@BoneJointOpen

# Minimally invasive robotic-assisted lumbar laminectomy

## development of a novel surgical technique

Correspondence should be sent to D. R. Lebl research@leblspinemd.com

Cite this article:
*Bone Jt Open* 2024;5(9): 809–817.

DOI: 10.1302/2633-1462.59.BJO-2024-0066.R1

**F. C. S. Altorfer,[1] M. J. Kelly,[1] F. Avrumova,[1] M. D. Burkhard,[1] D. B. Sneag,[2] J. L. Chazen,[2] E. T. Tan,[2] D. R. Lebl[1]**

[1]Department of Spine Surgery, Hospital for Special Surgery, New York, New York, USA
[2]Department of Radiology and Imaging, Hospital for Special Surgery, New York, New York, USA

### Aims
To report the development of the technique for minimally invasive lumbar decompression using robotic-assisted navigation.

### Methods
Robotic planning software was used to map out bone removal for a laminar decompression after registration of CT scan images of one cadaveric specimen. A specialized acorn-shaped bone removal robotic drill was used to complete a robotic lumbar laminectomy. Post-procedure advanced imaging was obtained to compare actual bony decompression to the surgical plan. After confirming accuracy of the technique, a minimally invasive robotic-assisted laminectomy was performed on one 72-year-old female patient with lumbar spinal stenosis. Postoperative advanced imaging was obtained to confirm the decompression.

### Results
A workflow for robotic-assisted lumbar laminectomy was successfully developed in a human cadaveric specimen, as excellent decompression was confirmed by postoperative CT imaging. Subsequently, the workflow was applied clinically in a patient with severe spinal stenosis. Excellent decompression was achieved intraoperatively and preservation of the dorsal midline structures was confirmed on postoperative MRI. The patient experienced improvement in symptoms postoperatively and was discharged within 24 hours.

### Conclusion
Minimally invasive robotic-assisted lumbar decompression utilizing a specialized robotic bone removal instrument was shown to be accurate and effective both in vitro and in vivo. The robotic bone removal technique has the potential for less invasive removal of laminar bone for spinal decompression, all the while preserving the spinous process and the posterior ligamentous complex. Spinal robotic surgery has previously been limited to the insertion of screws and, more recently, cages; however, recent innovations have expanded robotic capabilities to decompression of neurological structures.

### Take home message
- This study introduces a new robotic-assisted technique for minimally invasive lumbar decompression, showing promise in both cadaveric and clinical settings.
- It expands robotic spinal surgery capabilities, potentially improving precision and patient outcomes in treating lumbar spinal stenosis.

## Introduction
Over the last two decades, robotic surgery systems have become increasingly used in spinal instrumentation procedures. Until now, the primary capability of robotic-assisted

Bone & Joint Open

navigation (RAN) in spinal surgery has been in enhancing the accuracy and precision of pedicle screw placement. Other aspects of the procedure, namely neurological decompression, lack a fully developed robotic-assisted protocol.[1,2]

Decompressive lumbar laminectomy is a commonly performed surgical procedure that historically has been performed manually in an open fashion. Generally, the technique involves thinning and removing the lamina under direct visualization after first resecting the more dorsally located spinous process(es).[3] To facilitate the manual decompression portion of the procedure, a hand-held high-speed burr is often used. Thinning of the lamina involves first removing the dorsal laminar cortex and the intervening cancellous bone, leaving only the ventral cortex of the lamina intact. This precedes further bone removal with Kerrison rongeurs. While this technique remains effective, some conceptual limitations exist, specifically the surgeon requiring visual and haptic feedback to effectively and efficiently isolate the lamina's ventral cortex.

Additionally, determining the optimal amount of laminar decompression can pose significant challenges to even the most experienced surgeons. While inadequate decompression may limit symptom improvement and potentially precipitate revision surgery and its associated risks, excessive decompression may result in injury to biomechanically essential structures. Increased postoperative pain and blood loss have been reported,[4,5] with iatrogenic instability secondary to fracture of the pars interarticularis resulting in spondylolisthesis, a notable complication.[6,7]

While traditional open laminectomy remains a common surgical technique for lumbar spinal stenosis, minimally invasive approaches such as microscopic tubular and endoscopic spinal decompression have shown to be effective treatment alternatives.[8] Endoscopic techniques, in fact, have shown even greater advantages over microscopic tubular approaches, including reduced intraoperative blood loss, shorter hospital stays, and lower rates of incidental durotomy and surgical site infections.[8,9]

While very little literature exists to date, robotic systems have been considered as an adjunct to assist in spinal decompression procedures. In a preliminary animal study, Li et al[10] performed laminectomies using a robot-navigated piezoelectric osteotome in 30 porcine lumbar vertebrae, demonstrating acceptable safety when compared to manual laminectomy. In a follow-up study using the same robotic system, accuracy was demonstrated in consecutive human cadaveric thoracic and lumbar laminectomies.[11] While shown to be accurate, this instrument, a planar saw, has less geometrical adaptability to decompressive procedures that require smaller, more precise foci of decompression.

For this reason, a specialized robot-navigated acorn-shaped drill, originally conceptualized with the intention of facilitating facet joint decortication in posterior lumbar fusion surgery, has been developed as a robotic bone removal instrument.After noting promising results in posterior fusion procedures, this study assesses the feasibility, safety, and efficacy of employing this robotic bone removal instrument in performing a robotic-assisted lumbar laminectomy. Thus, we present a proof-of-concept study, initially conducted in a cadaveric in vitro model and subsequently extended to clinical use in a patient with symptomatic lumbar spinal stenosis.

## Surgical technique

The safety and efficacy of a specialized acorn-shaped bone removal robotic drill (Mazor X version 5.0; Medtronic, Ireland) in completing a lumbar laminectomy was evaluated in one cadaveric 73-year-old female specimen. Ethical approval was obtained from the Institutional Review Board at the Hospital for Special Surgery (USA) (IRB#2019-1402). The study was conducted following the Declaration of Helsinki (as revised in 2013).[12]

### RAN workflow

To optimize the workflow of this novel surgical technique, several principles of RAN were considered.[13] First, preoperative 3D imaging such as CT or MRI of the region of interest is essential for robotic navigation planning.[1,14] These images were uploaded to the robotic software (Mazor X version 5.0) for surgical pre-planning. The robotic system employed in this study was a table-mounted device that provides inherent stability through direct physical connection to the specimen or patient. This connection was established via a pin or clamp attached to the patient's bony anatomy, depending on the target area. To align preoperative imaging with the patient's physical anatomy, intraoperative radiographs are acquired and co-registered with the preoperative data. During the procedure, various surgical tools can be navigated, including drills and taps for pedicle screw placement, as well as an acorn-shaped drill for bone removal.

### Preprocedure imaging

For the cadaveric specimen, both a CT scan (GE Discovery/LightSpeed; GE Healthcare, USA) and a non-contrast MRI scan using a clinical 3.0 T magnet scanner (GE Healthcare) employing a spoiled gradient-recalled (SPGR) sequence, were completed in the pre-procedure stages.

### Surgical and robotic setup

The specimen was positioned prone on a Jackson table, and the robot's base was placed at the foot of the bed, allowing ample space for both the robotic arm mount and the image intensifier (OEC 9900 Elite; GE Healthcare). Docking the robotic system to bony anatomy required an incision over the right posterior superior iliac spine (PSIS), followed by placement of a Schanz pin for rigid fixation into which the Shanz ball adaptor can be secured.

### Imaging registration

The preprocedural images – a SPGR MRI – were loaded into the robotic navigation software. Prior to initial incision, an "intraprocedural-scan-and-plan" step was performed. Then, 2D fluoroscopic images were obtained with a mobile image intensifier in the anteroposterior and oblique views, which were then co-localized with the software planning template to confirm accuracy of the spinal segments.

### Planning the laminectomy

The acorn-shaped bone removal robotic drill was selected in the planning software to define the extent of laminar decompression. The decompression software model comprises the proposed defect (green) (Figure 1). Additionally, two numbers are displayed: one in millimetres (mm) indicating the entry point's distance from the midline, and another in

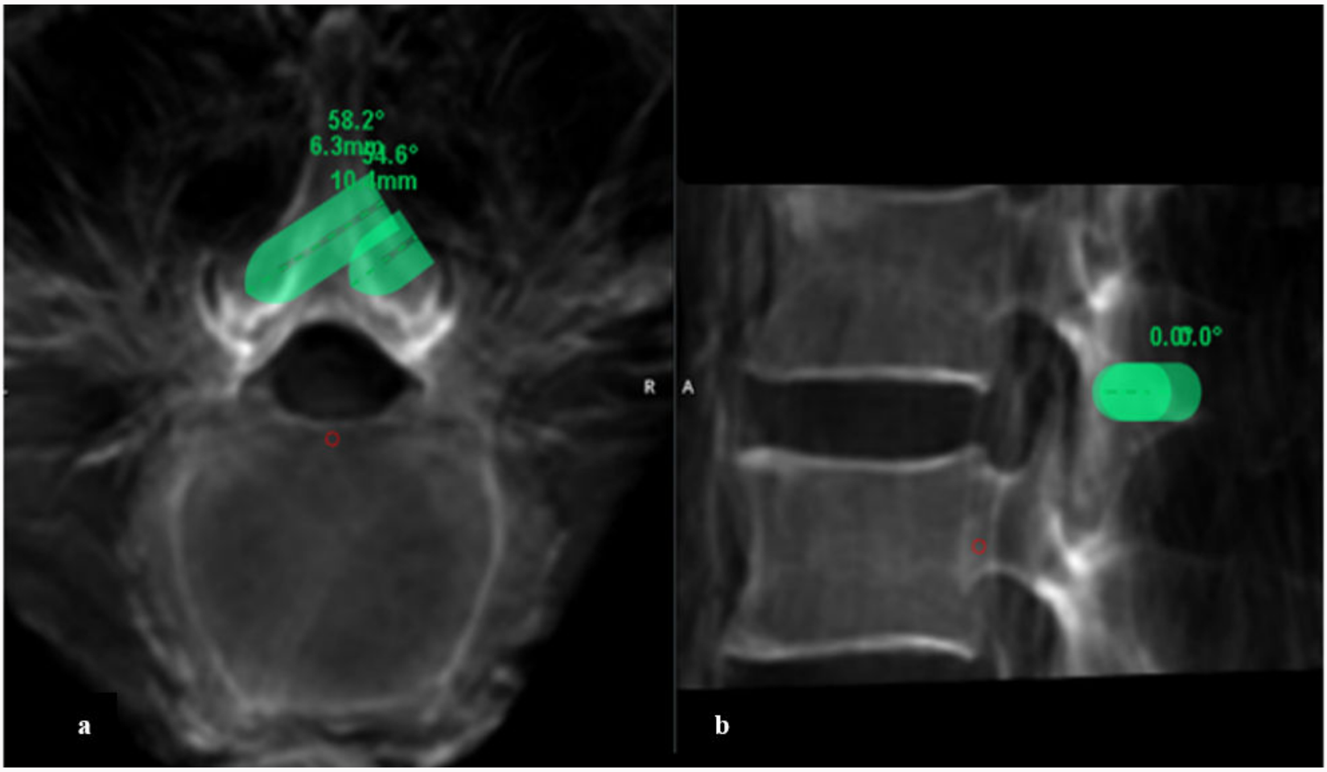


**Fig. 1**
Planning of the bone removal robotic drill for the laminectomy in the cadaver was done on the a) axial and b) sagittal views using two drills with depths of 10 mm and 20 mm, respectively. This allowed for sparing of the ventral laminar cortex and protection of the bilateral facet joints.

degrees representing the drill channel's angle relative to the midline. The diameter of the bone removal instrument is 7.5 mm; its penetration depth, however, is adjustable, ranging from 8 to 20 mm, and mostly dependent on the pre-procedure decompression plan.

Two drill trajectories were planned on the lamina at the level of the intervertebral disc for an "over-the-top" type laminar decompression. The diameter of the bone removal robotic drill (7.5 mm) at a depth of 15 mm was planned to remove the dorsal laminar cortex and intervening cancellous bone while sparing the ventral cortex as well as the adjacent facet joints (Figure 1).

### Cadaveric procedure

The robotic arm was sent to the starting point of each pre-planned drill trajectory. Once all starting points were marked at the skin level, one transverse incision was made paravertebrally, 3 cm from the midline, allowing for a unilateral, modified Wiltse approach with a longitudinal fascial incision (Figure 2).[15]

### Robotic-assisted laminectomy

A navigated localizing probe was used to confirm the appropriate trajectory for the predefined bone removal robotic drill (Figure 3). After approving the established anatomical trajectory, the robotic bone removal drill was inserted and advanced. Upon reaching the end of the pre-planned trajectory, a red circle appeared on the trajectory view, indicating completion of the decompressive drilling (Figure 3). In the cadaveric specimen, two drill tunnels were created at the L3/4 level. No additional manual decompression was done after using the bone removal robotic drill, in order to better evaluate the true extent of bony decompression on post-procedural imaging.

### Post-procedural imaging

A post-procedural CT scan of the cadaver was obtained to assess the laminectomy defect created with the acorn-shaped bone removal robotic drill. CT scan confirmed that the dorsal cortex of the lamina and the intervening cancellous bone were removed as planned, while only the ventral cortex was left (purposely) intact (Figure 4). No injury to the facet joints was evident on the post-procedural scan.

### Patient (clinical application)

A 72-year-old female patient was experiencing symptoms of spinal stenosis (neurogenic claudication) and radiculopathy (left leg pain) with imaging evidence of spinal canal stenosis (Schizas C) at the L3/4 level (Figure 5).[16] While the patient had evidence of a grade I spondylolisthesis at the affected level, this was deemed stable on dynamic flexion-extension radiographs. Thus, a minimally invasive, spinous process-sparing L3/4 decompression without fusion was recommended for this patient.

### Imaging

In the patient's preoperative workup, a CT scan using standard department protocol 0.75 mm axial slices and a non-contrast MRI scan using a clinical 3.0 T magnet scanner were obtained. After administration of general endotracheal anaesthesia, the patient was positioned prone on a Jackson table. The robotic setup was completed as previously described in

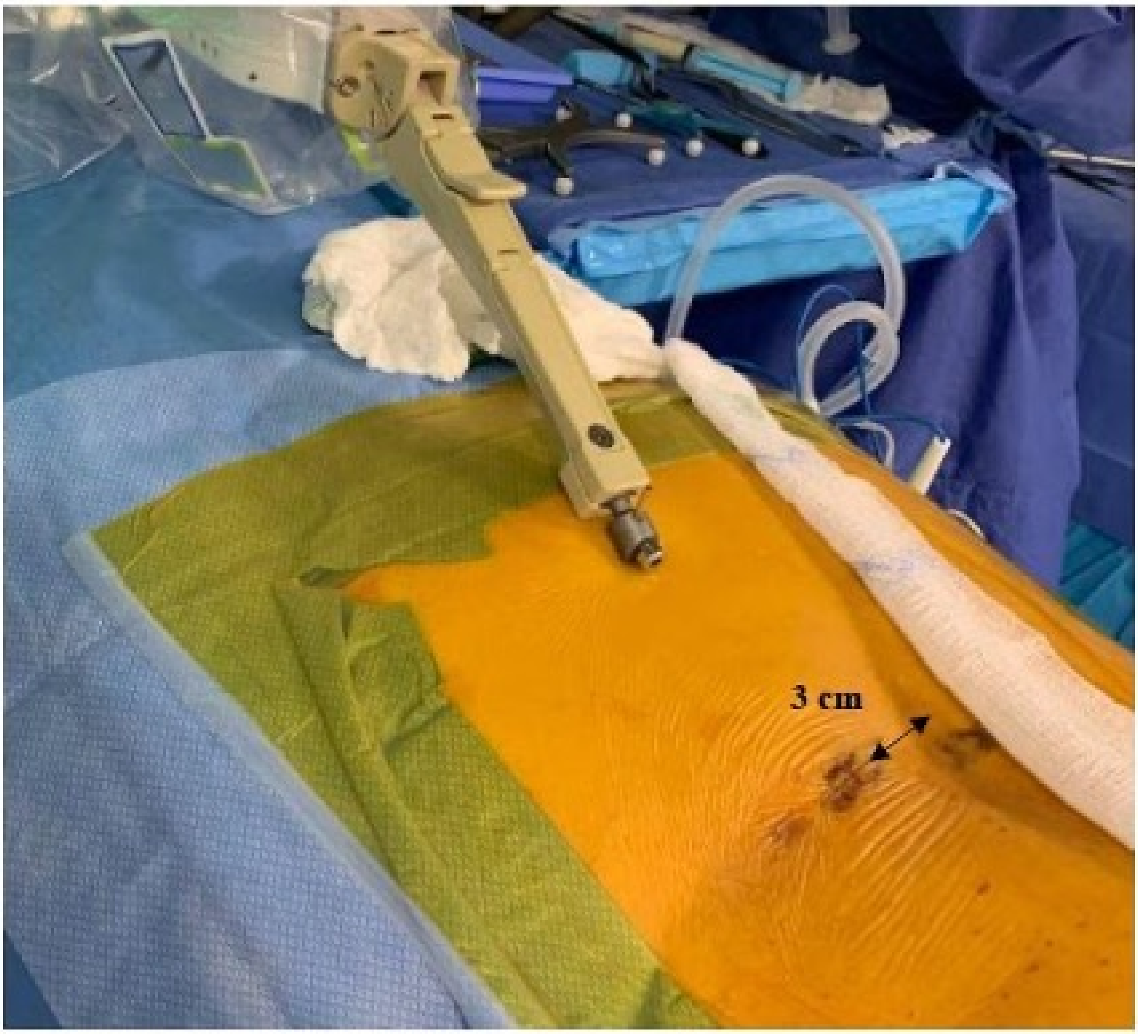


**Fig. 2**
Minimally invasive skin incision incorporating both trajectories at the level of the skin, along the paths predefined by the robot after preoperative surgical planning. Note the plan for a transverse skin incision located 3 cm lateral to the midline (unilateral, modified Wilste approach).

the cadaveric procedure section. The preoperative CT scan was loaded into the robotic navigation software. CT scan to fluoroscopy registration co-localization was performed, as previously described in the 'imaging registration' section.

### Planning the laminectomy

The planned decompressive laminectomy required four different passes of the robotic bone removal instrument (7.5 mm diameter) with depths of 8, 10, 15, and 15 mm (Figures 6a and 6b). As the patient was experiencing predominantly left leg pain, a right-to-left over-the-top decompression technique was chosen for maximal decompression of the left-sided lateral recess. In sum, four drill paths were planned, with two positioned inferiorly and two superiorly on the lamina in the sagittal plane. All four of the planned drill paths were parallel to one another when viewed in both the axial and sagittal planes. To facilitate the preplanning process, a 3D reconstruction of the planned drill trajectories was also created (Figure 6c).

During the preoperative planning phase, an important consideration for keeping the surgical approach minimally invasive (i.e. a small skin incision) is precisely planning the locations and angles of the drill trajectories. When multiple bone removal drill passes are required, such as for a full laminectomy versus a laminotomy procedure, it is crucial to plan all of the robotic drill trajectories to parallel one another. Ensuring the drill paths are parallel when extended out toward the patient's skin level avoids the need for multiple separate skin incisions and allows all of the deeper work to be possible through a single small skin incision.

### Surgery

The robotic arm was sent to the starting point of each predefined drill trajectory; all points were marked at the skin level, and one transverse incision was made, allowing for a unilateral, modified Wiltse approach to pass the robot-guided cannula down to the dorsal lamina.[15]

After reaching the lamina, the same procedure, employing a blunt localizing probe and the robotic bone removal instrument, was repeated in succession for the four predefined trajectories. The four drill paths were completed in an "over-the-top" fashion, with two focused on the ipsilateral and two focused on the contralateral lamina.

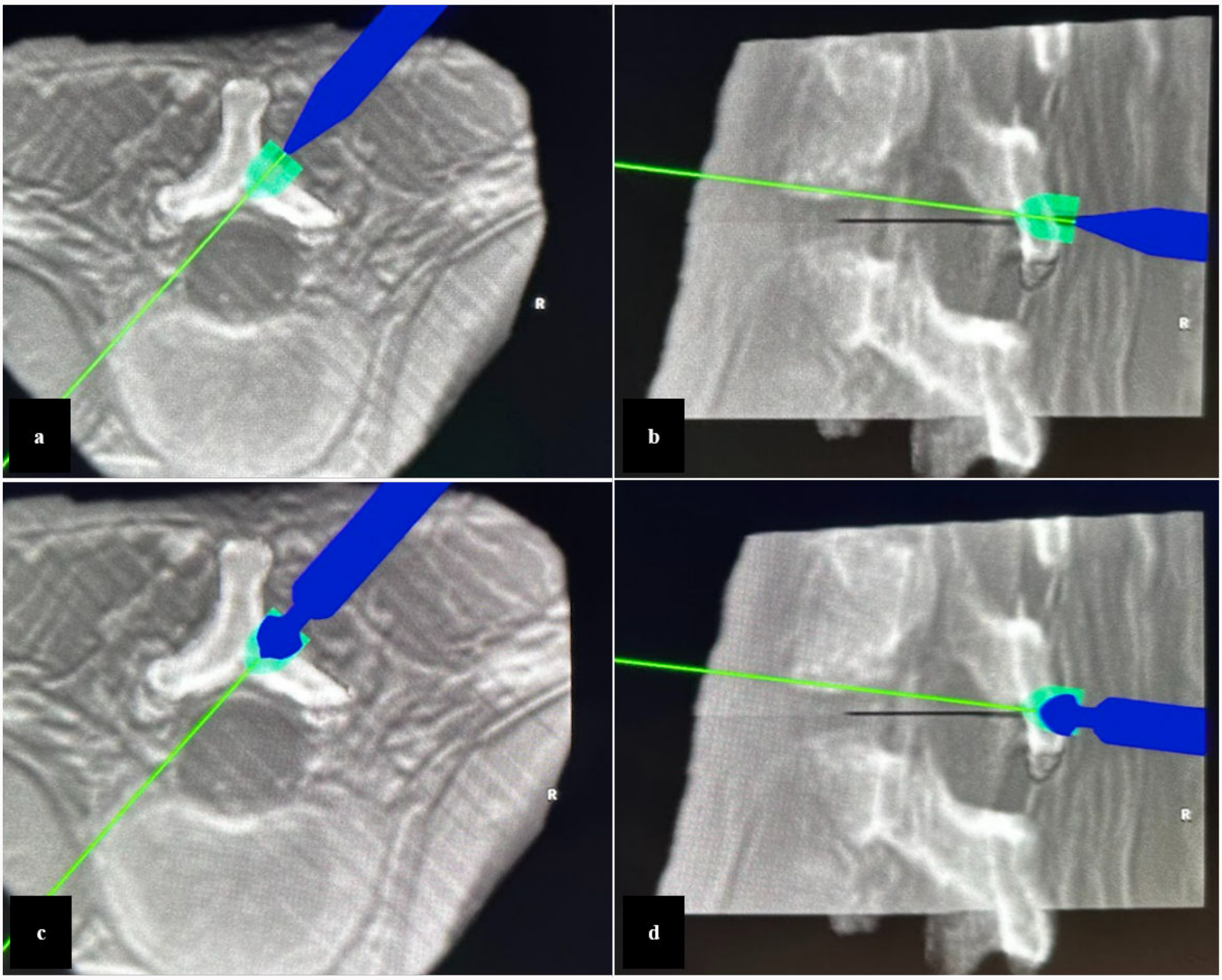


**Fig. 3**
After reaching the lamina, a navigated probe was used to confirm correct bony localization along the predefined drill in both the a) axial and b) sagittal planes. The bone removal robotic drill was inserted and drilled along the predefined trajectory in both the c) axial and d) sagittal views.

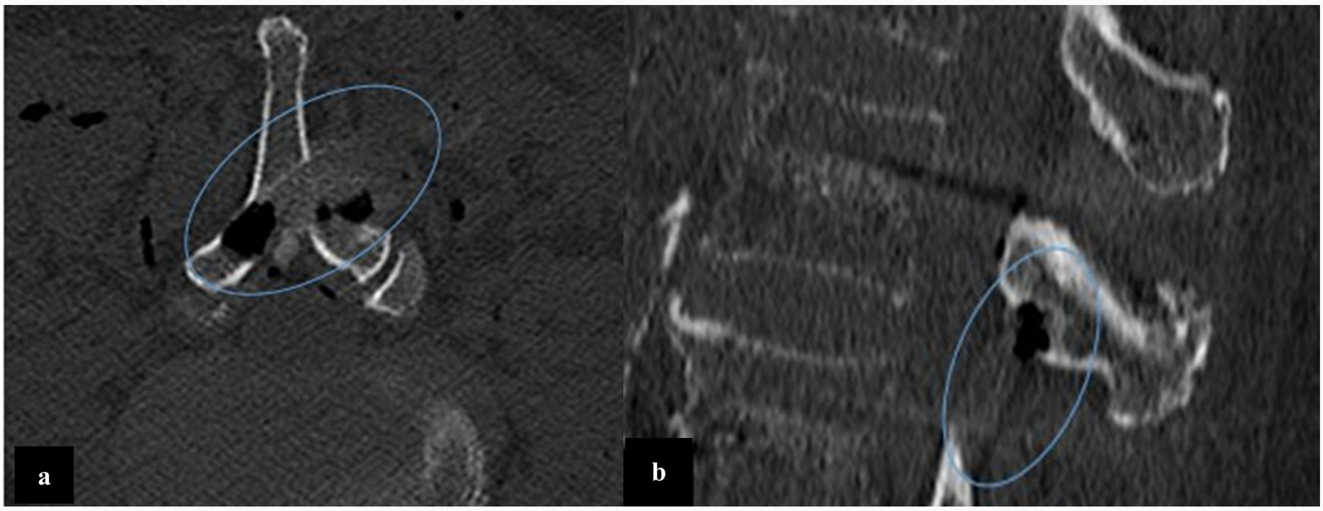


**Fig. 4**
Postoperative CT scan a) axial and b) sagittal views highlighting the extent of the laminectomy defect created by the robotic drill, with sparing of the ventral cortex evident.

**Fig. 5**
Preoperative MRI scan in a) sagittal and b) axial views showing spinal canal stenosis (Schizas C) at the L3/4 level.

### Intraoperative verification
To monitor the extent of the laminar decompression intraoperatively, an endoscopic view was obtained, confirming the four drill holes (Figure 7). Consistent with the preoperative plan, the dorsal cortex as well as the intervening cancellous bone was removed, leaving just the ventral laminar cortex intact. Additional bony removal was thus necessary to complete the neurological decompression. This was performed with a navigated handheld burr and a Kerrison rongeur to remove the last thin layer of ventral lamina. After complete ventral laminar bone removal, attention was turned to removal of the ligamentum flavum, ultimately exposing the thecal sac and completing the decompression.

### Postoperative imaging and clinical follow-up
The patient remained hospitalized overnight and was discharged to home the following morning without any complications. Her preoperative neurological symptoms had improved by the time of hospital discharge. At three weeks' follow-up, a postoperative MRI was obtained, which confirmed adequate neurological decompression (Figure 8).

## Discussion
Surgical procedures have historically required manual craftsmanship obtained only after years of training. In recent years, the healthcare industry, like many other industries, has prioritized automation and mechanization to improve precision and efficiency. General surgery was among the first of the surgical specialties to embrace robotics for this purpose. With increased robotics usage, general surgery experienced a decrease in traditional laparoscopic minimally invasive-type surgeries.[17] Subsequently, in the late 2010s, navigation was integrated with robotics into the field of spinal surgery. This development resulted in a spike in the adoption of robotic spinal surgery procedures worldwide, with the estimated market for robotics in spinal surgery increasing from $26 million in 2019 to $2.77 billion by 2022.[18]

While the benefits of robotic pedicle screw placement have been shown, before now, due to the intimate relationship of the spine anatomy to critical neurovascular structures, robotic spinal decompression has been underutilized, limited to manual techniques.[1] Here, we report the first study exploring robotic laminectomy using a specialized robotic bone removal instrument, with demonstrated efficacy both in vitro and in vivo. Based on our findings, with adequate preoperative planning, accurate removal of the dorsal laminar cortex and intervening cancellous bone can be efficiently performed using robotic assistance.

The proposed advantage of employing RAN is the swift and precise removal of the dorsal laminar cortex. While the dorsal laminar cortex is not compressive in nature, its presence anatomically limits the surgeons' ability to address and remove the compressive ventral structures – the ventral laminar cortical bone and the underlying hypertrophic ligamentum flavum. As illustrated in Figure 4, precise removal of the dorsal cortex (typically done with a hand-held high-speed burr, a potentially dangerous instrument) through robotic planning preoperatively is a safe manoeuvre that leaves only a thin residual ventral cortical shell for manual removal. Once the laminar bone has been 'egg-shelled' out robotically, the final layer of decompression may be achieved manually with instruments such as curettes and Kerrison rongeurs.

Future developments in instrumentation and robotic sensors may, in fact, one day allow for completion of the final layer of decompression robotically. However, while still in the early stages of development, this step remains manual for now. With current technology, there certainly exist opportunities to increase the depth of bone removal and thus further thin the ventral lamina, which would of course decrease the volume of residual manual decompression to be completed. This, for example, is likely most feasible at the caudal aspect of the lamina to be decompressed, where underlying ligamentum flavum reliably serves as a physical buffer between the tip of the robotic drill and the thecal sac.

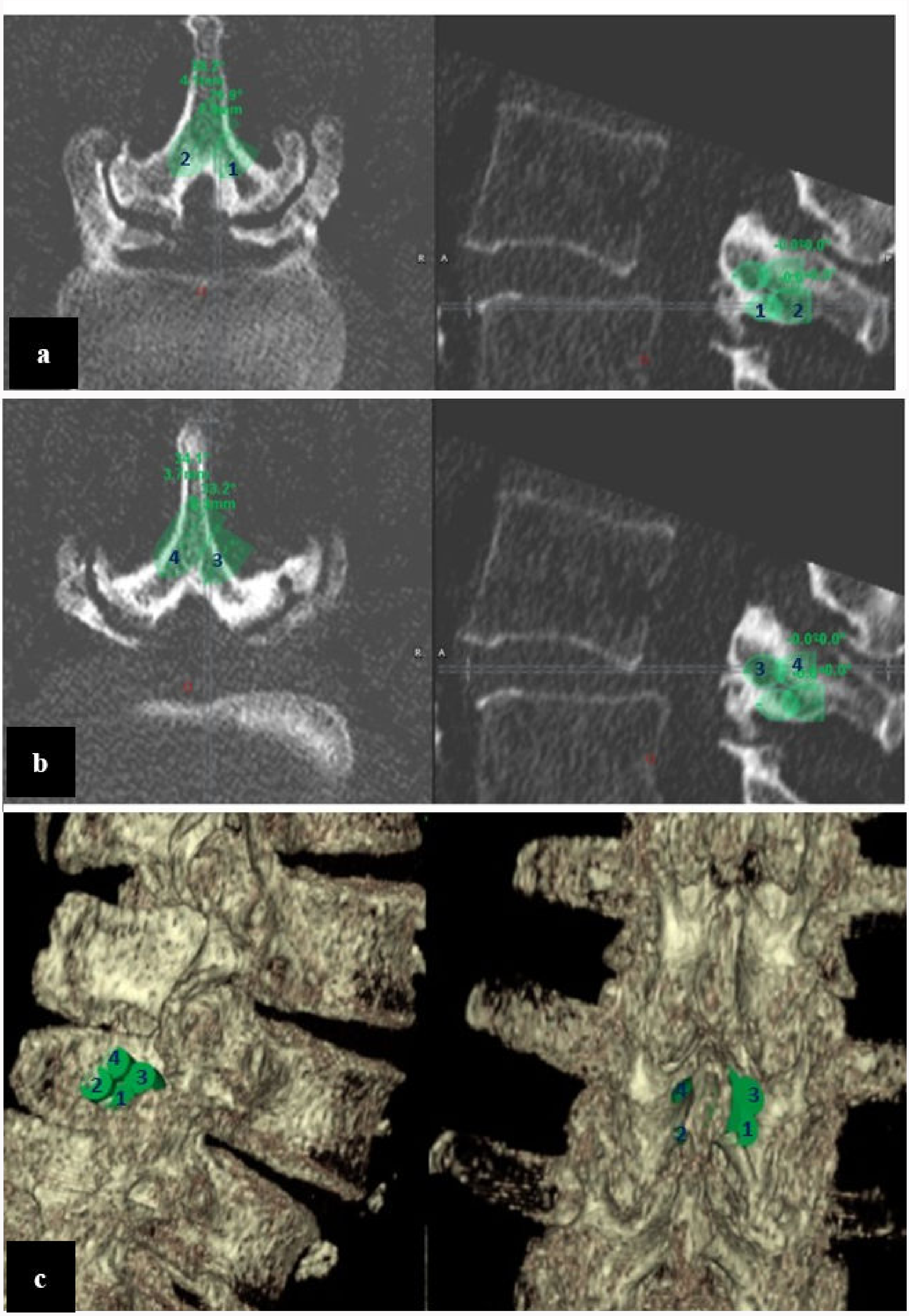


**Fig. 6**
The laminectomy planning process required four different drill paths, all 7.5 mm in diameter and 8 mm (1), 15 mm (2), 10 mm (3), and 15 mm (4) in depth. Two drill paths (1 and 2, image a) were planned more inferior (caudal) on the lamina in the sagittal plane than the other two (3 and 4, image b), which were planned more superior (cranial) on the lamina. In the caudal aspect of the lamina (1 and 2), the presence of the flavum provides a protective anatomical buffer, allowing a more aggressive approach with the drill when approaching the ventral laminar cortex. c) A 3D reconstruction of the planned drill trajectories is represented in posterolateral and posterior views.

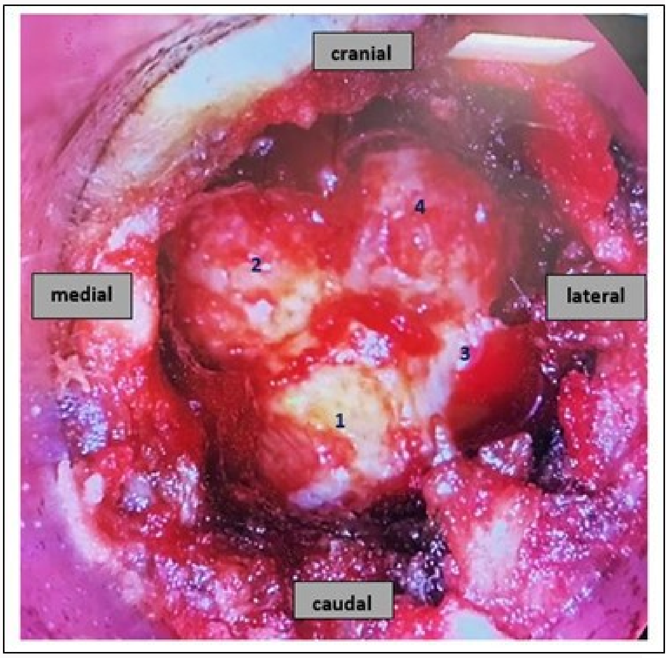


**Fig. 7**
To monitor the extent of the decompression of the lamina, an endoscopic viewing portal was used, showing the four drills created with the bone removal robotic drill.

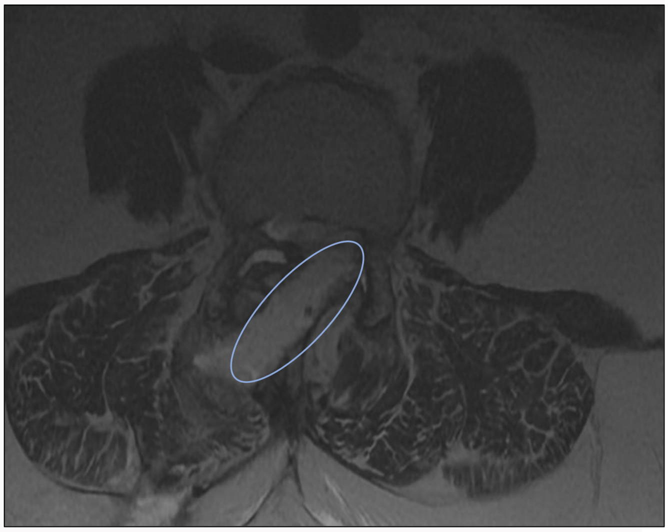

**Fig. 8**
Axial postoperative spoiled gradient echo (SPGR)-MRI at three weeks' follow-up. This image highlights the trajectories of the decompression made with the bone removal robotic drill. Notably, additional manual decompression with a navigated burr and a Kerrison rongeur was performed, as described.

It is well known that wide laminectomy can potentially result in future instability at the operative level.[19,20] In the lower lumbar levels, where the buttress of the pars interarticularis is small and provides little support to the lamina, an aggressive laminectomy is more likely to result in iatrogenic instability.[21] In addition to an automated and reproducible method for controlling the amount of bony decompression and limiting overresection, targeted robotic navigated decompression helps to preserve the structural integrity of the posterior ligamentous complex.[10] Through a unilateral, modified Wiltse approach that spares the midline structures, and completion of the laminar decompression in an over-the-top fashion, this procedure can be safely and effectively performed through a small incision, all with limited soft-tissue compromise.[22,23]

This study is limited by its sample size, including only a single cadaveric specimen and one patient, thereby restricting its generalizability to the broader lumbar spine surgery population. As we have highlighted, a limitation specific to the described technique is the final step of the decompression – removal of the ventral structure – which still must be performed manually. That being said, we believe that with increased experience and trust in the efficacy and safety of this new technique, a more thorough robotic-assisted decompression is certainly possible. Finally, another limitation of the proposed technique lies in the dimensions of the robotic bone removal instrument which, at the time of this study, is available only with a relatively robust 7.5 mm diameter. While not all patients are of equal size and shape, this drill may be oversized for some and must be considered in the preoperative planning phases. While recognizing that limitations currently exist, many design and development opportunities for a broadened selection of bone removal instruments exist with further customization of both the hardware and software involved.

Future studies should focus on a larger number of patients and attempt to quantify the benefits of robotic decompression in terms of improved operating time, perioperative recovery (with emphasis on minimal invasiveness), and, with time, long-term outcomes (limiting bony overresection and preventing injury to the posterior ligamentous complex).

In conclusion, robotic-assisted lumbar decompression utilizing a specialized robotic bone removal instrument was shown to be accurate and safe both in vitro and in vivo. The technical considerations and workflow reported here can serve as a foundation for future developments. This new technique applies existing technology in a new fashion, potentially offering improved precision, more reproducibility, and less invasiveness when performing spinal decompression surgery.

## References

1. **Abel F**, **Avrumova F**, **Goldman SN**, **Abjornson C**, **Lebl DR**. Robotic-navigated assistance in spine surgery: a single-surgeon experience with 1,001 pedicle screws. *Bone Joint J*. 2023;105-B(5):543–550.
2. **Elswick CM**, **Strong MJ**, **Joseph JR**, **Saadeh Y**, **Oppenlander M**, **Park P**. Robotic-assisted spinal surgery: current generation instrumentation and new applications. *Neurosurg Clin N Am*. 2020;31(1):103–110.
3. **Deyo RA**, **Gray DT**, **Kreuter W**, **Mirza S**, **Martin BI**. United States trends in lumbar fusion surgery for degenerative conditions. *Spine (Phila Pa 1976)*. 2005;30(12):1441–1445.
4. **Thomé C**, **Zevgaridis D**, **Leheta O**, **et al**. Outcome after less-invasive decompression of lumbar spinal stenosis: a randomized comparison of unilateral laminotomy, bilateral laminotomy, and laminectomy. *J Neurosurg Spine*. 2005;3(2):129–141.
5. **Postacchini F**, **Cinotti G**, **Perugia D**, **Gumina S**. The surgical treatment of central lumbar stenosis. Multiple laminotomy compared with total laminectomy. *J Bone Joint Surg Br*. 1993;75-B(3):386–392.
6. **Ramhmdani S**, **Xia Y**, **Xu R**, **et al**. Iatrogenic spondylolisthesis following open lumbar laminectomy: case series and review of the literature. *World Neurosurg*. 2018;113:e383–e390.

7. **Guha D**, **Heary RF**, **Shamji MF**. Iatrogenic spondylolisthesis following laminectomy for degenerative lumbar stenosis: systematic review and current concepts. *Neurosurg Focus*. 2015;39(4):E9.
8. **Chin BZ**, **Yong JH**, **Wang E**, **et al**. Full-endoscopic versus microscopic spinal decompression for lumbar spinal stenosis: a systematic review & meta-analysis. *Spine J*. 2024;24(6):1022–1033.
9. **Kotheeranurak V**, **Tangdamrongtham T**, **Lin G-X**, **et al**. Comparison of full-endoscopic and tubular-based microscopic decompression in patients with lumbar spinal stenosis: a randomized controlled trial. *Eur Spine J*. 2023;32(8):2736–2747.
10. **Li Z**, **Jiang S**, **Song X**, **et al**. Collaborative spinal robot system for laminectomy: a preliminary study. *Neurosurg Focus*. 2022;52(1):E11.
11. **Li Z**, **Wang C**, **Song X**, **et al**. Accuracy evaluation of a novel spinal robotic system for autonomous laminectomy in thoracic and lumbar vertebrae: a cadaveric study. *J Bone Joint Surg Am*. 2023;105-A(12):943–950.
12. **World Medical Association**. World Medical Association Declaration of Helsinki: ethical principles for medical research involving human subjects. *JAMA*. 2013;310(20):2191–2194.
13. **Cawley DT**, **Rajamani V**, **Cawley M**, **Selvadurai S**, **Gibson A**, **Molloy S**. Using lean principles to introduce intraoperative navigation for scoliosis surgery. *Bone Joint J*. 2020;102-B(1):5–10.
14. **Altorfer FCS**, **Burkhard MD**, **Kelly MJ**, **et al**. Robot-assisted lumbar pedicle screw placement based on 3D magnetic resonance imaging. *Glob Spine J*. 2024;21925682241232328.
15. **Wiltse LL**, **Spencer CW**. New uses and refinements of the paraspinal approach to the lumbar spine. *Spine (Phila Pa 1976)*. 1988;13(6):696–706.
16. **Schizas C**, **Theumann N**, **Burn A**, **et al**. Qualitative grading of severity of lumbar spinal stenosis based on the morphology of the dural sac on magnetic resonance images. *Spine (Phila Pa 1976)*. 2010;35(21):1919–1924.
17. **Sheetz KH**, **Claflin J**, **Dimick JB**. Trends in the adoption of robotic surgery for common surgical procedures. *JAMA Netw Open*. 2020; 3(1):e1918911.
18. **D'Souza M**, **Gendreau J**, **Feng A**, **Kim LH**, **Ho AL**, **Veeravagu A**. Robotic-assisted spine surgery: history, efficacy, cost, and future trends. *Robot Surg*. 2019;6:9–23.
19. **Maurer SG**, **Wright KE**, **Bendo JA**. Iatrogenic spondylolysis leading to contralateral pedicular stress fracture and unstable spondylolisthesis: a case report. *Spine (Phila Pa 1976)*. 2000;25(7):895–898.
20. **Yadhati A**, **Kurra S**, **Tallarico RA**, **Lavelle WF**. Lumbar vertebral body and pars fractures following laminectomy. *J Surg Case Rep*. 2017; 2017(2):rjx007.
21. **Weiner BK**, **Walker M**, **Wiley W**, **McCulloch JA**. The lateral buttress: an anatomic feature of the lumbar pars interarticularis. *Spine (Phila Pa 1976)*. 2002;27(17):E385–7.
22. **Burkhard MD**, **Calek A-K**, **Fasser M-R**, **et al**. Biomechanics after spinal decompression and posterior instrumentation. *Eur Spine J*. 2023;32(6): 1876–1886.
23. **Lee KK**, **Teo EC**. Effects of laminectomy and facetectomy on the stability of the lumbar motion segment. *Med Eng Phys*. 2004;26(3):183–192.


## Author information


**F. C. S. Altorfer**, MD, Research Fellow
**M. J. Kelly**, MD, Orthopaedic Surgeon
**F. Avrumova**, MS, Research Coordinator
**M. D. Burkhard**, MD, Orthopaedic Surgeon
**D. R. Lebl**, MD, Orthopaedic Surgeon, Associate Professor
Department of Spine Surgery, Hospital for Special Surgery, New York, New York, USA.

**D. B. Sneag**, MD, Radiologist
**J. L. Chazen**, MD, Radiologist
**E. T. Tan**, PhD, Physicist
Department of Radiology and Imaging, Hospital for Special Surgery, New York, New York, USA.


## Author contributions

F. C. S. Altorfer: Conceptualization, Investigation, Methodology, Writing – original draft.
M. J. Kelly: Conceptualization, Investigation, Methodology, Writing – original draft.
F. Avrumova: Investigation, Writing – review & editing.
M. D. Burkhard: Investigation, Writing – review & editing.
D. B. Sneag: Conceptualization, Investigation, Methodology.
J. L. Chazen: Conceptualization, Validation.
E. T. Tan: Conceptualization, Methodology, Visualization.
D. R. Lebl: Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – original draft.

## Funding statement


The authors disclose receipt of the following financial or material support for the research, authorship, and/or publication of this article: Rama and Shashi Marda Foundation.


## ICMJE COI statement

D. R. Lebl discloses being a consultant and on the advisory board for Choice Spine; being a consultant for Depuy Synthes; having an ownership interest in HS2, ISPH, and Vestia Ventures MiRus Investment; being a consultant and having ownership interest in Viseon; being a consultant and having royalties from Stryker; receiving royalties from Nuvasive; and getting research support form Medtronic Sofamor Danek USA, all of which is unrelated to this manuscript. D. B. Sneag declares research support from GE Healthcare, Siemens Healthcare, Medtronic, and AMAG Pharmaceuticals, which are unrelated to this work. J. L. Chazen reports being a consultant for Lexeo Therapeutics, which is also unrelated.

## Data sharing

The datasets generated and analyzed in the current study are not publicly available due to data protection regulations. Access to data is limited to the researchers who have obtained permission for data processing. Further inquiries can be made to the corresponding author.

## Ethical review statement

IRB# 2019-1402.

## Open access funding


The authors report the open access funding for this manuscript was self-funded.