID

Thomas Barz https://orcid.org/0000-0002-6314-9772

REFERENCES

1. Lurie J, Tomkins-Lane C. Management of lumbar spinal stenosis. *BMJ*. 2016;352:h6234. doi:10.1136/bmj.h6234
2. Yukawa Y, Lenke LG, Tenhula J, et al. A comprehensive study of patients with surgically treated lumbar spinal stenosis with neurogenic claudication. *JBJS*. 2002;84:1954-1959.
3. Schizas C, Kulik G. Decision-making in lumbar spinal stenosis: a survey on the influence of the morphology of the dural sac. *J Bone Joint Surg Br*. 2012;94-B:98-101. doi:10.1302/0301-620X.94B1.27420
4. Barz C, Melloh M, Staub LP, Lord SJ, Merk HR, Barz T. Reversibility of nerve root sedimentation sign in lumbar spinal stenosis patients after decompression surgery. *Eur Spine J*. 2017;26:2573-2580. doi:10.1007/s00586-017-4962-5
5. Sengupta DK, Herkowitz HN. Lumbar spinal stenosis: treatment strategies and indications for surgery. *Orthoped Clin North America*. 2003;34:281-295. doi:10.1016/S0030-5898(02)00069-X
6. Bae YJ, Lee JW, Lee E, Yeom JS, Kim KJ, Kang HS. Cervical compressive myelopathy: flow analysis of cerebrospinal fluid using phase-contrast magnetic resonance imaging. *Eur Spine J*. 2017;26:40-48. doi:10.1007/s00586-016-4874-9
7. Kheram N, Pfender N, Boraschi A, et al. Cerebrospinal fluid pressure dynamics reveal signs of effective spinal canal narrowing in ambiguous spine conditions. *Front Neurol*. 2022;13:9511018. doi:10.3389/fneur.2022.951018
8. Barz T, Melloh M, Staub LP, Lord SJ, Lange J, Merk HR. Increased intraoperative epidural pressure in lumbar spinal stenosis patients with a positive nerve root sedimentation sign. *Eur Spine J*. 2014;23:985-990. doi:10.1007/s00586-013-3071-3
9. Zipser CM, Pfender N, Spirig JM, et al. Study protocol for an observational study of cerebrospinal fluid pressure in patients with degenerative cervical myelopathy undergoing surgical deCOMPression of the spinal CORD: the COMP-CORD study. *BMJ Open*. 2020;10:e037332. doi:10.1136/bmjopen-2020-037332
10. Koch MJ, Duy PQ, Grannan BL, et al. Angiographic pulse wave coherence in the human brain. *Front Bioeng Biotechnol*. 2022;10:873530. doi:10.3389/fbioe.2022.873530
11. Yamada S. Cerebrospinal fluid dynamics. *Croat Med J*. 2021;62:399-410. doi:10.3325/cmj.2021.62.399
12. Kollmeier JM, Gürbüz-Reiss L, Sahoo P, et al. Deep breathing couples CSF and venous flow dynamics. *Sci Rep*. 2022;12:2568. doi:10.1038/s41598-022-06361-x
13. Attarpour A, Ward J, Chen JJ. Vascular origins of low-frequency oscillations in the cerebrospinal fluid signal in resting-state fMRI: interpretation using photoplethysmography. *Hum Brain Mapp*. 2021;42:2606-2622. doi:10.1002/hbm.25392
14. Bert RJ, Settipalle N, Tiwana E, et al. The relationships among spinal CSF flows, spinal cord geometry, and vascular correlations: evidence of intrathecal sources and sinks. *Am J Physiol Regul Integr Comp Physiol*. 2019;317:R470-R484. doi:10.1152/ajpregu.00101.2018
15. Sweetman B, Linninger AA. Cerebrospinal fluid flow dynamics in the central nervous system. *Ann Biomed Eng*. 2011;39:484-496. doi:10.1007/s10439-010-0141-0
16. Hirasawa M, de Lange ECM. Revisiting cerebrospinal fluid flow direction and rate in physiologically based pharmacokinetic model. *Pharmaceutics*. 2022;14:1764. doi:10.3390/pharmaceutics14091764
17. Kalata W, Martin BA, Oshinski JN, Jerosch-Herold M, Royston TJ, Loth F. MR measurement of cerebrospinal fluid velocity wave speed in the Spinal Canal. *IEEE Trans Biomed Eng*. 2009;56:1765-1768. doi:10.1109/TBME.2008.2011647
18. Poeggel S, Tosi D, Duraibabu D, Leen G, McGrath D, Lewis E. Optical fibre pressure sensors in medical applications. *Sensors (Basel)*. 2015;15:17115-17148. doi:10.3390/s150717115
19. Friedemann M, Voigt S, Kriebel D, et al. *Pressure sensor Catheter based on piezoelectric actuated aluminum nitride membrane and fiber tip Fabry-Pérot-Interferometer*. 2021; VDE e.V. ISBN 978-3-8007-5656-8.
20. Arkwright JW, Blenman NG, Underhill ID, et al. A fibre optic catheter for simultaneous measurement of longitudinal and circumferential muscular activity in the gastrointestinal tract. *J Biophotonics*. 2011;4:244-251. doi:10.1002/jbio.201000056
21. Voigt D-IS. *Drucksensorkatheter auf Basis von Faser-Bragg-Gittern*. 2012. https://nbn-resolving.org/urn:nbn:de:bsz:ch1-qucosa-83302
22. Degen L, Beglinger C. Motilitätstests des Gastrointestinaltraktes (inkl. Langzeit-pH-Metrie). In: Siewert JR, Harder F, Rothmund M, eds. *Praxis der Viszeralchirurgie: Gastroenterologische Chirurgie*. Springer; 2002:75-90.
23. Polito D, Caponero M, Polimadei A, et al. A needle-like probe for temperature monitoring during laser ablation based on FBG: manufacturing and characterization. *J Med Devices*. 2015;9:041006. doi:10.1115/1.4030624
24. Friedemann M, Voigt S, Mehner J. Pressure sensor catheter based on fiber tip Fabry-Pérot-interferometer and fiber Bragg grating for temperature compensation: fiber-optic hybrid sensor catheter for invasive pressure measuring. *Curr Dir Biomed Eng*. 2022;8:404-407. doi:10.1515/cdbme-2022-1103
25. Friedemann M, Voigt S, Otto R, et al. *In-vitro Verifikation medizinischer Drucksensoren am dynamischen Gefäßmodell*. 2022. Technische Universität Chemnitz.
26. Zhou Z, Wei F, Huang S, et al. In vivo magnetic resonance imaging evaluation of porous tantalum interbody fusion devices in a porcine spinal arthrodesis model. *Spine*. 2015;40:1471-1478. doi:10.1097/BRS.0000000000001068
27. Lin T-H, Hu H-T, Wang H-C, Wu MC, Wu SW, Yeh ML. Evaluation of osseous integration of titanium orthopedic screws with novel SLA treatment in porcine model. *PLoS ONE*. 2017;12:e0188364. doi:10.1371/journal.pone.0188364
28. Barz T, Lange J, Melloh M, et al. Histomorphometric and radiographical changes after lumbar implantation of the PEEK nonfusion interspinous device in the BB.4S rat model. *Spine*. 2013;38:E263-E269. doi:10.1097/BRS.0b013e318280c710
29. Li J-Q, Kwong W-H, Chan Y-L, Kawabata M. Comparison of in vivo intradiscal pressure between sitting and standing in human lumbar spine: a systematic review and meta-analysis. *Life*. 2022;12:457. doi:10.3390/life12030457
30. Liebsch C, Wilke HJ. The effect of multiplanar loading on the intradiscal pressure of the whole human spine: systematic review and meta-analysis. *Eur Cell Mater*. 2021;41:388-400. doi:10.22203/eCM.v041a25
31. Ambastha S, Umesh S, Dabir S, Asokan S. Spinal needle force monitoring during lumbar puncture using fiber Bragg grating force device. *JBO*. 2016;21:117002. doi:10.1117/1.JBO.21.11.117002
32. Carotenuto B, Micco A, Ricciardi A, et al. Optical guidance systems for epidural space identification. *IEEE J Sel Top Quantum Electron*. 2016;23:1. doi:10.1109/JSTQE.2016.2600027
33. De Tommasi F, Lo Presti D, Virgili F, et al. Soft system based on fiber Bragg grating sensor for loss of resistance detection during epidural procedures: in silico and in vivo assessment. *Sensors*. 2021;21:5329. doi:10.3390/s21165329
34. Takahashi K, Miyazaki T, Takino T, Matsui T, Tomita K. Epidural pressure measurements. Relationship between epidural pressure and posture in patients with lumbar spinal stenosis. *Spine* 1995;20:650-653.

35. Takahashi K, Kagechika K, Takino T, Matsui T, Miyazaki T, Shima I. Changes in epidural pressure during walking in patients with lumbar spinal stenosis. *Spine*. 1995;20:2746-2749. doi:10.1097/00007632-199512150-00017
36. Huang Z, Xie Z, Wu X. Research progress on nerve root sedimentation sign of lumbar spinal stenosis. *Zhongguo Xiu Fu Chong Jian Wai Ke Za Zhi*. 2019;33:795-800. doi:10.7507/1002-1892.201904034
37. Nathani KR, Barakzai MD, Rai HH, et al. Redundant nerve roots indicate higher degree of stenosis in lumbar spine stenotic patients. *Acta Neurol Belg*. 2022;123:1781-1787. doi:10.1007/s13760-022-02040-w
38. Papavero L, Ali N, Schawjinski K, Holtdirk A, Maas R, Ebert S. The prevalence of redundant nerve roots in standing positional MRI decreases by half in supine and almost to zero in flexed seated position: a retrospective cross-sectional cohort study. *Neuroradiology*. 2022;64:2191-2201. doi:10.1007/s00234-022-03047-z
39. Norimoto M, Eguchi Y, Kanamoto H, et al. Diffusion tensor imaging of the spinal canal in quantitative assessment of patients with lumbar spinal canal stenosis. *Asian Spine J*. 2021;15:207-215. doi:10.31616/asj.2020.0026

How to cite this article: Barz S, Friedemann M, Voigt S, Melloh M, Barz T. Epidural pressure measurement using a fiber-optic sensor (proof-of-principle in vivo animal trial). *Anim Models Exp Med*. 2024;7:769-776. doi:10.1002/ame2.12469