Novel Merging of CT and MRI to Allow for Safe Navigation into Kambin's Triangle for Percutaneous Lumbar Interbody Fusion—Initial Case Series Investigating Safety and Efficacy

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Received, January 28, 2022.
Accepted, September 18, 2022.
Published Online, December 20, 2022.

BACKGROUND: For percutaneous lumbar fusion (percLIF), magnetic resonance imaging and computed tomography are critical to defining surgical corridors. Currently, these scans are performed separately, and surgeons then use fluoroscopy or neuromonitoring to guide instruments through Kambin's triangle. However, anatomic variations and intraoperative positional changes are possible, meaning that safely accessing Kambin's triangle remains a challenge because nerveroot visualization without endoscopes has not been thoroughly described.

OBJECTIVE: To overcome the known challenges of percLIF and reduce the likelihood of iatrogenic injuries by showing real-time locations of neural and bony anatomy.

METHODS: The authors demonstrate an intraoperative navigational platform that applies nerve root segmentation and image fusion to assist with percLIF. Five patients from a single institution were included.

RESULTS: Of the 5 patients, the mean age was 71 ± 8 years and 3 patients (60%) were female. One patient had general anesthesia while the remaining 4 patients underwent awake surgery with spinal anesthesia. The mean area for the L4-L5 Kambin's triangle was 76.1 ± 14.5 mm^2. A case example is shown where the side of approach was based on the fact that Kambin's triangle was larger on one side compared with the other. The mean operative time was 170 ± 17 minutes, the mean blood loss was 32 ± 16 mL, and the mean hospital length of stay was 19.6 ± 8.3 hours. No patients developed postoperative complications.

CONCLUSION: This case series demonstrates the successful and safe application of nerve segmentation using magnetic resonance imaging/computed tomography fusion to perform percLIF and provide positive patient outcomes.

KEY WORDS: CT/MRI merging, Kambin's triangle, Neurosurgery, Percutaneous fusion, Spinal anesthesia, Spine surgery

Operative Neurosurgery 24:331–340, 2023 https://doi.org/10.1227/ons.0000000000000531

A procedure that has gained popularity in the care of patients with degenerative spondylolisthesis or disk disease is percutaneous lumbar interbody fusion (percLIF) through Kambin's triangle.[1,2] Kambin's triangle is an anatomic window defined as the exiting nerve root (ENR), superior endplate of the caudal vertebral body, and superior articulating process that provides safe access to the lumbar disk.[3,4] Multiple studies have examined the triangle's dimensions but have come to varying conclusions.[5-7] Owing to this variation, minimally invasive surgeries may have higher frequencies of nerve root injuries compared with conventional open surgeries. ENR injuries, specifically, are the most common complication of transforaminal percutaneous endoscopic lumbar discectomy with rates up to 20% having been reported.[8]

ABBREVIATIONS: EMG, electromyography; **ENR,** exiting nerve root; **LOS,** length of stay; **percLIF,** percutaneous lumbar interbody fusion; **SVA,** sagittal vertical axis; **TLIF,** transforaminal lumbar interbody fusion.

Although interbody fusion through Kambin's triangle is well-described, previous methods have

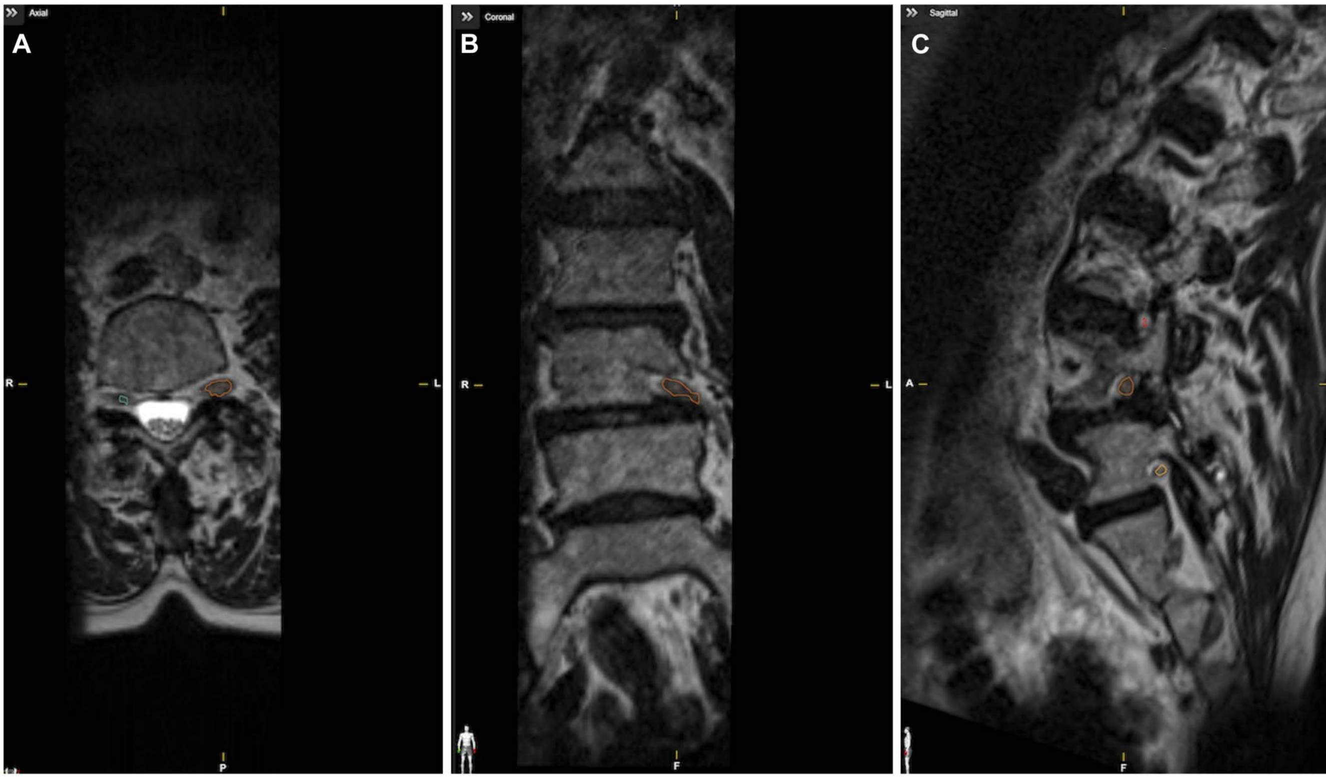

FIGURE 1. *Preoperative segmentation of the L3, L4, and L5 nerve roots for patient 2 using Brainlab software.* **A**, *The axial,* **B**, *coronal, and* **C**, *sagittal are all shown. The orange outline is the left L4 nerve being traced with the Smartbrush feature which uses a region growing algorithm.*

relied heavily on fluoroscopy and nerve stimulation. There are no current strategies to plan a trajectory into the disk with knowledge of where the important neural structures are preoperatively. In these cases of percLIF, the authors attempt to address these shortcomings with a technology capable of merging preoperative magnetic resonance imaging (MRI) with intraoperative computed tomography (CT) to help identify the safest trajectory into the disk space.

METHODS

The authors performed a single-center, retrospective review of patients undergoing percLIF or transforaminal lumbar interbody fusion at a major academic research institution. From August 2021 to April 2022, patients were included according to the established indications for percLIF in the literature. Patients with severe central canal and foraminal stenosis were excluded.

Informed consent was obtained before every procedure. Institutional Review Board (IRB) approval was approved by our ethics committee. Patient permission to publish deidentified data was not necessary because this case series fell under the university's IRB's guidelines for "exempt" patient research. All patient identifiers were removed from case examples and imaging.

Neuromonitoring

Intraoperatively, free running electromyography (EMG) was monitored with electrodes placed in selected muscles of the lower extremities bilaterally. A baseline EMG reading was performed to ensure a quiet background. Throughout each case, triggered EMG (tEMG) was also monitored. Periodically, the surgeon stimulated within the surgical site, and EMG was monitored as well. When a response was noted, the surgeon was informed of the stimulation intensity required to elicit the response.

Nerve Segmentation

Using T2-Space MRI sequences, individual nerves were identified first in the coronal plane and then sagittal with the Brainlab Smartbrush (Brainlab) completing segmentation based on a region-growing algorithm (Figure 1). The Smartbrush feature allows for precise outlining of the nerve with variable brush sizes to account for minor deviations. A neuroradiologist confirmed each segmentation.

Kambin's Triangle Measurements

After nerve segmentation, the *Align* feature in Brainlab was used to orient the image in the direction that the dilator would most likely be entering the disk space (Figure 2). Switching over to Smartbrush, Kambin's triangle was located using the anatomic boundaries described above. Because the ENR had already been segmented, it helped ensure

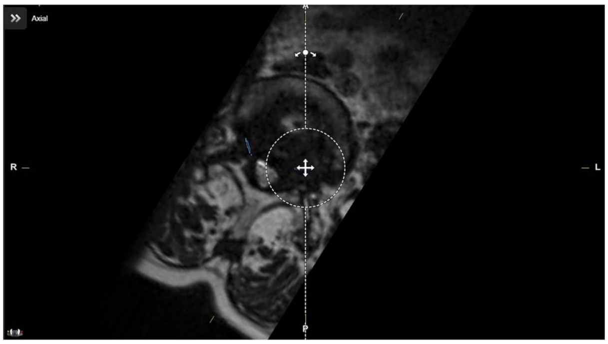

FIGURE 2. *Brainlab's "Align" feature used preoperatively to help visualize the trajectory into Kambin's triangle.*

that we were not overlapping Kambin's triangle with any of the ENR. To measure area, we used approximation of the largest triangle that contained every part of the outlined space. Brainlab generated a 3-dimensional (3D) representation of the structures to visualize spatial proximity (Figure 3).

Pedicle Screw Placement

Pedicle screws (J&J/DePuy Spine) were placed bilaterally at the proper levels using instrument tracking previously described by our group.[9,10] An intraoperative CT (AIRO) was performed to confirm accurate positioning. This CT was merged with preoperative MRI using Brainlab Spine Curvature Correction. Although the patient was supine for the preoperative MRI scan and prone for the intraoperative CT, this software is capable of overlapping the images despite changes in flexion.[11-13] For accuracy, the software has been shown to provide elastic fusion of preoperative MRI and intraoperative CT image data with a median error below 1.34 mm.[12] Safe trajectories entering the disk space at the mid-pedicle point on coronal imaging were then planned (Figure 4).

Interbody Cage Placement and Fusion

An incision 6 cm lateral of the midline was made. A stimulating dilator (Spineology) was then used to pierce through the fascia and into the annulus of the desired disk using the preplanned trajectory above (Figure 5 and 6, Video). Compound muscle action potentials (CMAP) were recorded in bilateral lower extremities. As long as no potentials were recorded during activation of a threshold of 4 mA, it was felt that a "safe" trajectory was used. Further dilation was performed until an 8-mm portal was placed. Discectomy was then performed using a combination of drills, brushes, and curettes. The ELITE expandable titanium cage (Spineology)

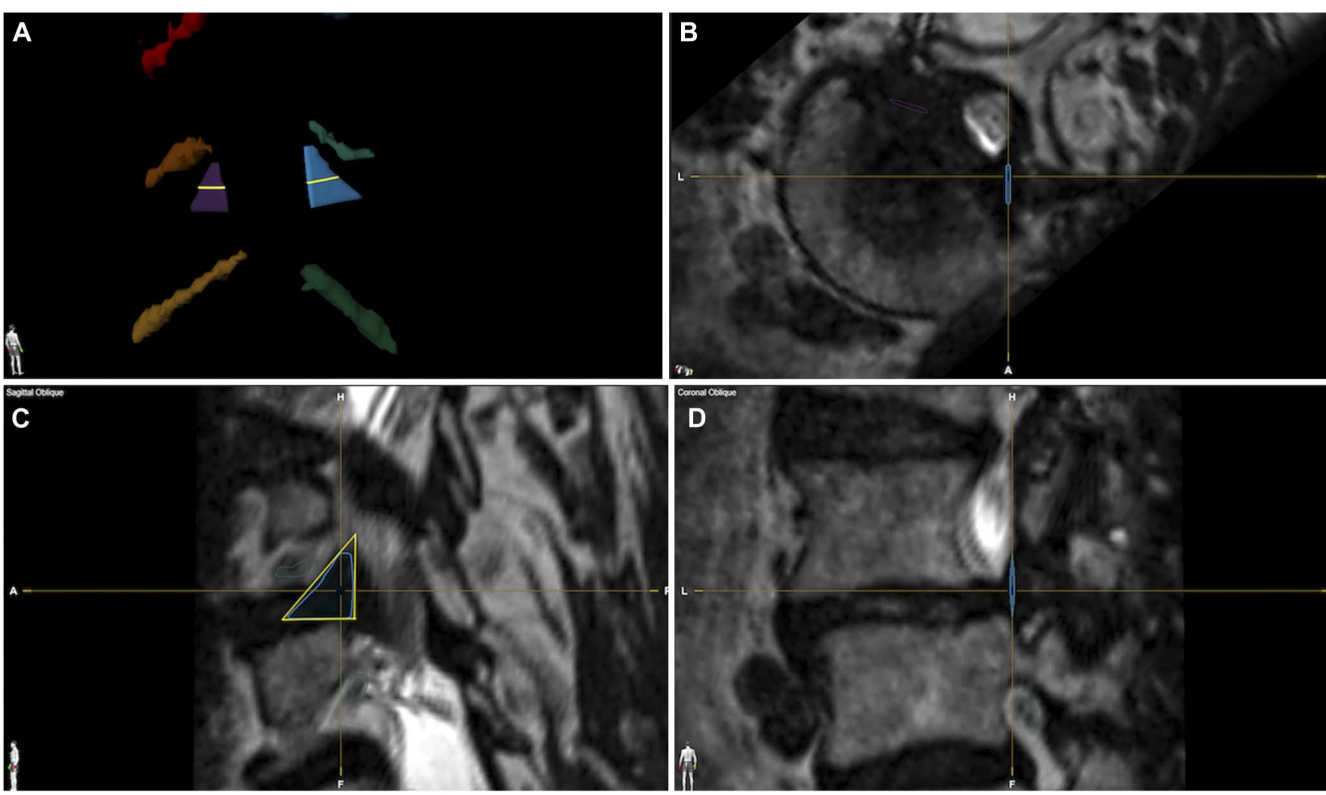

FIGURE 3. A, *3D representation of patient 2's segmented nerves and outlined Kambin's triangle at the L4-L5 level.* B, *The axial view is shown with the blue area representing the triangle.* C, *Triangle approximation was done to determine the area.* D, *The coronal oblique view is also shown.*

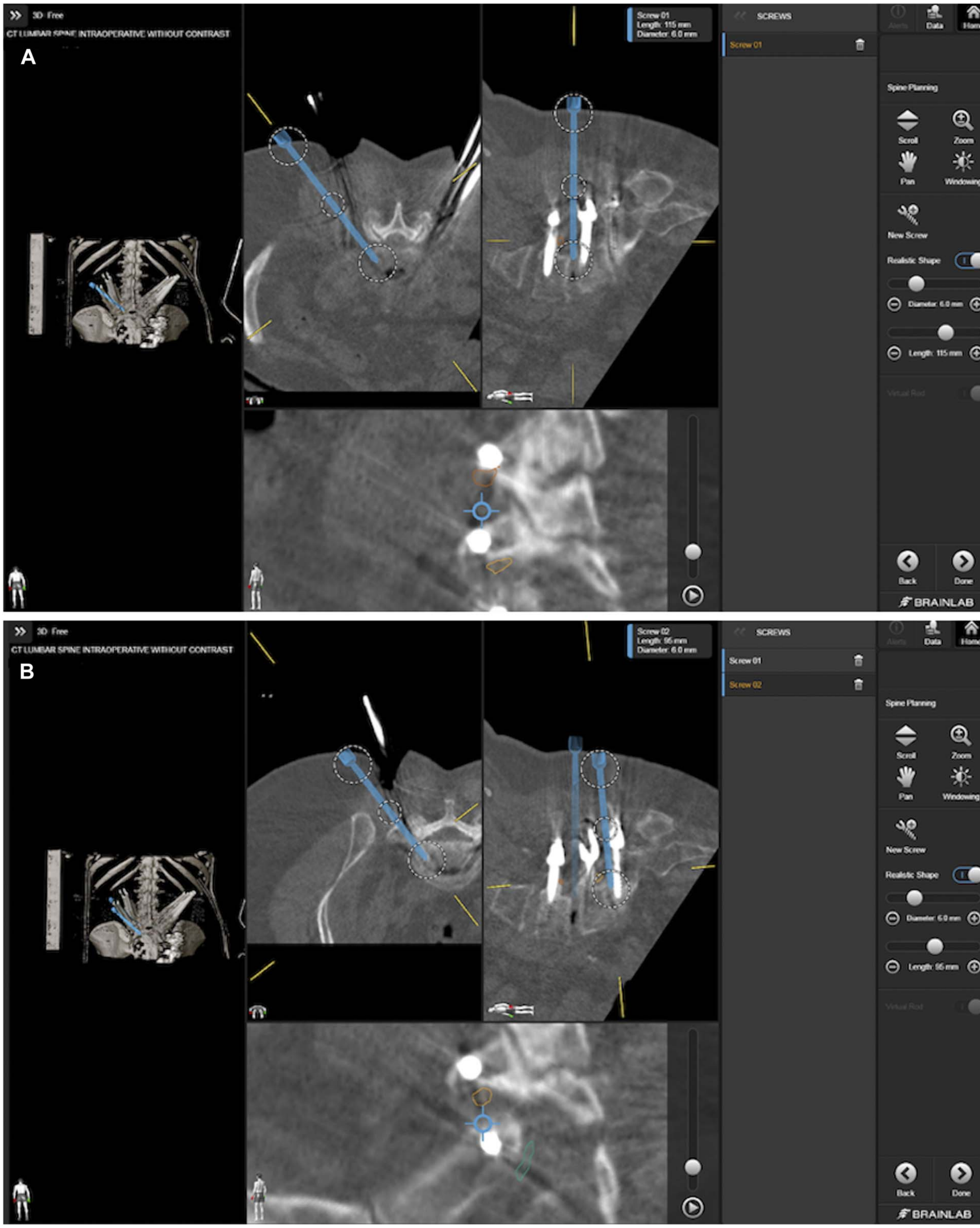

FIGURE 4. *Intraoperative planned trajectories into* **A**, *L4-L5 and* **B**, *L5-S1 disk spaces using Brainlab tracking software for patient 1.*

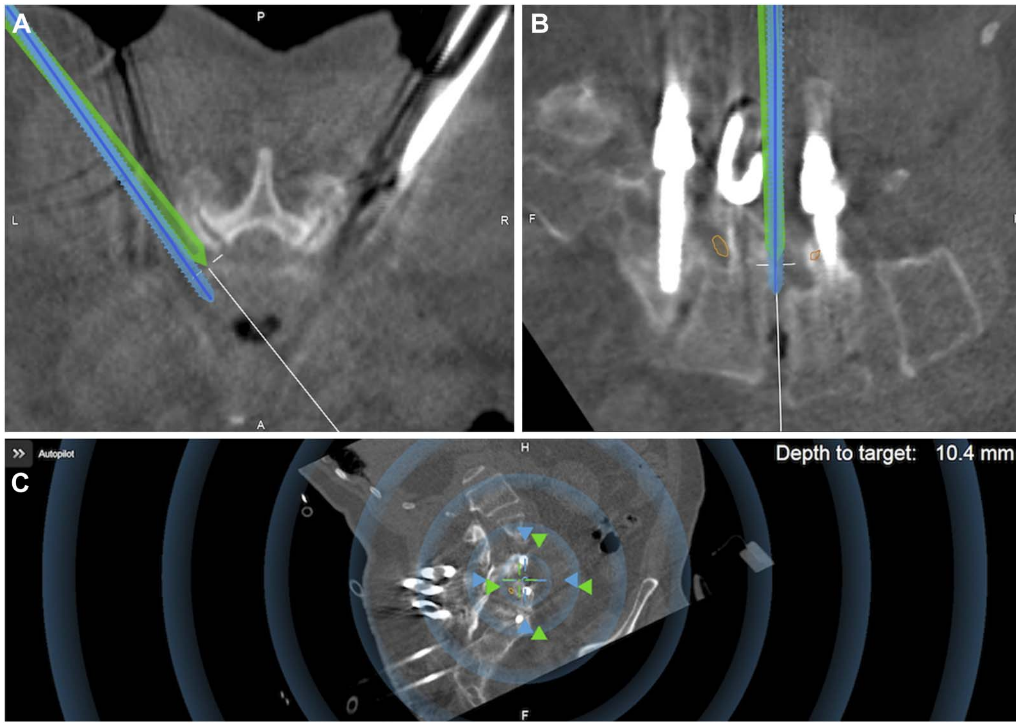

FIGURE 5. *Intraoperative trajectory with image tracking overlaid with the preoperatively planned trajectory into the L4-L5 disk space for patient 1.* **A**, *The axial and* **B**, *sagittal views are both shown.* **C**, *The depth to the target feature is also shown.*

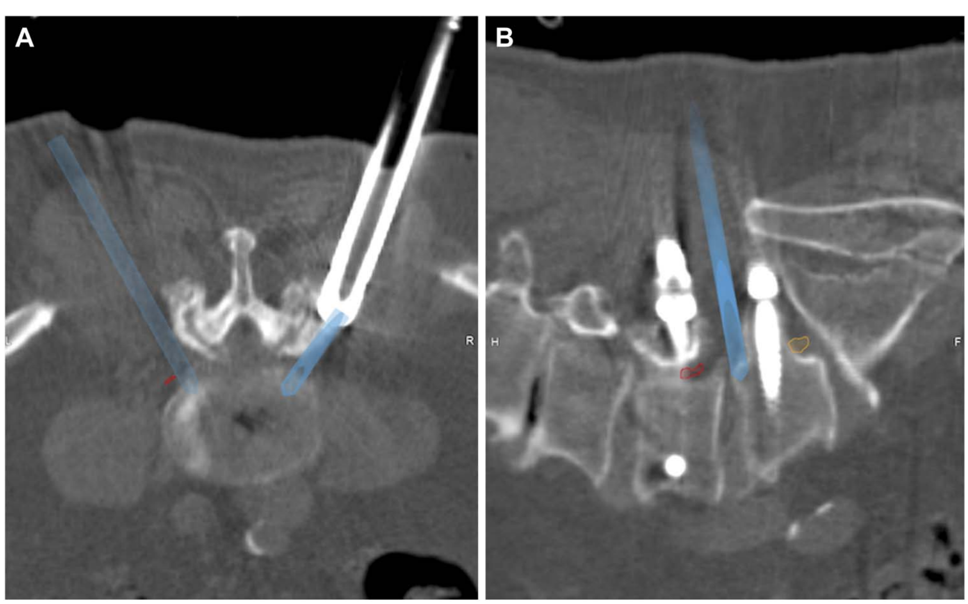

FIGURE 6. *Preoperative trajectory showing alignment with the dilator into the L4-L5 disk space for patient 5.* **A**, *The axial and* **B**, *sagittal views are both shown.*

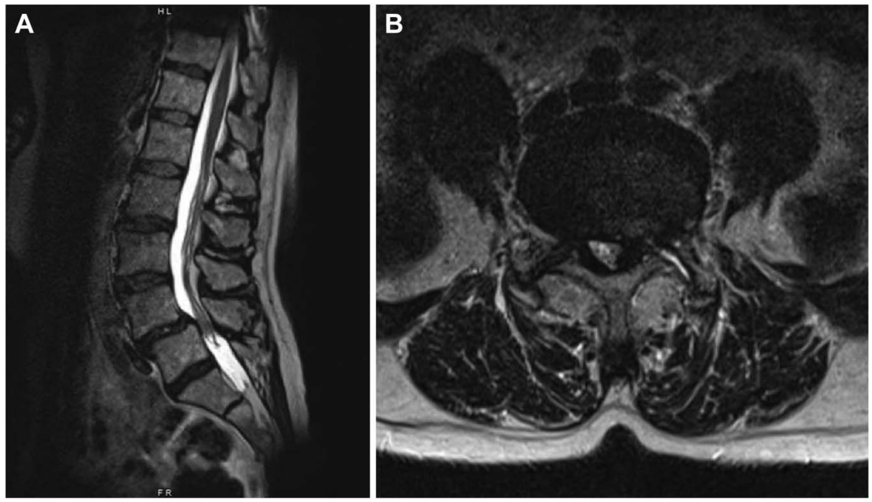

FIGURE 7. A, *Preoperative lumbar sagittal T2 MRI and* B, *axial T2 MRI through L4-L5 showing left-sided nerve compression for patient 2.*

was hammered into the space and expanded. Bilateral rods connected the screws for fusion.

Case Presentation (Patient 2)

Preoperative Course

A 68-year-old woman with degenerative disk disease and arthritis presented with bilateral lower extremity radicular pain for 4 months. Imaging demonstrated degenerative disk disease with disk desiccation and foraminal stenosis at the level of L4/L5 (Figure 7). After failing conservative measures, the patient was scheduled for surgery.

Operative Details

The anesthesia team proceeded with their general anesthesia protocol and a L4 erector spinae plane block. This was performed under ultrasound with 1.3% liposomal bupivacaine.

The patient then received a percLIF as described above. The L4 and L5 screws were placed, and all screws were stimulated to above 20 mA. The CT was merged with preoperative MRI as described above, and safe trajectories were planned into the L4/L5 disk space.

This patient's right Kambin's triangle was significantly larger than the left, measuring at 105.5 mm^2 compared with 86.36 mm^2. Therefore, a stab incision 6 cm right of midline was made. The Spineology Dilator was used to enter Kambin's triangle at L4/L5. Safe entry into the disk space was confirmed with fluoroscopy imaging. Discectomy and expandable cage placement were performed as described above. EMG was quiet throughout.

Postoperative Course

The postoperative course was uneventful, and she was full strength on examination. Owing to some dizziness, the patient stayed overnight until physical therapy cleared her for discharge on postoperative day 1. At her 8-week follow-up, her preoperative symptoms have abated. Standing films show intact instrumentation (Figure 8).

RESULTS

Five patients who underwent lumbar fusion using the MRI/CT fusion technique at Duke University Hospital were reviewed. The mean age was 71 ± 8 years, with a median body mass index of 26.9; 3 patients (60%) were female (Table 1). All patients successfully underwent their procedures without complications or the need to covert to open surgery. One patient had general anesthesia while the remaining 4 patients underwent awake surgery with spinal anesthesia. The mean operative time was 170 ± 17 minutes with a mean estimated blood loss of 32 ± 16 mL. The median hospital length of stay was 19.6 ± 8.3 hours (Table 1). The mean area for the L4-L5 Kambin's triangle was 76.1 ± 14.5 mm^2 (Table 2). No patients developed postoperative complications, weakness, or reported nerve injuries. Only 2 patients reported intermittent dysesthesias, mainly numbness of the knee postoperatively, which have both resolved. Baseline spinopelvic parameters were compared with their respective postoperative values using full-length standing x-rays (Figure 9). The average changes were as follows: lumbar lordosis (LL) −0.4°, sagittal vertical axis +0.742 cm, pelvic incidence (PI) −2°, and sacral slope −2°. Owing to the recency of these surgeries, only patient 1 has had a 6-month follow-up. For patient reported outcomes, their Oswestry Disability Index decreased from 70 (crippled) to 32 (moderate disability); back and leg pain both decreased from 10 and 7 to 5 and 3, respectively; and their Patient-Reported Outcome Measurement Information System (PROMIS) physical function score increased from 29 (severe dysfunction) to 31 (moderate dysfunction).

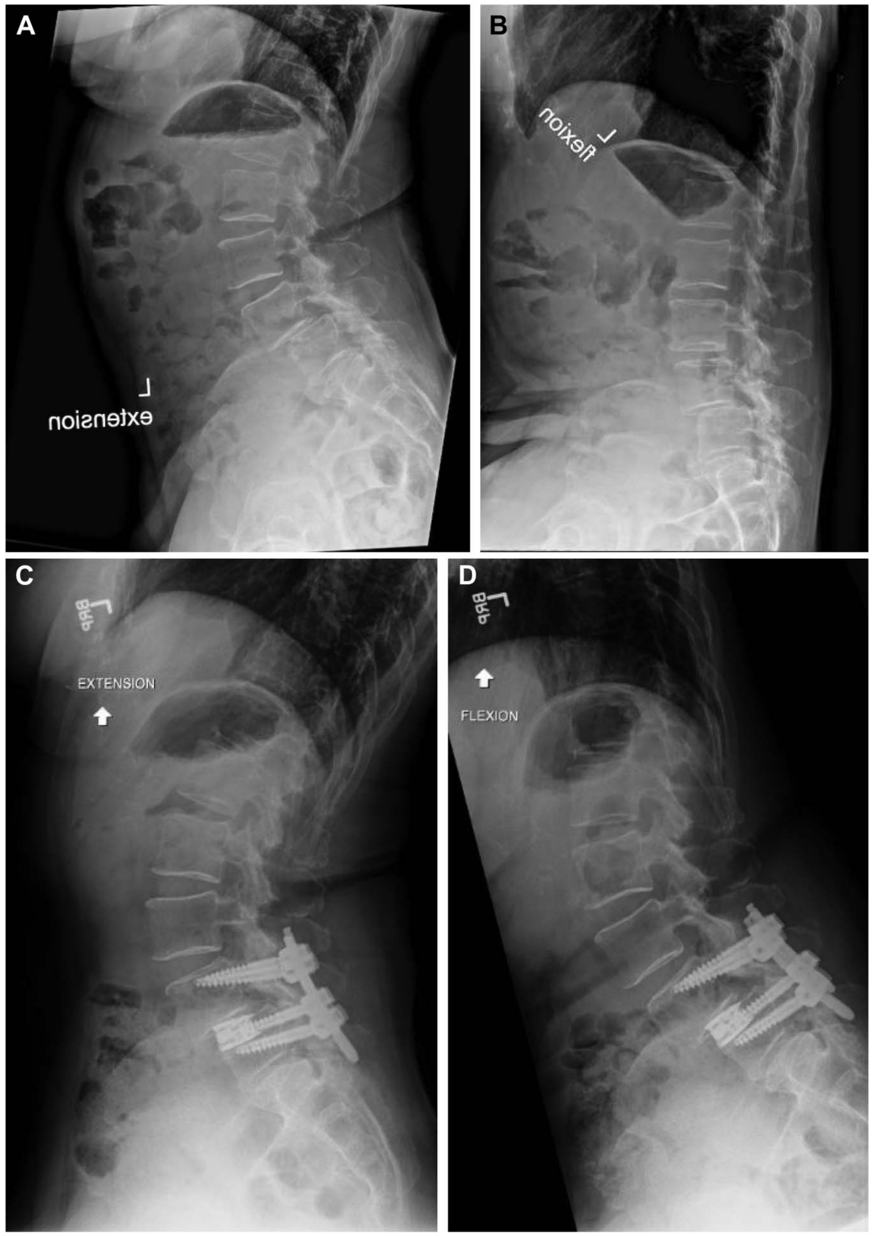

FIGURE 8. *Comparative radiographs for patient 2. Preoperative lumbar x-rays of both extension/flexion* **A** *and* **B**, *showing mobile spondylolisthesis at the L4-5. Postoperative extension/flexion x-rays* **C** *and* **D**, *showing good instrumentation, no acute fractures, and accurate placement of hardware.*

DISCUSSION

In most transforaminal surgeries, an endoscopic cannula is placed between the dural canal and the ENR lateral to the superior articular process. Therefore, the slightest of errors can damage the neurovascular structures.[14,15] As discussed by Morgenstern and Morgenstern, a 32% postoperative complication rate consisting of ipsilateral dysesthesias and transitory muscle weakness was noted after trans-Kambin's PLIF.[16] In addition, foot drop injuries have been noted in the literature, especially for anterior lumbar fusions caused by irritation of the L5 ENR.[15] Unlike the presented work, these studies all mention that the "working safe zone" (Kambin's triangle) was not visualized preoperatively.

TABLE 1. Patient and Operative Characteristics

Case	Age	Sex	BMI	Procedure	EBL (mL)	Operative time (min)	Length of Stay (h)	Follow-up (mo)
Patient 1	76	Female	31.6	Awake L4-S1 percLIF	50	180	12	6
Patient 2	68	Female	21.6	General anesthesia L4-L5 percLIF	10	183	24	2
Patient 3	61	Male	29.6	Awake L3-L4 percLIF	25	160	14	2
Patient 4	67	Female	23.5	Awake L4-L5 percLIF	50	140	14	1
Patient 5	85	Male	27.7	Awake L4-L5 TLIF	25	184	34	N/A
Mean, SD	71.4, 8.3	–	26.9, 3.73	–	32, 15.7	169.4, 17.1	19.6, 8.3	2.75, 2.22

BMI, body mass index; EBL, estimated blood loss; percLIF, percutaneous lumbar fusion.

In addition, the presence of conjoined nerve roots, facet hypertrophy, and degenerative changes to the anatomy can all affect a patient's unique spinal landscape. Haijiao et al found a 17% incidence of nerve root anomalies out of 376 lumbar MRI scans, whereas previous studies relied mainly on CT scans which only caught 2% of the conjoined roots.[17] With MRI being the imaging modality of choice for ligaments, disks, and neurovascular abnormalities, the combination with the more osseous sensitive CT further enhances preoperative planning.[18-20] Of note, some groups who have also used the image fusion technique report instances in which ligaments can be depicted as slightly thicker on CT vs MRI. In our institutional experience, this issue has not arisen during preoperative planning; however, there could be multiple explanations for this discrepancy. First, each image fusion technology operates under different software mechanics. In our cases, Brainlab Spine Curvature Correction software was implemented, which automatically calculates rigid fusions for each vertebra and interpolates a 3D deformation field to simultaneously matches all vertebrae once the images are combined.[12] Other softwares may operate under different principles leading to slight but important variations in the dimensions of ligaments or other soft tissue structures. Second, there are reports that CT systems have limited spatial resolution when measuring the density or thickness of thin structures, including the vertebral cortical shell.[21] For this reason, it is crucial that further studies are performed to accurately assess the dimensional accuracy of each image fusion technologies to elucidate any differences. If there are proven changes in soft tissue dimensions after MRI/CT fusion, this would be crucial information for surgeons to have while planning their intraoperative approach into Kambin's triangle.

We recently published a case series illustrating the use of intraoperative CT in combination with the ExcelsiusGPS (Globus) robot to enter Kambin's triangle.[22] However, in that series, there was no attempt to segment out the ENR. In this series, we not only segmented the ENR but also outlined Kambin's triangle bilaterally. For patient 2, there was a 19.14 mm^2 discrepancy between sides, so the dilator entered from the patient's right side which provided a greater 'safe zone.' In future studies, it would be beneficial to measure the area of Kambin's triangle bilaterally before any percLIF.

Of note, Abbasi et al described the oblique lateral interbody fusion, which uses Kambin's triangle as the entry into the disk space. The approach is very similar to the one described here in the sense that it approaches the disk from the same oblique angle, uses dilators, spares musculature, and does not require facet removal.[23] The main differences are the addition of live instrument tracking, the novel CT/MRI image fusion technology, and preoperative visualization of Kambin's triangle.

Recently, studies have started looking at the fusion of CT and MRI.[24,25] A new study built an AI-programmed software that could automatically, rather than manually, create 3D images by extracting data from MRI and merging them with CT.[13] With these new technological breakthroughs comes a potential concern: the change in expenses compared with conventional minimally invasive spine surgeries. Although exact charges depend on many factors, the only additional cost would be the new software. However, reduced hospital LOS could play a crucial role in counteracting this increase. Other studies have reported that the mean LOS for minimally invasive spine surgery without nerve segmentation can range from 2.46 to 4.10 days.[26,27] The

TABLE 2. Kambin's Triangle Areas

Case	L3-L4 area (mm^2)	L4-L5 area (mm^2)	L5-S1 area (mm^2)
Patient 1	–	Left: 70.88/Right 69.3	Left: 75.65/Right: 81.42
Patient 2	–	Left: 86.36/Right: 105.5	–
Patient 3	Left: 89.6/Right: 101.3	–	–
Patient 4	–	Left: 76.44/Right: 67.1	–
Patient 5	–	Left: 67.2/Right: 76.0	–
Mean, SD	95.5, 8.3	76.1, 14.6	78.5, 4.1

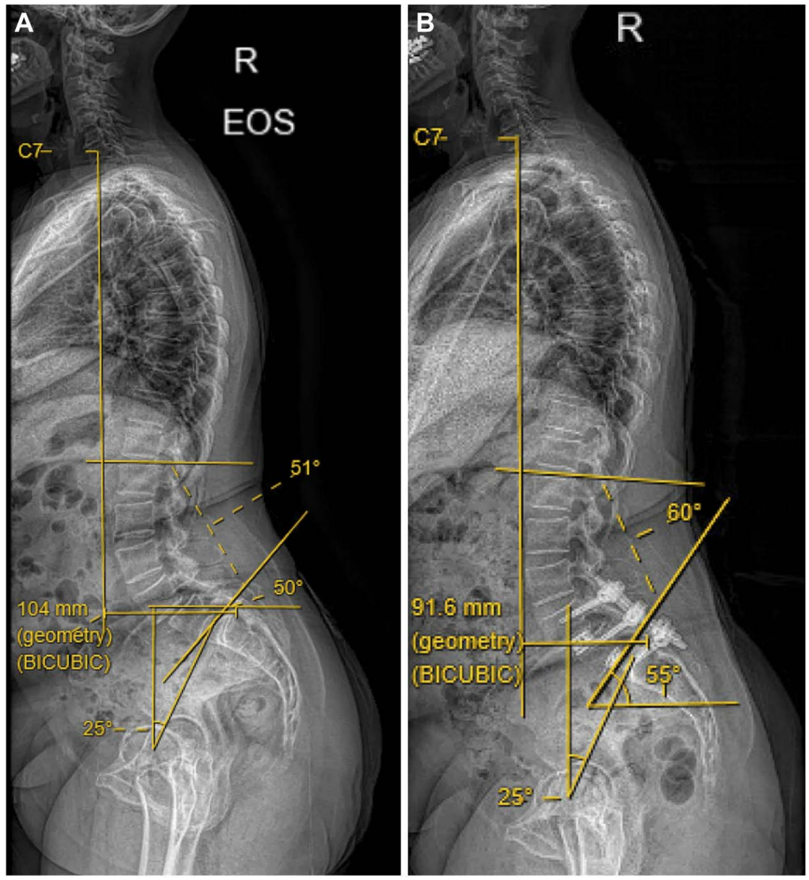

FIGURE 9. A, *Preoperative and* B, *4-month postoperative standing x-rays with respective spinopelvic parameters labeled for patient 1. The same analysis was repeated for each patient.*

average LOS for our cohort was 0.82 days. Furthermore, work is needed to accurately assess the economic impact of these techniques.

Limitations

Consistent with small case series, surgeons should be cautious to make large-scale generalizations regarding our results. While our patients did not have complications, it is important to recognize the ever-present risk of ENR injury. Second, because triangle approximation was used, the dimensions noted for these patients are only comparable with studies that also used triangle approximation. Finally, because this was a single-surgeon study, there may be differences in methodology or patient selection within the inclusion/exclusion criteria that may have affected clinical outcomes.

CONCLUSION

In these 5 cases, we successfully used commercially available software to preoperatively visualize Kambin's triangle, nerve roots, and trajectories to minimize risk for nerve damage and successfully perform percLIF. Although this is a small group of patients, the gradual adoption of these methods will lead to larger cohort studies that can reveal the long-term benefits of these techniques.

Funding

This study did not receive any funding or financial support.

Disclosures

Dr Abd-El-Barr is a consultant for Spineology and has a financial relationship with DePuy Synthes. The other authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article. Dr Wang has received grant funding from *AlphaTec*. Dr Shaffrey has financial relationships with NuVasive, Medtronic, SI Bone, and Proprio.

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VIDEO. Intraoperative trajectory into the left Kambin's triangle at the L4-L5 level for patient 5.

COMMENT

I congratulate the authors on this manuscript. There are several limitations of both MRI and CT and very few surgeons have attempted to merge them to gain a superior spine navigation profile. It is state of the art in cranial surgery for several years now. The ligament-bone-neural interface can appear to be different between the 2 imaging. A high tesla MRI, thin-cut CT, and an advanced computing system can enable the merger of the 2 images as shown in this manuscript. This is however a process in evolution. On the other hand, Kambin's triangle itself is not just a 2-dimensional structure but a 3-dimensional corridor. This paper will provide a stepping stone to map out this corridor with submillimeter accuracy. This can enable both robotic trajectory planning and artificial intelligence algorithms to track both structural improvement and recovery processes.

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