Chen et al. BMC Medical Education (2024) 24:1361
https://doi.org/10.1186/s12909-024-06333-x

BMC Medical Education

RESEARCH

Open Access

Simulated spinal durotomy repair for orthopaedic resident training: a perfusion-based porcine cadaveric specimen as an in vitro animal model

Chiu-Ming Chen[1], Fu-Huang Lin[2] and Jui-Jung Yang[1*]

Abstract

Background Training in delicate spinal dura mater suturing techniques poses significant challenges due to patient safety and medicolegal concerns, driving the need for alternative training methods beyond traditional mentorship models. This study aimed to introduce and validate a training model for orthopaedic residents using perfusion-based porcine spines to simulate intraoperative durotomy and subsequent repair.

Methods Nine junior orthopaedic residents were invited to participate. Three attending orthopaedic spine surgeons were included in the control group. Fresh porcine spines were used for the simulation, and a perfusion-based system was implemented to replicate cerebrospinal fluid circulation and apply hydrostatic pressure to the dura. Durotomies were made and mended with 6–0 prolene sutures, and the participants' performance was assessed across six trials for repair speed and leakage pressure. Additionally, the self-confidence levels of the residents were analyzed before and after the training.

Results While attending surgeons showed consistent performance across trials, residents demonstrated a 70% reduction in mean total time and a 62% increase in mean leakage pressure after training. Residents showed significant improvements in repair speed from Trial 4 and in repair quality from Trial 3 compared with Trial 1 as the baseline. The difference compared with attending surgeons became insignificant in repair speed from Trial 4 and in repair quality from Trial 2, indicating that the residents' performance approached that of the attending surgeons. Residents' self-confidence increased significantly from a mean pre-training score of 1.1 to a mean post-training score of 4.3.

Conclusions This simulation model, which utilizes fresh porcine spines and a perfusion-based system, is an accessible, cost-effective, and high-fidelity training method for dural repair during spinal surgery.

Keywords Cerebrospinal fluid (CSF) leakage, Spinal durotomy repair, Surgical simulation, Orthopaedic resident training, Perfusion-based model, Porcine spine animal model

*Correspondence:
Jui-Jung Yang
doc931012003@yahoo.com.tw
[1] Department of Orthopaedic Surgery, Tri-Service General Hospital, National Defense Medical Center, No. 325, Cheng-Kung Road Section 2, Taipei 114, Taiwan, R.O.C.
[2] School of Public Health, National Defense Medical Center, Taipei, Taiwan, R.O.C.

Background

Spinal dura mater tear and resultant cerebrospinal fluid (CSF) leakage is not a rare complication in spinal surgery, with a reported incidence ranging from 1 to 17% [1]. Although there is still debate regarding the size and location of dural defect that require surgical repair, the generally accepted opinion is that a tiny tear can be managed with application of tissue glue, but large defects require surgical repair [2]. A structured ten-step guideline, summarized with the acronym "Bird Dove, MD," provides a comprehensive approach of dural repair: Bone removal to expose the tear, Intradural inspection, Repositioning extruded fibers, Dural closure, Outside patch application, Valsalva maneuver for leak testing, Epidural pedicled muscle flap placement, Multilayer closure, and Drainage [3]. The consequences of a suboptimal repair that allows persistent CSF leakage include pseudomeningocele, headache, postoperative meningitis, myelocutaneous fistula, nerve rootlet entrapment, wound infection and/or dehiscence, and intracranial hemorrhage [4–6]. Dural closure and suture repair require a considerable fine surgical technique in a narrow space to achieve "water-tightness", and avoid the complication of nerve rootlet entrapment.

Traditionally, surgical skills are acquired and developed through a mentorship model, i.e. residents gain hands-on experience by performing procedures on live patients in real-time under supervision [7]. As suturing the dura matter requires experience to avoid inadequate water-tightness and prevent complications such as nerve rootlet entrapment, senior surgeons may be unwilling to allow junior surgeons to suture the dura mater due to patient safety and medicolegal concerns [8, 9]. As such, there has been much pressure on training institutions to develop alternative training methods. Technique simulation with an in vivo animal model or a human cadaveric model can be an alternative when opportunities to learn certain skills are not otherwise readily available [10].

In recent years, there has been a decrease in the use of in vivo animal model simulations. This can be attributed to an increased emphasis on animal ethical concerns, and the high expense of live animal models [11]. A perfusion-based simulation using a fresh human cadaver had been proposed to recreate the conditions of CSF circulation, and apply hydrostatic pressure to the dura mater. This model involves the use of infusion tubes to deliver fluid into the subdural space, replicating the in vivo CSF circulation. This perfusion-based system aims to mimic the physiological conditions and hydrostatic pressure of the dura in real life [12–14]. Although the use of this method is an ideal approach, its accessibility is impeded by the limited availability of fresh human cadavers. To overcome this limitation, fresh animal cadavers can be used with some modifications of this method. Various animal spine models, including those of calf, sheep, deer, pig, and cow have been employed for training purposes [15]. Of these animal models, porcine specimens are frequently chosen due to their similarities to human tissue, particularly in terms of spine structure [16]. Moreover, porcine models offer the highest accessibility for research purposes, primarily due to their comparatively lower cost.

To develop a simulation of intraoperative durotomy, we used fresh porcine spines as a large animal model. Perfusion of infusion fluid into the subdural space was used for recreation of CSF hydrostatic pressure. For the simulation, a durotomy was made and then repaired. The feasibility of this model was evaluated by examining orthopaedic resident's pre- and post-training performance improvement, and self-confidence enhancement. Attending surgeons served as a control group for comparison.

Methods

Porcine spine preparation and CSF reconstitution

Fresh 9-month-old porcine spines were obtained from a local slaughterhouse, and consisted of the whole spinal column from lumbar to coccygeal region. After carefully removing the soft tissue and the lamina while ensuring dural integrity, the intact thecal sac was fully exposed (Fig. 1). The bilateral accompanying nerve roots were ligated with a suture. A 20G catheter connected to the infusion tube was inserted into the cephalic end of the subdural space of the spinal canal, and fixed with a suture. Physiologic hydrostatic pressure of CSF was simulated through saline infusion, with adjustments made via the altitude of the saline reservoir. A pressure transducer (Asahi Keiki, Tokyo, Japan) was connected in parallel to the infusion system to record the pressure within the system at the

Fig. 1 Spinal column with exposed thecal sac

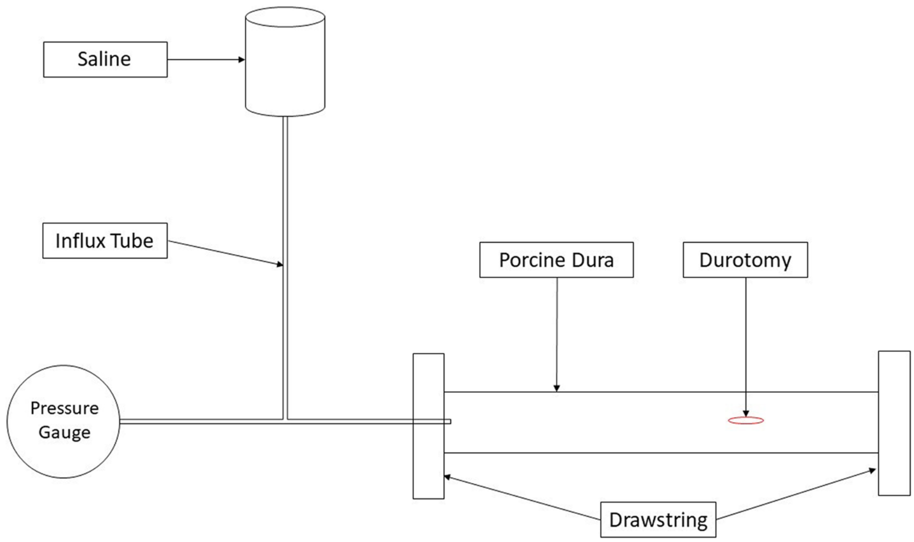

Fig. 2 Schematic illustration of porcine spine with infusion system

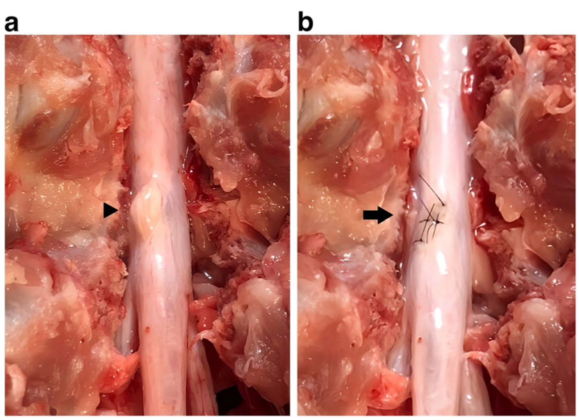

Fig. 3 **a** 1.5-cm dural defect for durotomy simulation (black arrowhead). **b** Dural repair with suture (black arrow)

height of the spinal canal (Fig. 2). The watertightness of the whole infusion system was checked by saline infusion to exclude any leakage, thereby ensuring accurate hydrostatic pressure measurements within the subdural space.

Simulated durotomy and suture repair

Every two spinal segments were sequentially used as a test unit to maximize the use of the entire specimen. A midline 1.5-cm durotomy was made using a #15 scalpel blade. Monofilament 6–0 prolene sutures (Ethicon, Somerville, NJ, USA) were used for repair in an interrupted pattern. The sutures were placed approximately 4 mm apart, and each suture was tied using a surgeon's knot (Fig. 3).

Study participants

Junior orthopaedic residents (R1, R2, and R3) were invited to participate in the study. Attending orthopaedic spine surgeons were also included in the control group. After receiving a brief overview from the senior author, participants were instructed about the fundamentals of dural repair, including instrument handling and suture techniques. Each participant performed the simulation six times on a new test unit.

Performance improvement and self-confidence enhancement

The performance of each participant was evaluated based on the speed and quality of suture repair. The speed of repair was measured by recording the time to completion of closure in seconds. After the completion of each suture repair, the saline bag was elevated to increase the simulated CSF pressure. Leakage pressure was defined as the pressure at which fluid began to leak from the repaired dural defect. Before and after completing all six repairs, the residents were asked to rate their confidence levels on a 5-point Likert scale, with 5 indicating very confident and 1 indicating very unconfident in performing the procedure (Supplementary Table 1).

Statistical analysis

Friedman's tests were used to assess the improvement of each participant's performance, including both the speed and quality of suture repair between each consecutive trial and the initial trial. The change in the self-confidence of each resident before and after all six repairs was analyzed using the Wilcoxon signed-rank test. The difference in performance between the resident and attending surgeon groups in each trial was analyzed using the Mann–Whitney U test. All analyses were performed using the SPSS version 20 for Windows (IBM Corp., Armonk, NY, USA). The level of significance was set at $P=0.05$.

Results

Nine orthopaedic residents and three attending surgeons were included in the study. The performance of all participants and the self-confidence levels of all residents are listed in Table 1. While no significant differences in performance were observed among attending surgeons across different trials, residents demonstrated significant improvements in both the speed and quality of suture repair (Fig. 4). The mean total time required for residents to perform dural repair decreased by approximately 70% from Trial 1 (203.4 s) to Trial 6 (60.8 s). A significant decrease in time was noted from Trial 4 onwards, persisting through Trials 5 and 6, compared with Trial 1 as the baseline. The significant difference in repair speed between the resident and attending surgeon groups diminished with consecutive trials during training and became insignificant from Trial 4 (Fig. 4A). There was a 62% increase in the mean leakage pressure after dural repair from Trial 1 (mean 25.1 mmHg) to Trial 6 (40.7 mmHg). A significant elevation in leakage pressure was observed starting from Trial 3 and continued through Trials 4, 5, and 6 when compared with Trial 1 as the baseline. The significant difference in repair quality between the resident and attending surgeon groups became insignificant from Trial 2 (Fig. 4B). Regarding residents'self-confidence, there was a significant increase from a mean pre-training score of 1.1 to a mean post-training score of 4.3 ($P=0.06$) (Fig. 5).

Discussion

In this study, we developed and tested a dural repair simulation model using fresh porcine spine specimens combined with saline perfusion to simulate CSF. A durotomy was made for simulation of an intraoperative dural injury. The model allowed residents to practice suturing a dural defect and gain experience in using the instruments required for dural repair. The effectiveness of the model was demonstrated by significant improvements in resident performance and self-confidence through pre- and post-training comparisons alongside comparisons with attending surgeons. This model does not require the use of human tissues or live animals.

With advances in technology, virtual reality and augmented reality are being used in medical education to provide 3-dimensional (3D) computer-based surgical simulations [7]. However, whether this type of training translates to improved outcomes remains to be investigated. Importantly, these simulations lack the tactile feedback which is part of an actual surgical procedure. Although efforts have been made to incorporate tactile feedback into simulation systems, such as simulating the insertion of pedicle screws using haptic feedback [17], replicating the realistic touch sensation of soft tissues like the dura mater and the CSF within has not been achieved. Therefore, animal or human cadaveric simulation models

Table 1 Dural repair performances across 6 trials of participants and self-confidence of residents

Participant	Total Time (sec)						Leakage Pressure (mmHg)						Self-Confidence[a]	
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Pre-training	Post-training
Resident 1	150	112	98	66	68	58	35	47	52	47	42	47	1	5
Resident 2	142	105	75	59	64	49	25	29	32	30	28	29	1	4
Resident 3	200	150	99	87	46	57	24	25	39	41	38	37	1	4
Resident 4	336	190	115	79	95	86	27	32	38	40	42	38	1	5
Resident 5	185	125	130	86	81	66	19	27	32	36	38	40	1	5
Resident 6	191	145	106	94	77	53	26	24	37	47	41	42	1	4
Resident 7	220	188	140	97	62	68	28	27	39	42	32	47	1	3
Resident 8	181	140	102	66	72	54	19	26	36	41	39	47	1	4
Resident 9	226	134	145	83	97	56	23	28	41	52	41	39	2	5
Average	203.4	143.2	112.2	79.7	73.6	60.8	25.1	29.4	38.4	41.8	37.9	40.7	1.1	4.3
Attending 1	101	88	76	55	67	56	38	40	42	39	42	40	n/a	n/a
Attending 2	121	79	85	67	74	56	34	43	38	44	42	50	n/a	n/a
Attending 3	99	76	65	55	49	52	41	45	38	42	40	39	n/a	n/a
Average	107	81	75.3	59	63.3	54.7	37.7	42.7	39.3	41.7	41.3	43	n/a	n/a

n/a no applicable

[a] Based on a 5-point Likert scale: 1 = no confidence; 5 = high confidence

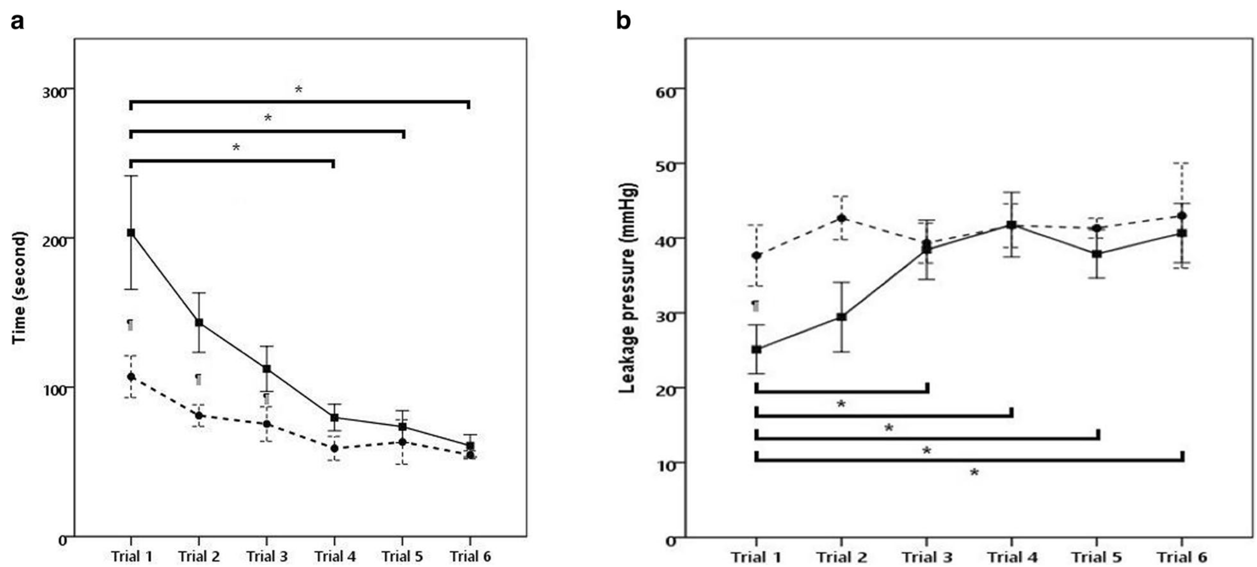

Fig. 4 Performance improvement for dural repair among all participants over six trials. **a** Time to complete the task (second). **b** Leakage pressure (mmHg). The dashed curve with filled circle and error bars indicates the performance of attending surgeons. The solid curve with filled square and error bars indicates the performance of residents. An asterisk indicates significant comparisons between trial 1 and subsequential trials with P value < 0.05. A pilcrow indicates significant comparisons between residents and attending surgeons in each trial with P value < 0.05

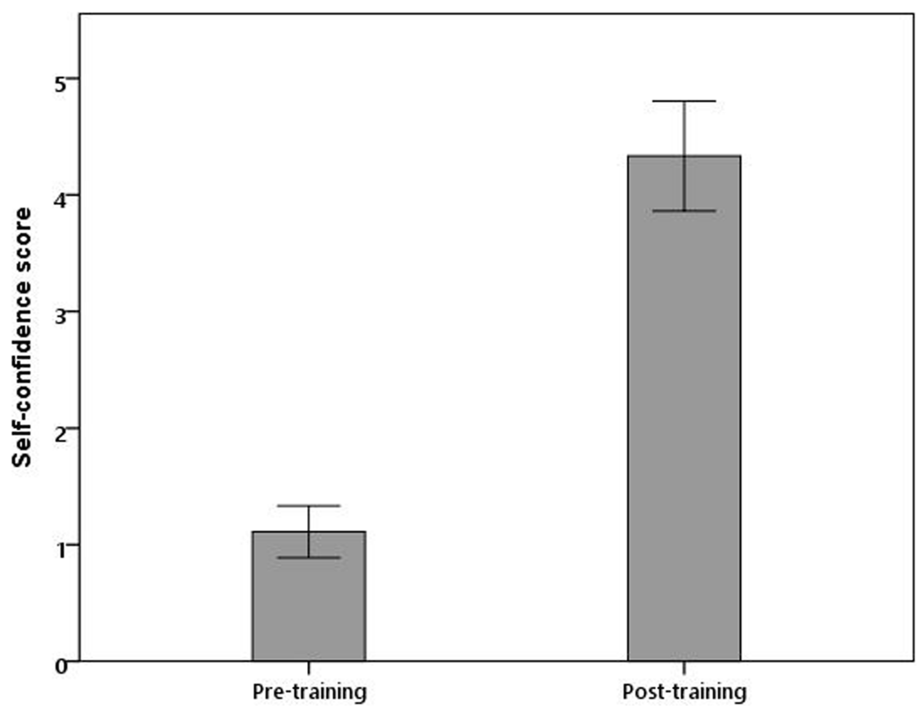

Fig. 5 Mean self-confidence score of residents for performing dural repair before and after simulation

remain necessary training methods before undertaking actual surgical procedures.

The concept of a perfusion-based model by infusing fluid into a tubular system to simulate physiologic hydrostatic pressure was first introduced for vascular surgery applications. Circulation can be established through cadaveric vessels [18], which facilitates education and reduces the need for live experimental animals [19]. A similar application of a perfusion-based model was developed for CSF reconstitution by infusing fluid into the ventricular system. A human fresh cadaveric study demonstrated that the ventricular system can be dilated postmortem [20]. As an extension of this approach, fluid can be injected into the subdural space to produce hydrostatic pressure, and several models have been developed using this method to fulfil the requirements of surgical training. Calf spines were first used as a perfusion-based model for performing laminectomies, and preserving the integrity of the dura mater. 14F Foley catheter balloons were used to occlude the proximal and distal ends of the spinal cord, creating a closed circuit. A saline reservoir was connected to the proximal catheter to provide adjustable hydrostatic pressure in the dura mater by infusing saline. This allowed durotomy and repair to be performed on the expanded dura mater [21, 22]. Modification of this method was made by using a watertight tube to serve as a dural substitute, which was placed in a sawbone to mimic the theca sac. Human cadaveric specimens were used to create similar perfusion-based models by insertion of a 12-gauge arterial catheter in the subdural-subarachnoid space to infuse fluid [12–14, 23]. Although this novel model provides a more realistic surgical simulation compared with animal models, the accessibility of fresh human cadavers is limited.

It is important for simulation models to possess a high level of reproducibility, closely resembling real surgical scenarios. The cost-effectiveness and accessibility are equally important considerations. Porcine spines have been commonly used as an alternative to human specimens for both in vivo and in vitro experiments involving spinal fusion and instrumentation techniques [24]. The ready availability of porcine spines makes them a popular choice for such experiments, especially when compared to human cadavers, as they can be obtained from local slaughterhouses without ethical concerns related to live animals. Moreover, porcine spines are cost-effective, with each specimen costing approximately $350 USD. Given their accessibility and cost-effectiveness, we utilize fresh porcine spines as a perfusion-based model for durotomy simulation.

Although there have been a few studies using the perfusion-based model for durotomy simulation, only 2 focused on its potential for surgical training. In a study using a synthetic material as dural substitute, all the participants demonstrated technical improvements; however, the degree of improvements was not statistically significant. The mean time to closure of the durotomy showed improvement in both the first (490 s) and second (456 s) closures, as did the median leak rate (14 drip/30 s and 7 drip/30 s in the first and second closures, respectively) [25]. In another study involving human cadaveric spines for dural repair for minimally invasive spine surgery, participants demonstrated consistent improvement across 3 trials, with a significant reduction in closure time between their initial and the third final trial (12 min, 7 s to 7 min, 4 s in the first and third trials, respectively; $p=0.02$). All trainees achieved a robust dural closure that withstood simulated Valsalva maneuvers. Furthermore, participants reported a high level of model realism, and displayed significant increases in post-procedure confidence scores [14].

The results of the current study revealed differing performances between residents and attending surgeons in pre-training and post-training comparisons. While attending surgeons did not exhibit significant improvements across the different trials, the training model significantly enhanced the repair speed and quality of the residents. Specifically, repair speed improved significantly from Trial 4, and repair quality improved notably from Trial 3 compared to Trial 1. Residents achieved performance levels comparable to those of attending surgeons from Trial 4 for repair speed and from Trial 2 for repair quality. Considering all comparative results, residents were able to achieve repair speed and quality comparable to those of attending surgeons with proficient dural repair skills after the fourth trial of this simulation. The mean total time required for residents to perform dural repair decreased by approximately 70% from Trial 1 (203.4 s) to Trial 6 (60.8 s). The efficacy is further emphasized for residents by achieving an average leakage pressure of 40.7 mm Hg in the final trial, falling within the range observed in previous studies examining dural suture repair (ranging from 13.3 to 70 mm Hg) [23, 26–28]. Moreover, there was a significant increase in the residents' self-confidence ratings for performing dural repair after completing the simulation exercises. Taken together, these findings confirm the efficacy of this simulation model in improving both residents' performance and confidence levels.

This perfusion-based model can be extended to enhance its utility across different training and bench-study scenarios. Incorporating minimally invasive tubular retractors into this simulation model could enhance its applicability for durotomy repair in minimally invasive spine surgery [14]. Moreover, this model holds potential for further refinement to develop surgical techniques specifically for full-endoscopic dural repair. Additionally, it can be used in mechanical studies to analyze hydrostatic pressure, and quantify the sealing effectiveness of various dural repair techniques or sealants [21, 22, 29].

This study has several limitations. First, we performed extensive decompression, including facet joint excision, to optimize nerve root ligation for achieving watertight closure. However, this approach may not accurately represent real-world clinical scenarios, in which bone excision is often limited, resulting in a narrower and deeper surgical field. Second, the sample size of nine residents and three attending surgeons is limited, warranting further validation with larger cohorts. Third, although we simulated a dural defect with CSF leakage, our protocol could not replicate epidural bleeding, which is a common occurrence during intraoperative durotomy. These factors can complicate dural closure significantly. Therefore, achieving a good simulation performance does not guarantee similar outcomes in clinical practice.

Nevertheless, simulation training offers benefits to residents with less experience and confidence, allowing them to gain cumulative surgical experience without the risk of nerve rootlet entrapment during dural suturing. Although it cannot replace actual clinical practice, this simulation can serve as an important preparatory step before performing hands-on procedures. Our study provides valuable training for spinal durotomy repair aimed at better equipping junior surgeons to handle real-world complexities. It may also help reduce the mental stress caused by unexpected intraoperative dural injuries through prior practice.

Conclusion

In this study, a novel simulation model for intraoperative spinal durotomy repair using fresh porcine spines and perfusion-based CSF reconstitution was developed. Orthopaedic residents demonstrated significant improvements in repair speed, quality, and self-confidence after six simulation trials. The model offers cost-effective, high-fidelity training for spinal surgery.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12909-024-06333-x.

Supplementary Material 1: Supplementary Table 1: self-confidence questionnaire.

Acknowledgements

Thank you to all the participating surgeons for their invaluable contributions.

Authors' contributions

The study conception and design were carried out by JJY. Material preparation and experiment execution were conducted by JJY and CMC. The questionnaires for participants and self-assessment were designed by FHL and JJY. Data collection and analysis were performed by FHL and JJY. The first draft of the manuscript was written by CMC and JJY, and all authors reviewed the manuscript.

Funding

This study was financially supported by a research grant from the Research Foundation of Tri-Service General Hospital (grant number TSGH_D_113123) and Ministry of National Defense-Medical Affairs Bureau, Taiwan (grant number MND-MAB-D-114115), which are nonprofit funding entites supported by the hospital surplus to encourage clinical studies. The funding sources did not play a role in this investigation.

Data availability

Most of the data generated or analysed during this study are included in this article. The remaining datasets used and/or analysed during the study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Ethics approval for this study was waived by the Institutional Review Board of Tri-Service General Hospital (TSGHIRB) because the experiment involved the use of in vitro tissue purchased from a butcher and did not involve animals raised specifically for research purposes. Additionally, the participation of orthopedic residents did not require ethics approval, as the study posed no more than minimal risk to all participants. Informed written consent was obtained from all participants prior to the commencement of the study. The study was conducted in accordance with the Declaration of Helsinki.

Consent for publication

Not Applicable.

Competing interests

The authors declare no competing interests.

Received: 2 August 2024 Accepted: 11 November 2024
Published online: 26 November 2024

References

1. Guerin P, El Fegoun AB, Obeid I, Gille O, Lelong L, Luc S, et al. Incidental durotomy during spine surgery: incidence, management and complications. A retrospective review Injury. 2012;43:397–401. https://doi.org/10.1016/j.injury.2010.12.014.
2. Galarza M, Gazzeri R, Alfaro R, de la Rosa P, Arraez C, Piqueras C. Evaluation and management of small dural tears in primary lumbar spinal decompression and discectomy surgery. J Clin Neurosci. 2018;50:177–82. https://doi.org/10.1016/j.jocn.2018.01.008.
3. Papavero L, Engler N, Kothe R. Incidental durotomy in spine surgery: first aid in ten steps. Eur Spine J. 2015;24:2077–84. https://doi.org/10.1007/s00586-015-3837-x.
4. Bosacco SJ, Gardner MJ, Guille JT. Evaluation and treatment of dural tears in lumbar spine surgery: a review. Clin Orthop Relat Res 2001:238–47. https://doi.org/10.1097/00003086-200108000-00033.
5. Zimmerman RM, Kebaish KM. Intracranial hemorrhage following incidental durotomy during spinal surgery A report of four patients. J Bone Joint Surg Am. 2007;89:2275–9. https://doi.org/10.2106/00004623-200710000-00025.
6. deFreitas DJ, McCabe JP. Acinetobacter baumanii meningitis: a rare complication of incidental durotomy. J Spinal Disord Tech. 2004;17:115–6. https://doi.org/10.1097/00024720-200404000-00007.
7. Wang Z, Shen J. Simulation training in spine surgery. J Am Acad Orthop Surg. 2022;30:400–8. https://doi.org/10.5435/JAAOS-D-21-00756.
8. Phan K, Phan P, Stratton A, Kingwell S, Hoda M, Wai E. Impact of resident involvement on cervical and lumbar spine surgery outcomes. Spine J. 2019;19:1905–10. https://doi.org/10.1016/j.spinee.2019.07.006.
9. Baisiwala S, Shlobin NA, Cloney MB, Dahdaleh NS. Impact of Resident Participation During Surgery on Neurosurgical Outcomes: A Meta-Analysis. World Neurosurg 2020;142:1–12. https://doi.org/10.1016/j.wneu.2020.05.266.
10. Farah GJ, Rogers JL, Lopez AM, Brown NJ, Pennington Z, Kuo C, et al. Resident training in spine surgery: a systematic review of simulation-based educational models. World Neurosurg. 2023;174:81–115. https://doi.org/10.3171/2020.6.SPINE20795.
11. Ghasemi M, Dehpour AR. Ethical considerations in animal studies. J Med Ethics Hist Med. 2009;2:12. https://doi.org/10.20529/IJME.2004.010.
12. Winer JL, Kramer DR, Robison RA, Ohiorhenuan I, Minneti M, Giannotta S, et al. Cerebrospinal fluid reconstitution via a perfusion-based cadaveric model: feasibility study demonstrating surgical simulation of

neuroendoscopic procedures. J Neurosurg. 2015;123:1316–21. https://doi.org/10.3171/2014.10.JNS1497.
13. Christian EA, Bakhsheshian J, Strickland BA, Fredrickson VL, Buchanan IA, Pham MH, et al. Perfusion-based human cadaveric specimen as a simulation training model in repairing cerebrospinal fluid leaks during endoscopic endonasal skull base surgery. J Neurosurg. 2018;129:792–6. https://doi.org/10.3171/2017.5.JNS162982.
14. Buchanan IA, Min E, Pham MH, Donoho DA, Bakhsheshian J, Minneti M, et al. Simulation of dural repair in minimally invasive spine surgery with the use of a perfusion-based cadaveric model. Oper Neurosurg (Hagerstown). 2019;17:616–21. https://doi.org/10.1093/ons/opz111.
15. Morosanu CO, Nicolae L, Moldovan R, Farcasanu AS, Filip GA, Florian IS. Neurosurgical cadaveric and in vivo large animal training models for cranial and spinal approaches and techniques - a systematic review of the current literature. Neurol Neurochir Pol. 2019;53:8–17. https://doi.org/10.5603/PJNNS.a2019.0001.
16. Wilke HJ, Geppert J, Kienle A. Biomechanical in vitro evaluation of the complete porcine spine in comparison with data of the human spine. Eur Spine J. 2011;20:1859–68. https://doi.org/10.1007/s00586-011-1822-6.
17. Hou Y, Lin Y, Shi J, Chen H, Yuan W. Effectiveness of the thoracic pedicle screw placement using the virtual surgical training system: a cadaver study. Oper Neurosurg (Hagerstown). 2018;15:677–85. https://doi.org/10.1093/ons/opy030.
18. Garrett HE Jr. A human cadaveric circulation model. J Vasc Surg. 2001;33:1128–30. https://doi.org/10.1067/mva.2001.114214.
19. Aboud E, Suarez CE, Al-Mefty O, Yasargil MG. New alternative to animal models for surgical training. Altern Lab Anim. 2004;32(Suppl 1B):501–7. https://doi.org/10.1177/026119290403201s80.
20. Tubbs RS, Loukas M, Shoja MM, Wellons JC, Cohen-Gadol AA. Feasibility of ventricular expansion postmortem: a novel laboratory model for neurosurgical training that simulates intraventricular endoscopic surgery. J Neurosurg. 2009;111:1165–7. https://doi.org/10.3171/2009.3.JNS081653.
21. Faulkner ND, Finn MA, Anderson PA. Hydrostatic comparison of nonpenetrating titanium clips versus conventional suture for repair of spinal durotomies. Spine (Phila Pa 1976) 2012;37:E535–9. https://doi.org/10.1097/BRS.0b013e31824cf756.
22. Dafford EE, Anderson PA. Comparison of dural repair techniques. Spine J. 2015;15:1099–105. https://doi.org/10.1016/j.spinee.2013.06.044.
23. Bakhsheshian J, Strickland BA, Patel NN, Jakoi AM, Minneti M, Zada G, et al. The use of a novel perfusion-based cadaveric simulation model with cerebrospinal fluid reconstitution comparing dural repair techniques: a pilot study. Spine J. 2017;17:1335–41. https://doi.org/10.1016/j.spinee.2017.04.007.
24. Busscher I, Ploegmakers JJ, Verkerke GJ, Veldhuizen AG. Comparative anatomical dimensions of the complete human and porcine spine. Eur Spine J. 2010;19:1104–14. https://doi.org/10.1007/s00586-010-1326-9.
25. Ghobrial GM, Anderson PA, Chitale R, Campbell PG, Lobel DA, Harrop J. Simulated spinal cerebrospinal fluid leak repair: an educational model with didactic and technical components. Neurosurgery. 2013;73(Suppl 1):111–5. https://doi.org/10.1227/NEU.0000000000000091.
26. Hadley MN, Martin NA, Spetzler RF, Sonntag VK, Johnson PC. Comparative transoral dural closure techniques: a canine model. Neurosurgery. 1988;22:392–7. https://doi.org/10.1227/00006123-198802000-00021.
27. Cain JE, Jr., Rosenthal HG, Broom MJ, Jauch EC, Borek DA, Jacobs RR. Quantification of leakage pressures after durotomy repairs in the canine. Spine (Phila Pa 1976) 1990;15:969–70. https://doi.org/10.1097/00007632-199009000-00024.
28. Shenoy K, Donnally CJ 3rd, Sheha ED, Khanna K, Prasad SK. An Investigation of a Novel Dural Repair Device for Intraoperative Incidental Durotomy Repair. Front Surg. 2021;8:642972. https://doi.org/10.3389/fsurg.2021.642972.
29. Ye J, Hong Z, Chu B, Wang Z, Jiang L, Zhu Z, et al. Comparison of dural closure methods for dural repair to reduce the incidence of cerebrospinal fluid leakage. Br J Neurosurg 2021:1–6. https://doi.org/10.1080/02688697.2021.1950626.

Publisher's Note