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Original Article

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An Experimental Model for Fluid Dynamics and Pressures During Endoscopic Lumbar Discectomy

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Objective: Endoscopic spine surgery is an emerging technique of minimally invasive spine surgery. However, headache, seizure, and autonomic dysreflexia are possible irrigation-related complications following full-endoscopic lumbar discectomy (FELD). Pressure elevation through fluid irrigation may contribute to these adverse events. A validated experimental model to investigate parameters for guideline definition is lacking. This study aimed to create an experimental setting for FELD with pressure assessments to prove the concept of repeatable and sensitive measurement of intracranial, intra- and epidural pressures during spine endoscopy.
Methods: To measure intradural pressure, catheters were introduced through a sacral approach and advanced to lumbar, thoracic, and cervical levels in human cadavers. Similarly, lumbar epidural and intracranial probes were placed. The dural sac was filled with Ringer solution to a physiologic pressure of 15 cmH_2O. Lumbar endoscopy was performed on 3 human cadavers at the L3–4 level. Pressure changes were measured continuously at all sites and the effects of backflow-occlusion were monitored.
Results: Reproducibility of the experimental model was validated with catheters at the correct locations and stable compartmental pressure baselines at all levels for 3 specimens (mean ± standard deviation: 1.3 ± 2.9 mmHg, 9.0 ± 2.0 mmHg, 6.0 ± 1.2 mmHg, respectively). Pressure increase could be detected sensitively by closing the system with backflow-occlusion.
Conclusion: An experimental setup for feasible, repeatable, and precise pressure measurement during FELD in a human cadaveric setup has been developed. This allows investigation of the effects of endoscopic techniques and pump pressures on intra-, epidural and intracranial pressure and enables ranges of safe pump pressures per clinical situations.

Keywords: Spine endoscopy, Endoscopic spine surgery, Irrigation pressure, Intradural pressure, Minimally invasive spine surgery, Experimental endoscopic setup

INTRODUCTION

Spinal endoscopy requires continuous irrigation to allow visualization. Very little is known about pressure changes caused by continuous irrigation at different sites (intradural, extradural and intracranial).

Postoperative headache, seizures, impaired vision, hypo- or hypertension up to autonomic dysreflexia appear to be complications related to irrigation during interlaminar endoscopic lumbar discectomy, especially after incidental durotomy.[1,2]

An international surgeon survey on durotomy- and irrigation-related serious adverse events during spinal endoscopy revealed that a relevant share of surgeons assume that they had patients with neurological deficits (nerve root injuries, cauda equina syndrome) related to the irrigation.[1] We believe that the aforementioned complications may occur due to irrigation fluid entering the epi- and/or intradural space, causing pressure related symptoms in the further cranial parts of the spinal axis. To date, the mechanisms of these complications have not been studied systematically and no recommendations for pump pressure or flowrate settings for saline irrigation exist. For a better understanding, pressure measurements are needed at different intradural and epidural sites along the spinal axis and intracranially, which is hardly feasible *in vivo*. Therefore, we aimed to develop a experimental setup for reliable measurement of epidural, intradural, and intracranial pressure during endoscopic surgery in human cadavers.

Table 1. Anthropometric specimen data

Variable	Specimen		
	1	2	3
Height (cm)	178	167.6	170.2
Age (yr)	79	75	95
Sex	Female	Male	Female
Weight (kg)	108.4	86.2	74.8
Body mass index (kg/m^2)	34.2	30.7	25.8

MATERIALS AND METHODS

The study was performed according to the Helsinki Declaration and approved by the Kantonale Ethikkommission Zürich (Basec No. KEK-ZH-Nr. 2023-01986).

1. Experimental Setup

The experiment was conducted sequentially in 3 human cadavers (fresh frozen, torso including head) which were thawed at room temperature. Anthropometric data of all 3 specimens is displayed in Table 1. Computer tomography of the spine and skull prior to the experiments was acquired to exclude relevant spinal stenosis or other significant spinal pathologies.

After a skin incision of 6 cm, a sacral approach of 10×10 mm is performed (Fig. 1A). After a durotomy of 5×5 mm 3 polyurethane lumbar catheters (Neuromedex Lumbalkatheter 4.5F, Neuromedex GmbH, Hamburg, Germany) are advanced to the levels C 5/6, Th 8/9, and L3–4 through the durotomy using flu-

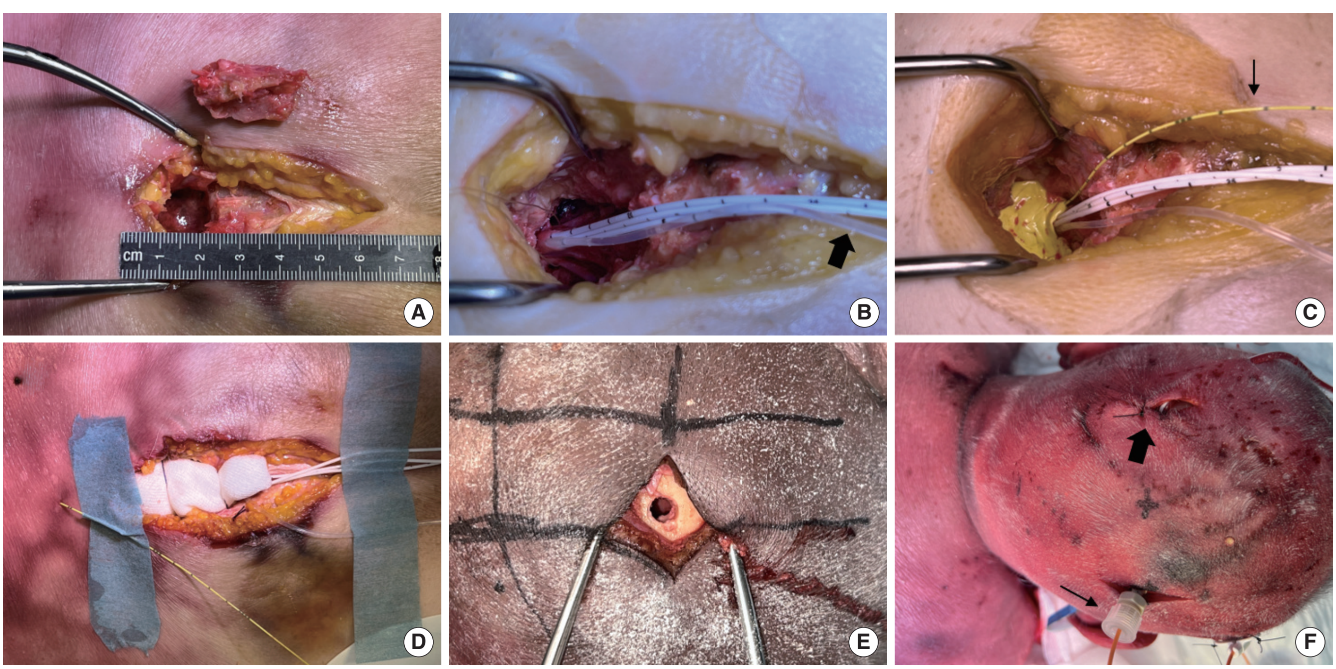

Fig. 1. Dorsal sacral and cranial approach. (A) Sacral dorsal approach of 10×10 mm. (B) Intradural insertion of 3 lumbar catheters for pressure measurements and an additional catheter for filling of the thecal sac and the ventricular system (thick arrow). (C) Closure of the approach with epidurally placed pressure transducer (thin arrow). (D) Watertight approach after additional sealing. (E) Parietal burr hole. (F) Insertion of intraventricular catheter (thick arrow), and intraparenchymal pressure sensor (thin arrow).

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oroscopy to confirm the level (Fig. 1B). Epidural pressure is measured using a pressure transducer (Codman microsensor, Codman Specialty Surgery, Integra LifeSciences Corp., Princeton, NJ, USA), which is introduced through the same approach and placed epidural at L3–4 (Fig. 1C). The thecal sac and ventricular system are filled through a catheter with Ringer solution through the same approach. The durotomy is then closed using tobacco-pouch sutures and superglue (Fig. 1C and D). To simulate a physiological intradural pressure of approximately 15 cmH_2O, the feeding catheter is connected to a Ringer solution bag at a level 15 cm above the spinal canal. Simultaneously to the sacral approach, 2-burr holes are placed on each side on the parietal bone at Frazier's Point using an electric rose drill, followed by a point-like durotomy (Fig. 1E).[3,4] We consider the thecal sac sufficiently filled, once the irrigation solution exits the subdural space through the burr holes. Then, a ventricular catheter is introduced (TraumaCath Ventricular Catheter Set, Integra LifeSciences Corp.) in the lateral ventricle (Fig. 1F). The correct location is verified using contrast agent and cranial fluoroscopy. A pressure sensor (Neurovent P, RAUMEDIC AG, Helmbrechts, Germany) is introduced through the contralateral burr hole with radiological verification of the intraparenchymal position of its tip (Fig. 1F).

2. Data Acquisition

For the purpose of measuring intradural pressure, catheters are connected to separate pressure transducers (VentrEX system, Neuromedex GmbH, Hamburg, Germany), which in turn are connected to 3 interface monitors (RAUMED NeuroSmart, RAUMEDIC AG) (Fig. 2A). Similarly, for the purpose of measuring ventricular and parenchymal pressure, the catheter and pressure sensor, respectively, are connected to an interface monitor. If the pressure transducer is kept at the same hydrostatic level of the catheter tip within the lumbar cerebrospinal fluid (CSF) space, it can be assumed that the static value of the actual intradural CSF pressure and that of the measured pressure signal are equal. This is warranted by measuring the depth of the surgical site and marking of the skin. This setup for intradural measurements was previously established in patients with spinal cord disorders.[5-10] All consumables and monitors for intradural, ventricular and parenchymal pressure assessments are CE-certified for the use in humans. The epidural pressure transducer is connected to a Codman DirectLink ICP box, then linked to an interface monitor (Philips X2-Pat. Interface+MX 700, Philips, Amsterdam, the Netherlands), through which the pressure signal is transmitted to a laptop for recording with ICM+ software (Cambridge Enterprise, Cambridge, UK). The epidur-

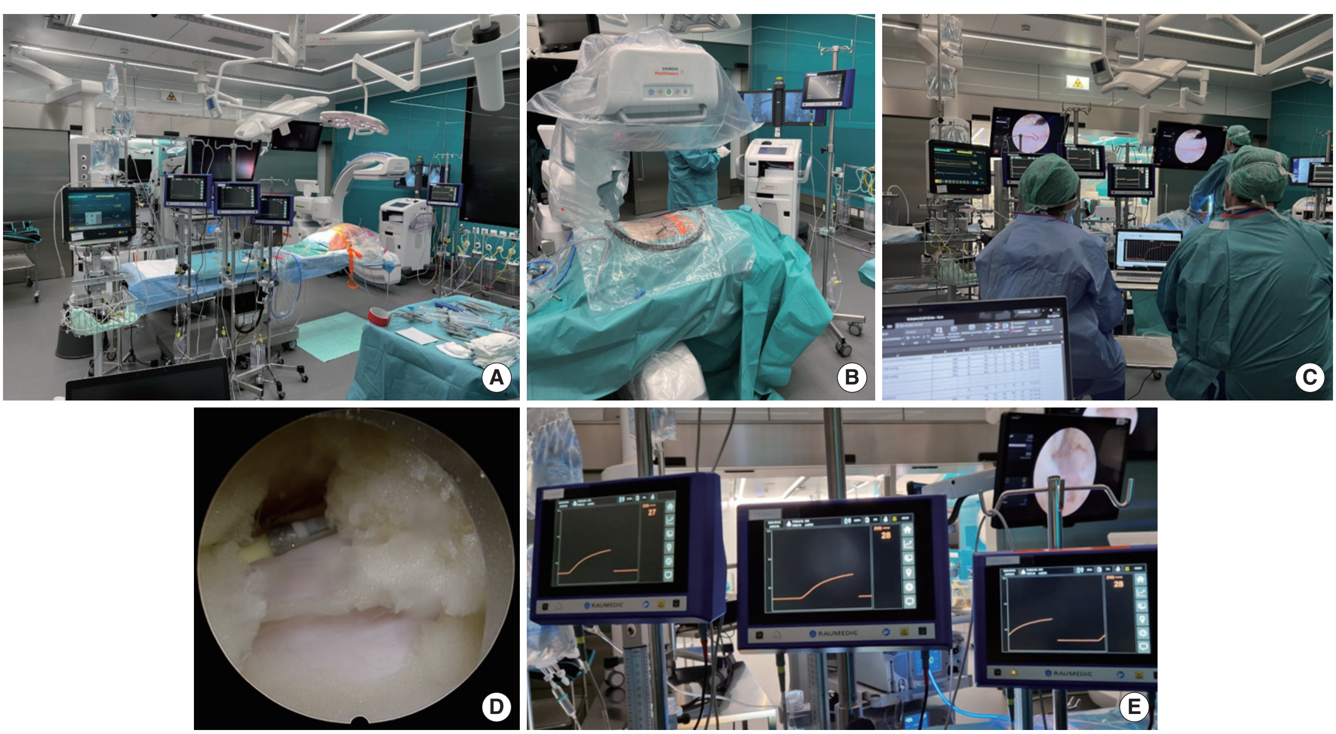

Fig. 2. Experimental setup. (A) Overview. (B) X-ray guided endoscopic approach at L3–4. (C) Setup of monitors measuring epidural, cervical, thoracic, lumbar, and intracranial pressure. (D) Endoscopic view on thecal sac and epidural probe. (E) Interface monitors showing increase in pressure in all intradural probes, as a reaction to application of occlusion during endoscopy.

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al transducer is CE-certified for parenchymal, subdural, or intraventricular measurements, but is commonly used for epidural measurements.[11] This part of the setup is established according to standard operating procedures for using ICM+ with Philips Intellivue monitors (icmplus.neurosurg.cam.ac.uk). ICM+ is designed as a flexible platform for investigations of cerebrospinal pressure dynamics in clinical practice.[12]

3. Performance of Baseline Measurements

After installation of catheters and probes as described in detail above (Fig. 2A and C), pressures of the lumbar epidural, intraventricular, cerebral intraparenchymal, cervical, thoracic and lumbar intradural probes are registered as baseline, once the values have reached a steady state. Then, endoscopic approaches—transforaminal and interlaminar—are sequentially conducted in a standard fashion. A tube-in-tube system for full endoscopy with a single working channel diameter of 4.7 mm, outer diameter of the shaft of 7.6 mm, a working length of 171 mm and an optic angle of 30° is used. Spine endoscopy is performed with gravity-based irrigation and 2 different endoscopic pump systems after performance of an x-ray guided approach at L3–4 (Fig. 2B). After each system change, repeated baseline measurements without water inflow were performed defined as timepoints 1–6 for 3 systems with 2 sequentially performed approaches with intervals of 20 to 30 minutes in between. In detail: T1: Gravity-based system, transforaminal approach, T2: Pump pressure system 1, transforaminal approach, T3: Pump pressure system 2, transforaminal approach, T4: Gravity-based system, interlaminar approach, T5: Pump pressure system 1, interlaminar approach, T6: Pump pressure system 2, interlaminar approach.

4. Validation of the Setup

After installation of all probes, a liquid bolus is instilled in order to register changes in pressure and thereby control for proper functionality. If all probes react to the application with an increase in pressure, the validation of the setup is completed.

In addition to standard endoscopic irrigation flow, occlusion was performed (Fig. 2E). Occlusion is defined by blocking the irrigation backflow. This maneuver is clinically often used to increase the hydraulic pressure for bleeding control. Sensitivity of the system to measure pressure differences between occlusion and nonocclusion was tested. Furthermore, we investigated the effect of a pump pressure increase with the endoscopic system 1 on intradural, epidural and intracranial pressure.

Table 2. Mean baseline pressures of lumbar, thoracic, cervical, and intracranial level in specimens 1–3

Specimen	Mean ± SD (range) (mmHg)
1	1.3 ± 2.9 (-3 to 3)
2	9.0 ± 2.0 (6–10)
3	6.0 ± 1.2 (5–7)

SD, standard deviation.

RESULTS

It was feasible to place all catheters at the correct locations, which has been controlled endoscopically for the epidural probe at the level L3–4 and by the inserted length of the catheter for the intradural catheters. Stable compartmental pressure baselines at all levels could be individually maintained for all 3 specimens at the beginning of the experiment after equilibrium was maintained (mean ± standard deviation: 1.3 ± 2.9 mmHg, 9.0 ± 2.0 mmHg, 6.0 ± 1.2 mmHg, respectively) (Table 2). However, there were interindividual differences between those baselines.

Mean baseline pressures of 3 different timepoints, as described above, was highest at the intracranial level (ICP) in levels 1 and 2 and increased along the spinal axis from the lumbar to ICP in specimen 1 (Fig. 3A). We observed no relevant differences in baseline pressure measurements when comparing the interlaminar to the transforaminal approach (Fig. 3A).

Compartmental pressure could be maintained within a constant range during the experiment after performing both a transforaminal and interlaminar approach (Fig. 3B) at different timepoints.

Pressure increase could be detected sensitively by closing the system with occlusion (Fig. 4) and increasing the pump pressure (Fig. 5). There was a linear regression of L3–4 intradural pressure and pump pressure with endoscopic system 1. The relative change of pressure measured at the epi- and intradural spaces, except for intraventricular, was approximately 30–40 mmHg in the example of specimen 2.

DISCUSSION

Irrigation-related complications of spinal endoscopy are not well understood. Water pump pressures in spinal endoscopy can be considerably high (theoretically up to 120 mmHg) and induce external pressure on the dura, which in turn might hypothetically increase pressure in other compartments. In clinical studies Joh et al.[13] and Choi et al.[14] identified neck pain occurring during percutaneous endoscopic lumbar discectomy

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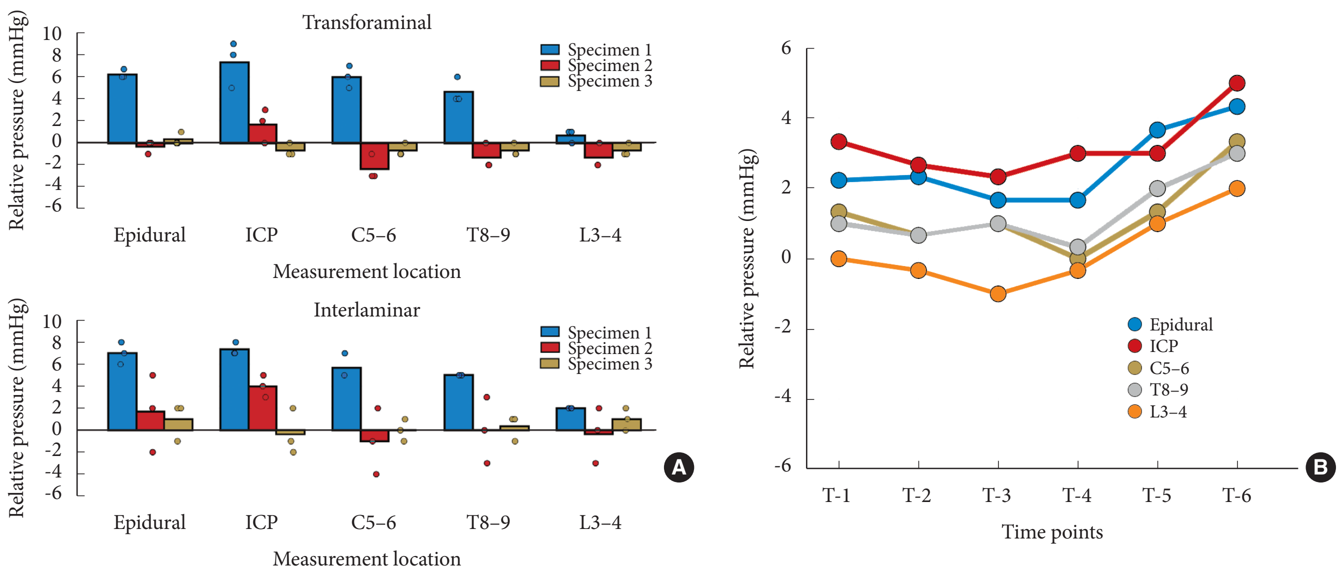

Fig. 3. (A) Relative baseline pressure (mean baseline at timepoint 1–3 minus baseline at the beginning of the whole experiment) with a transforaminal and interlaminar approach in all 3 specimens. Data displayed as mean, different data points represent system 1–3. (B) Relative mean baseline pressure of all levels and specimens at 6 different timepoints 1–6 (3 systems, 2 approaches) did not change relevantly (e.g., more than 5 mmHg) over the course of the whole experiment. ICP, intracranial level.

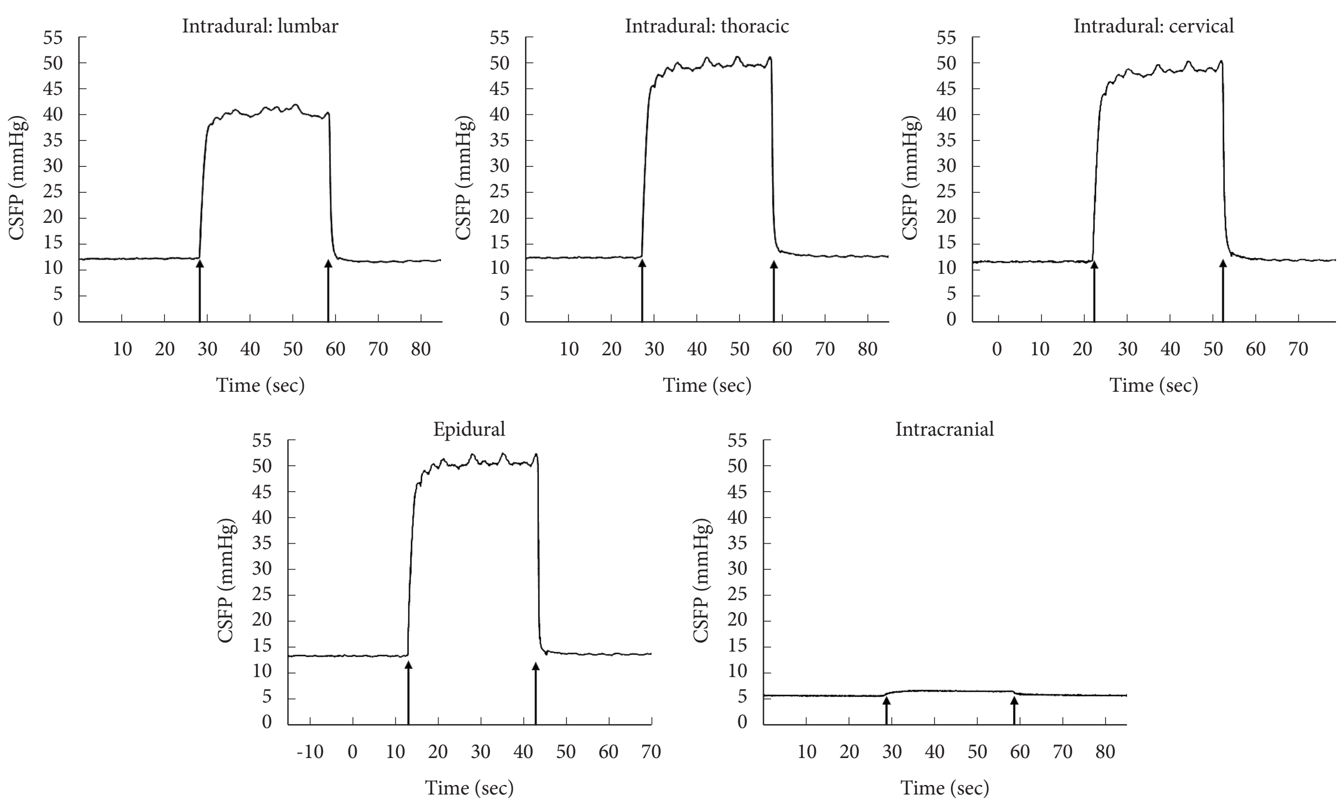

Fig. 4. Absolute pressure curve increases at the example of specimen 2 at all levels by performing occlusion maneuver (beginning and end indicated by arrows) with the endoscope resulting in a relative pressure increase of around 30–40 mmHg (pump pressure set at 40 mmHg). CSFP, cerebrospinal fluid pressure.

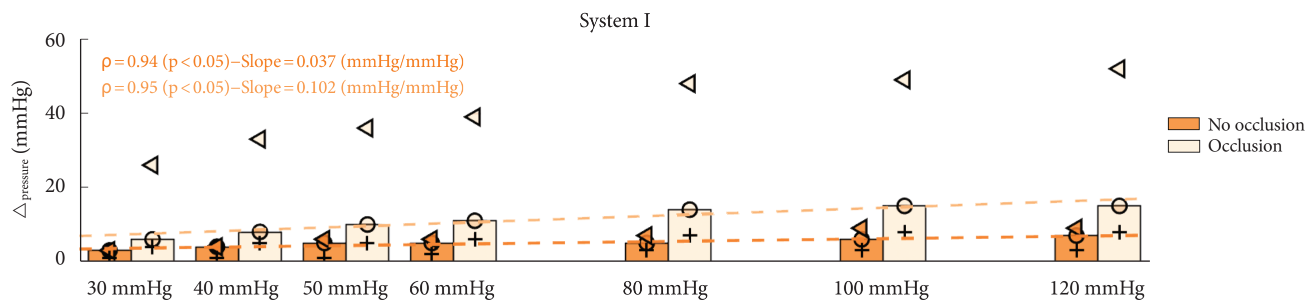

Fig. 5. Linear regression of L3–4 median intradural pressure in relation to pump pressure with and without occlusion in endoscopic system 1 with a transforaminal approach.

being associated with a highly increased cervical epidural pressure probably generated by continuous infusion. Similarly, we observed a relative increase in the measured pressure correlating with an increase in pump pressure. Even more, in cases with dural lesions and CSF leakage, irrigation might access the intradural space, leading to a direct pressure increase. To account for different pressure across the craniospinal axis, pressures need to be assessed at different sites and compartments. Currently, there is no evidence-based consensus on which pressure setting should be used, respectively avoided, during spinal endoscopy. Further, it is largely unknown if the numbers displayed on pump systems represent the immediate pressures that are delivered.[1] Therefore, we initiated several experiments to systematically address this knowledge gap. As the first important step, an experimental setup to investigate specificities of irrigation during endoscopy has been developed, validated and presented here in detail. The here provided detailed description of the experimental setup allows future experimental research illuminating irrigation-related scientific questions. This setup can display pressure and volume changes induced at the spinal level that translate across the spinal axis up to the brain. However, definitive pressure recommendations for spinal endoscopy cannot be provided yet, since further research for specific scenarios during endoscopy has to be conducted first.

It should be considered that pressures that are built up in different spinal compartments are depended on multiple factors, including patient-related factors as well as instrument design factors.[15] Therefore, we interpret the different baseline pressures between the cadaveric specimens due to different anthropometrics, particularly body mass index, and data should be interpreted intraindividual and not interindividual. However, mean baseline pressure over the whole spinal axis within each specimen was constant, showing a nearly closed system at the beginning of the experiment. Although change in integrity of anatomical structures can affect liquid pressures in spinal elements, such as observed with dural tears during spinal endoscopy.[16] Furthermore, the exact location of the epidural probe is unknown because of placement through the dorsal sacral approach. This might lead to alterations of the absolute epidural pressure caused by the different proximity of the endoscope to the probe. Also, absolute pressure measurement might not be impeccable in the here described model, since the system is not entirely closed, given the dural incision for insertion of the probes, the sacral osteotomy and skin incision. Furthermore, we cannot extrapolate to a physiological pressure in a living patient, since the natural barrier between the intradural space and surrounding tissue is at least partly abolished. This might partly explain lower absolute epidural and intradural pressures than pump pressures. However, for the purpose of measuring differential pressures, these drawbacks are acceptable considering this model's simplicity and lack of alternative *in vivo* human models. A more sophisticated model would also account for CSF pulsation and flow, as well as for the complex and manifold interactions between the respiratory-cardiovascular systems and the epi- and intradural spaces. This is hardly feasible and limited by the many unknowns about the interaction between these systems. Also, thawing of the fresh-frozen specimens may play a role in an altered soft-tissue status. Further approximation would be possible through animal studies, which however might not be directly transferable to the human. However, for measuring differential pressures this is not deemed necessary and evaluating advantages versus disadvantages, in our opinion, the cadaveric model described here represents the most suitable experimental setup for further detailed experiments illuminating technical factors affecting irrigation pressures.

CONCLUSION

Irrigation during spinal endoscopy creates pressures on the epi- and intradural compartments. However, little is known

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about actual pressures during full-endoscopic lumbar discectomy along the spinal axis, especially at the ICP. We present a validated experimental setup for repeatable measurements of epidural, intradural, and intracranial pressures during endoscopic surgery of the lumbar spine in human cadavers. This setup can be used as base for further experiments to illuminate save ranges of flow rates and pump pressures in different settings of spinal endoscopy.

NOTES

Conflict of Interest: Mazda Farshad reports being a consultant for Arthrex and Medacta, Board member and stock owner of Moving Spine (Balgrist University Startup), recipient of research support from Medacta and fellowship support from DePuy Synthes. Vincent Hagel reports being a consultant for Arthrex. All the other authors report no conflicts of interest.

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