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Anterior to Dorsal Root Entry Zone Myelotomy (ADREZotomy): A New Surgical Approach for the Treatment of Ventrolateral Deep Intramedullary Spinal Cord Cavernous Malformations

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Abstract

Study Design.A retrospective review of prospectively collected data.

Objective. To confirm the feasibility of using anterior to dorsal root entry zone myelotomy (ADREZotomy), a new surgical approach, for the treatment of ventrolateral deep ISCCMs.

Summary of Background Data. Surgical removal of ventrolateral deep intramedullary spinal cord cavernous malformations (ISCCMs) is highly risky and remains problematic.

Methods. The authors performed a retrospective study exploring the surgical removal of ventrolateral intrinsic ISCCMs using ADREZotomy in 10 patients. The Frankel grading system was used to evaluate the patients' neurological function at the preoperative, postoperative and follow-up stages. American Spinal Injury Association (ASIA) Scale scores at the preoperative and postoperative were also obtained. The patient characteristics and surgical outcomes were analyzed. The indication, operative steps, complications, and anatomical basis of the myelotomies were described and discussed.

Results. In total, 9(90%) patients presented with mild symptoms prior to surgery. Gross total resections were performed in all 10 patients. Immediately after surgery, the neurological function of 8(80.0%) patients remained the same. 1 patient improvedand 1 (10%) patient worsened. There were no other immediate or delayed complications related to the surgical procedure.No decrease of total ASIA sensory scores was observed. The follow-up neurological function evaluation showed that 2 (20%) patientsimproved from a Frankel grade of D to E and 8 (80.0%) patients were stable. No recurrences or other additional neurological deterioration was observed.

Conclusion. Surgical removal of ventrolateral deep ISCCMs can be feasible using proper surgical techniques. ADREZotomy is a minimally invasive technique for the removal of cervical and thoracic ventrolateral deep ISCCMs,without disrupting the important spinal cord tracts or the need to broadly expose bone.

Key words:cavernous malformations, dorsal root entry zone, intramedullary tumor, myelotomy, outcome, resection,surgical approach, spinal cord, surgical technique, vascular malformations

Level of Evidence:4

INTRODUCTION

Intramedullary spinal cord cavernous malformations (ISCCMs) constitute 5% to 12% of all spinal vascular diseases.[1] ISCCMs can be clinically apparent with an acute or progressive onset of neurological deficits due to the formation of a space-occupying lesion by an acute macrohemorrhage or repetitive intralesional microhemorrhages.[2] The reportedannual hemorrhagic risk of symptomatic ISCCMs is 1.4% to 6.8%.[3-8] Compared with their intracranial counterparts, ISCCMs are more aggressive because of the low tolerance for space-occupying lesions in the spinal cavity.[9]Our experience with symptomatic ISCCMs has been reported separated.[10]

Surgical resection of the lesions remains the only treatment method for most symptomatic ISCCMs.[8,10]But for ventrolateral deep ISCCMs that do not reach the surface of the spinal cord, surgical removal through traditional myelotomy approaches is still highly risky and remains problematic.[8,10,11]A traditional posterior midline myelotomy or a dorsal root entry zone myelotomy (DREZotomy) (equivalent to the posterolateral sulcus (PLS) approach) would require a deep myelotomy with traction of the spinal cord, which is associated with an increased risk of worsening the patient's neurological condition.[10]Lateral myelotomybetween the ventral and dorsal nerve roots on the ventral side of the dentate ligamentneeds more liberal lateral bony removal with the spinal cord rotated to optimize exposure, which also poses both technical challenges and surgical risks.[11]

We report a new myelotomy approach involving an anterior to dorsal root entry zone myelotomy (ADREZotomy) for ventrolateral and deep ISCCMs. The ADREZotomy is anterior and adjacent to the posterolateral tract of Lissauer and the dorsal root entry zone. This surgical corridor can provide satisfactory exposure for ventrolateral and deeply located lesions without disrupting the important spinal cord tracts or the need to rotate the spinal cord or broadly expose bone. The blood supply in this region is also preserved. We report our experience using this approach in 10 cases of ventrolateral ISCCMs, describe the anatomical basis, operative steps and outcomes of our cases, and analyze the efficacy and safety of this new approach.

METHODS

We retrospectively analyzed 10 consecutive patients who were selected from combined prospectively maintained spinal vascular disease databases between July 2010 and March 2017. Our institution is a referral medical center for the treatment of spinal vascular lesions. All 10 patients had ventrolateral and deep ISCCMs. The patients' clinical characteristics, magnetic resonance imaging (MRI) results, and follow-up outcomes were analyzed. This study was approved by the local ethics board of our institutions and was performed in accordance with the ethical standards of the 1964 Declaration of Helsinki. Consent was obtained from each patient enrolled in this study.

Patients

The 10 patients in this series include 5 males and 5 females, ranging in age from 22 years to 63 years (mean, 39.9 years). The locations of their ISCCMs were as follows: 8 cervical and 2 thoracic. The neurological symptoms included sensory disorders, motor disabilities, or disturbances in bladder or bowel control. The duration of the symptoms was defined as the time from the onset of the symptoms to surgery. The clinical characteristics of the patients are summarized in Table 1.

We used the Frankel grading system (Table 2) to evaluate the neurological function of the patients at the preoperative, postoperative, and follow-up stages. A favorable outcome at follow-up was defined as a Frankel grade of D or E. Improvement or worsening was defined as a change by at least one grade on the scale.American Spinal Injury Association (ASIA) Scale scores at the preoperative and postoperative were also obtained from each patient, including light touch sensory score, pinprick sensory score, and motor score.

All 10 patients underwent spinal MRIs before surgery, and the diagnosis, segment and location were confirmed according to the T1 MRI sequence to provide guidance for surgery. Although preoperative MR imaging is not ideal for determining whether lesions reach the pial surface, T1-weighted imaging is relatively more reliable than T2-weighted imaging. Consensus diagnoses and operations were performed by the 2 senior authors. After surgery, all 10 patients underwent at least one spinal MRI for a reexamination.

Surgical Technique

In all surgical procedures, the patients were placed in the prone position. For cervical lesions, the head was fixated with a three-point Mayfield head holder (Codman, Inc., Raynham, MA). Laminectomy or laminoplasty was performed. Unilateral hemilaminectomy was performed on selected patients.Intraoperative neurophysiological monitoring (IONM), including somatosensory evoked potential (SEP) and trans-cranial motor-evoked potential (tcMEP),was used during the surgical procedure. After the bone removal, the dura was opened off the midline toward the side of the lesion longitudinally with a traction suture using 4–0 polypropylene sutures tied bilaterally to the paraspinal muscles. The arachnoid membrane was incised and immobilized by silver clips. Intraoperative ultrasound imaging was used to locate the lesion. After careful visual inspection of the spinal cord and the lesion or discoloration is not visible, amyelotomy anterior and adjacent to the posterolateral tract of Lissauerand the dorsal root entry zone (ADREZotomy) was used. A 1-ml syringe needle was used to dissect the pia mater longitudinally, and the length covered the entire lesion to allow complete removal. Traction sutures (8–0 monofilament nylon sutures) were placed into the bilateral anterior and posterior pia mater to expose the lesions. The rostral or caudal extension of the myelotomy was performed by gently splaying the tissue.Small branches of the posterior pial vein may have been sacrificed to obtain sufficient exposure. The spinal cord was, thus, entered between the dorsolateral tract and the dorsal spinocerebellar tracts, anterior to the lateral fasciculus proprius of the spinal cord and posterior to the lateral corticospinal tract. The lesions were removed piecemeal but completely, and the surrounding hemosiderin-stained tissue were not resected. If associated venous malformations were observed, they were preserved(Figures1A-1F).

Follow-Up Data

All 10 patients underwent clinical follow-up and a spinal MR imaging follow-up. Follow-updata was obtained from office visits or telephone interviews. The follow-up period in this series ranged from 3 months to 6.8 years (mean, 1.4 years). The outcome data included the patient's current neurological status data, which were compared with the results of their preoperative and immediate postoperative neurological function data(Table 3).

RESULTS

In total, 9 (90%) patients presented with mild symptoms prior to surgery.ADREZotomy was chosen as the myelotomy technique for all 10 patients to treat their ventrolateral deep lesions. Gross total resections were performed in all 10 patients. The characteristics of intraoperative neurophysiological monitoring changes and detailed neurologicalfunction pre- and postoperatively are listed in Table 4.

Immediately after surgery, the neurological function of 8(80.0%) patients remained the same. One patient improved from a Frankel grade of D to E,and 1 (10%) patient worsened from a Frankel grade E to D, presenting a grade 4/5 in motor strength in the right extremities. After surgery, no decrease of total ASIA sensory scores was observed in comparison to the preoperative score. There were no other immediate or delayed complications related to the surgical procedure.The follow-up period in this series ranged from 3 months to 6.8 years (mean, 1.44 years). Compared with the preoperative evaluation, 2 (20%) patients improved from a Frankel grade D to E,and 8 (80.0%) patients were stable. No obvious deterioration was observed. Of these 10 patients, the outcomes of 9 (90.0%) patients were favorable as follows: The Frankel grade in 7 (70.0%) patientswasE, and 2 (20.0%) patients had a Frankel grade of D. One patient exhibited severe symptoms and signs, which were the same as those observed at the preoperative time point(Table 5).No additional signs of neurological deterioration, such as bowel/bladder dysfunction, were observed.

Among the 9 favorably recovered patients, local pain or subjective sensory abnormalities were present in 8 (88.9%) patients.

After surgery, all 10 patients underwent at least one spinal MRI for reexamination. These MRIs showed no recurrences.

Illustrative Case

Case 5

A 30-year-old woman presented with a sudden onset of pain and numbness in the neck and right shoulder. A spinal MRI indicated ventrolateral cervical ISCCMs located at the C2-C3 vertebral level. A neurological examination revealed normal motor strength in the bilateral extremities and hypesthesia for pain, temperature, and touch at the C3-C5 metamere. The

Frankel grade was E (normal motor control). The patient underwent a C2-C3 laminoplasty. The lesion was not visualized clearly on inspection of the spinal cord. Slightly yellowish abnormal surface was noticed at the right lateral column. A myelotomy was performed through the abnormal surfacefirstly, ventral to the site of ADREZotomy and dorsal to the dentate ligament. After the myelotomy, the tcMEP of the right extremities disappeared. The procedure was stopped but the tcMEP data didn't recover. Instead, ADREZotomy was used and gross total resection was performed. The SEP data was stable throughout surgery.Immediately after surgery, the neurological examination revealed a grade 4/5 motor strength in the right extremities. The Frankel grade was D (useful motor control). Total ASIA motor score decreased from 100 to 90. No decrease of total ASIA sensory scores or additional neurological deterioration was observed in comparison to the preoperative score.The early postoperative MR imaging showed no residual lesions. The patient recovered normal motor function at about 50 days later after surgery. At the time of the final follow-up, which occurred 6 months after surgery, the Frankel grade was E (normal motor control), but the subjective sensory numbness at C3-5 remained.Repeat MR imaging showed no residual lesions.

Discussion

Treatment Strategies for Ventrolateral Deep ISCCMs

The locations of the ISCCMs in the horizontal plane are defined as anterior, central, posterior, or lateral compared with the midline and dentatus ligament planes.[12] According to previous studies, ventral or deep lesions are associated with poorer functional results.[8,10,12,13] By analyzing the outcomes of 58 surgically treated patients,Liang concluded that deep lesions had significantly worse outcomes compared with superficially locatedlesionsat follow-up.[8] Considering the high surgical risk associated with deep and ventral lesions, some surgeons chose rigorous follow-up or conservative management instead of surgery.[8,10]Some surgeons have concluded that deep lesions should be resected only when the patient has progressive, recurrent, or significant initial symptoms. Asymptomatic, transient or minimally symptomatic patients with deep lesions should be observed carefully.[13,14]But in young patients with minor symptomatic lesions, as ISCCMs tend to worsen clinically and present a high lifelong accumulative

hemorrhagic risk, preventive removal of ISCCMs might be more beneficial than surgery after bleeding occurs.[13] Meanwhile, a recent systematic review of ISCCMs concluded that the rates of neurological improvement after surgery were no higher in patients with superficial lesions than in those with deep or ventral lesions.[5] In our series, of the 10 cases with ventrolateral and deep lesions, 9 patients with mild symptoms (Frankel grades D or E) underwent resection using ADREZotomy. All these 9 patients had favorable outcomes.

Surgical outcomesof ADREZotomy

In the literature, the rate of transient worsening of the sensorimotor symptoms after surgery ranged from 24% to 50% in a large series.[15,16] The rate of permanent worsening after surgery during long-term follow-up ranged from 0% to 20%.[2,15,17-19]

In our series, 1 (10%) patient (case 5) had a worse Frankel grade (from E to D) during the immediate postoperative period compared with the preoperative status. At the 6-month follow-up, the patient had recovered normal motor function with only subjective sensory numbness, which was the same as the patient's preoperative status. This was the only case that had a permanent tcMEP loss intraoperatively and transient deterioration of motor function on the approach side early after surgery in our series. The first myelotomy was overly anterior to the DREZ and might disturbed the lateral corticospinal tract. This case highlights the importance of a proper approach for ventrolateral lesions and the incision through ADREZotomy should be slightly anterior and exactly adjacent to the DREZ.

At follow-up, 9 (90%) patients had favorable outcomes. Of the 10 patients, no worsening in neurological function, compared with their preoperative status, was observed at follow-up.ASIA scores were not acquirable through telephone interviews in follow up. Thus, for accuracy, we did not include follow-up ASIA scores.

In our series, 9 (90%) patients complained of local pain or subjective sensory abnormalities before surgery. After surgery, no decrease of total ASIA sensory scores was observed in comparison to the preoperative score.At follow-up, the sensory disturbances of 8 (80%) patients persisted. This result is consistent with previous studies in which sensory disturbances recovered more slowly and less frequently than motor deficits.[14,20-23]One hypothesis of the pathogenesis of persistent paresthesias or pain is the surrounding hemosiderin staining of normal spinal cord

parenchyma around the resection bed, found even during long-term follow-up, produces firing of adjacent neurons, particularly in the dorsal horn of spinal laminae, and has the potential to generate persistent paresthesias, pain and itch.[22,24,25]

Anatomical Basis of ADREZotomy

The anatomical description of the spinal DREZ and related anatomical structures can help determine the surgical feasibility of ADREZotomy. Somatosensory fibers enter the spinal cord through the DREZ, which includes the proximal portion of the dorsal nerve rootlets, the dorsolateral tract, and the dorsal gray column laminae I-V of the spinal cord.[26] The posterior spinocerebellar tract originates from this nucleus and ascends ipsilaterally into the posterior portion of the lateral funiculus. The anterior spinocerebellar tract originates from secondary neurons in the posterior horns and the central portion of the spinal gray matter and ascends the spinal cord ipsilaterally and contralaterally.[27] Afferent fibers at the medial fasciculus gracilis and the lateral fasciculus cuneatus from the lower extremities and upper extremities, respectively, ascend in posterior columns. The anterior spinothalamic tract originates from the secondary neurons in the gray matter of the posterior horn and are contacted by dorsal root ganglion cells that collaterally travel 1 or 2 segments downward. The fibers of the anterior spinothalamic tract in the anterior spinal form a commissure and ascend in the contralateral anterolateral funiculus. Funicular neurons in the substantia gelatinosa contact the short collaterals that are divided longitudinally from the central processes passing the pseudounipolar neurons in the lateral portion of the dorsal roots. These funicular neurons cross the midline in the anterior spinal commissure to the opposite site and form the lateral spinothalamic tract.[28]The major ascending pathways are illustrated in Figures2A-2B.

Motorimpulses from the motor cortex travel along the long fiber pathways down the spinal cord to the anterior horn and synaptically contact the second motor neuron. In total, 80-85% of the pyramidal fibers of the corticospinal tract cross to the opposite side at the lower end of the medulla and descend along the contralateral lateral funiculus of the spinal cord as the lateral corticospinal tract. The other pyramidal fibers descend the spinal cord in the ipsilateral anterior funiculus as the anterior corticospinal tract and cross to the opposite side through the anterior

commissure.[29] The corticospinal tract and descending motor tracts are illustrated in Figures 2A-2B.

For ventrolateral intrinsic lesions, a posterior midline myelotomy would require a deep myelotomy and involvement of the posterior column tracts, whichmay cause postoperativedorsal column dysfunction.[30]DREZotomy requires dissection of thesubstantia gelatinosa and the posterolateral tract of Lissauer, often associated with postoperative paresthesias and dysesthesias in the distribution of the nerve emerging from that entry zone.[14]Lateral myelotomybetween the ventral and dorsal nerve roots on the ventral side of the dentate ligamentneeds more liberal lateral bony removal with the spinal cord rotated to optimize exposure, which also poses both technical challenges and surgical risksfor its closely adjacent to the lateral corticospinal tract and lateral spinothalamic tract.[11]Using ADREZotomy, the spinal cord is entered between the posterolateral tract of Lissauer and the dorsal spinocerebellar tracts, anterior to the lateral fasciculus proprius of the spinal cord and posterior to the lateral corticospinal tract, without disrupting important spinal cord tractsor the need to rotate the spinal cord or broadly expose bone.Compared with previous approaches for ventrolateral deep lesions, ADREZotomy is relatively minimally invasive.

Conclusions

The surgical removal of ventrolateral deep ISCCMs can be safe and feasible with the use of proper surgical techniques, including in patients with mild symptoms. ADREZotomy offers a minimally invasive technique for the removal of deep cervical and thoracic ventrolateral ISCCMs.

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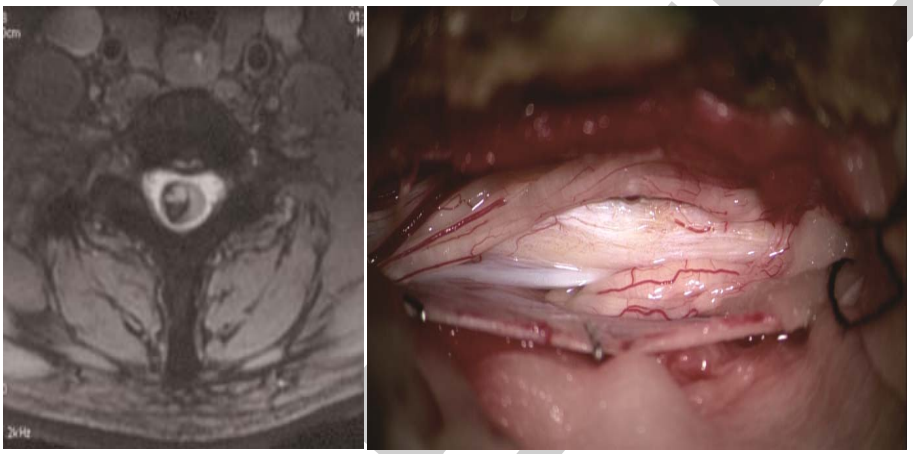
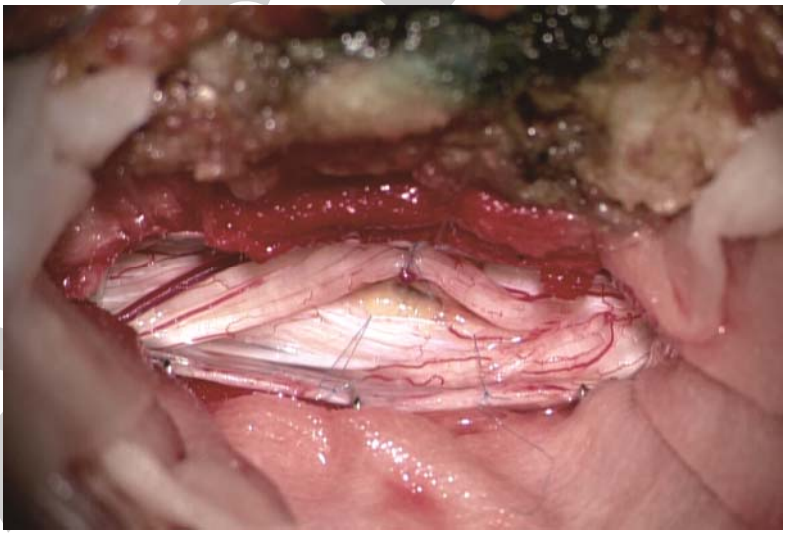
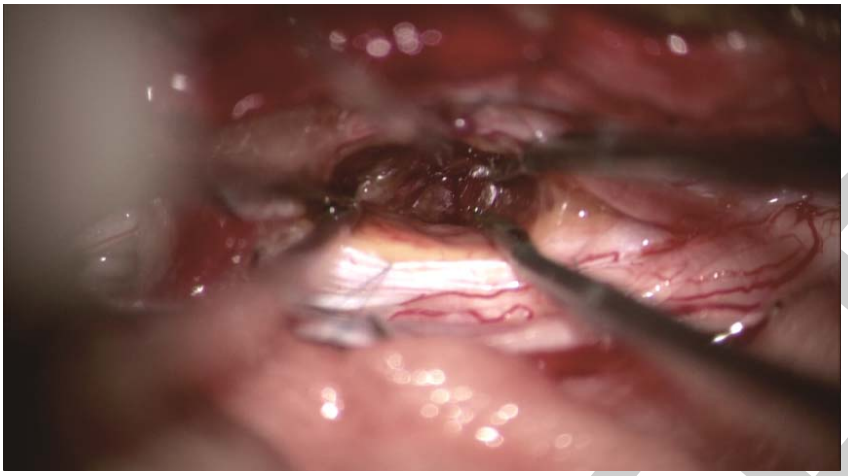
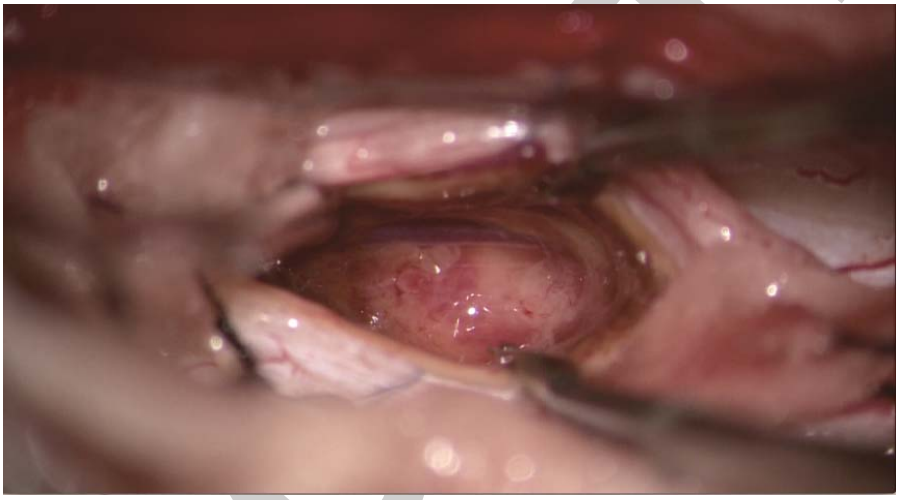
Figure Legends

FIGURE 1.A 49-year-old woman presented with pain in the neck and right upper limb. Preoperative MRI (A) indicated ventrolateral cervical ISCCMs. Intraoperative photographs (B-E) showing the surgical steps of the ADREZotomy and total removal of the lesion.Illustration (F) showing a posterior overview of the exposure of a deep intramedullary lesion via ADREZotomy.









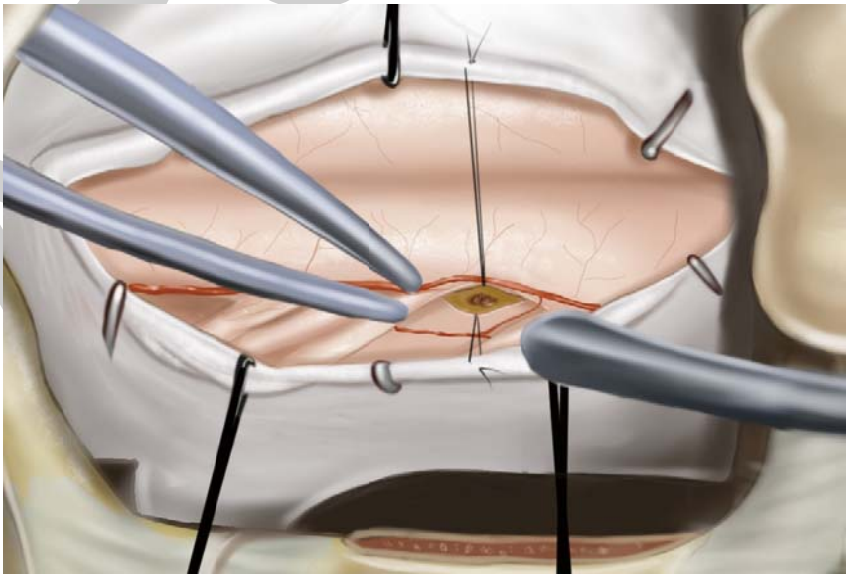
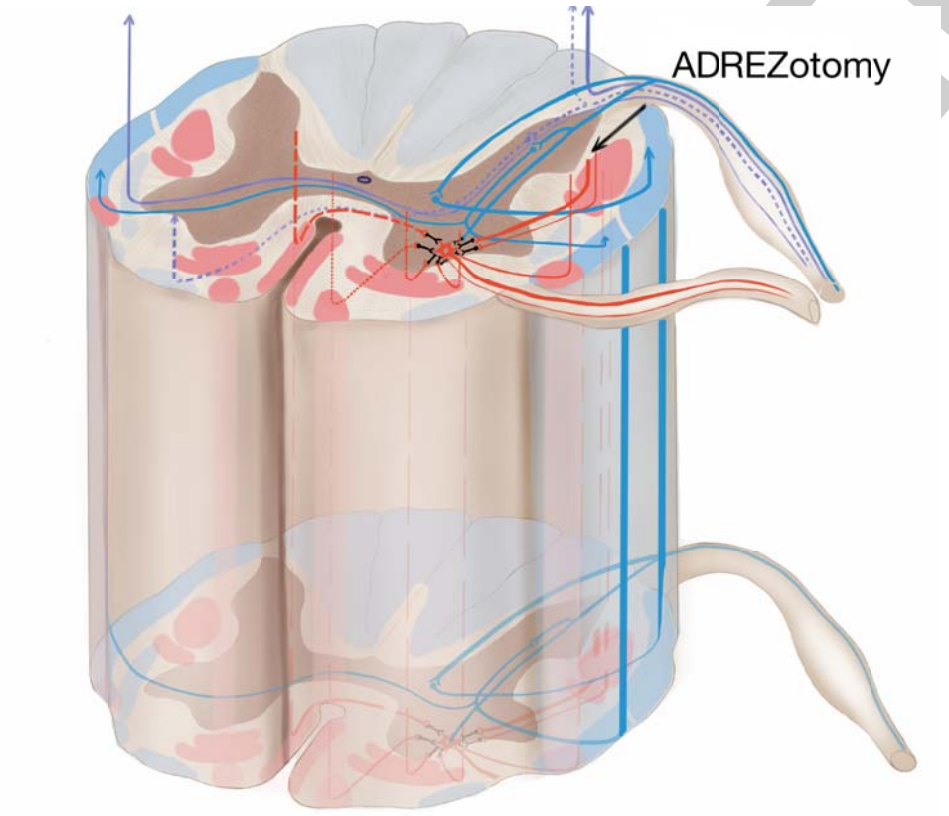


FIGURE 2. A, illustrationshowing the major ascending pathways, descending motor tracts and the location of the ADREZotomy. B, illustration showing the space-occupying of a ventrolateral deep ISCCMs, compressing spinal cord tissues. The lesion is exposed through ADREZotomy. The major tracts are preserved.



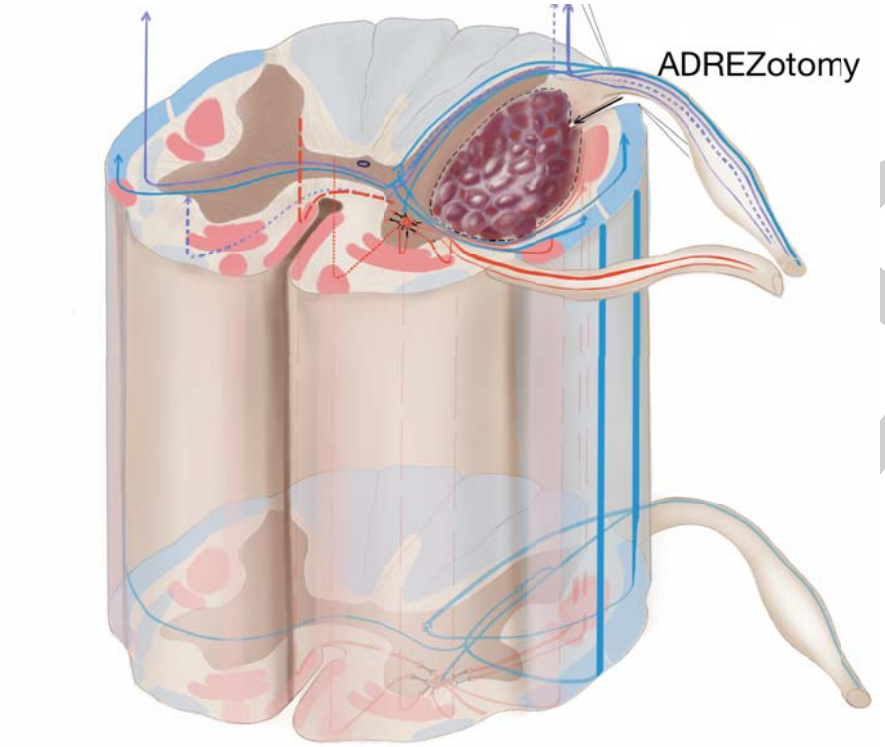


TABLE 1. The clinical characteristics of the patients with ventrolateral deep ISCCMs[a]

Patient No.	Age at initial symptom (yr)/sex	Initial symptoms	Duration of symptoms(mo)
1	24/M	Neck pain, Bi trunk and Lt LE hypesthesia, Lt UE and LE weakness, Bd	2
2	29/M	Neck and shoulder pain, Rt UE weakness	4
3	40/M	Neck pain, Lt UE and LE hypesthesia& weakness, Bd	3
4	47/F	Head and Lt shoulder pain, Lt UE hypesthesia	1
5	30/F	Neck and Rt shoulder pain, Rt UE hypesthesia	6
6	49/F	Neck and Rt UE pain,	2
7	63/F	Complete paralysis	3
8	33/M	Lt UE pain, Lt UE hypesthesia	9
9	22/M	Lt LE hypesthesia, Bd	6
10	62/F	Bi UE and LE weakness and hypesthesia	1

[a]No, number; F, female; M, male; mo, month; yr, years; Bi, bilateral; Lt, left; Rt, right; LE, lower extremity; UE, upper extremity; Bd, Bowel/bladder dysfunction

TABLE 2. The Frankel scale

Grade	Definition
A (complete)	No motor or sensory function clinically detected below the level of the injury
B (sensation only)	No motor function clinically detected below the level of the injury; sensory function remains below the level of the injury but may include only partial function (sacral sparing qualifies as preserved sensation)
C (motor useless)	Some motor function observed below the level of the injury, but is of no practical use to the patient
D (motor useful)	Useful motor function below the level of the injury; patient can move lower limbs & walk w/ or w/o aid but does not have a normal gait or strength in all motor groups
E (normal motor)	No clinically detected abnormality in motor or sensory function with normal sphincter function; abnormal reflexes & subjective sensory abnormalities may be present

TABLE 3. Surgical outcome of the patients [a]

Patient No.	Location of the lesion	Duration of follow-up (mo)	Frankel scale			ASIA motor score (0-100)		ASIA sensory score (0-224)		Results/ Complications
			Preop	Postop	Follow-up	Preop	Postop	Preop	Postop	
1	Lt ventral at C2-C3	27	D	D	D	90	90	152	152	Stable/no
2	Rt ventral at C7	12	D	E	E	98	100	224	224	Improved/ no
3	Lt ventral at C2	6	D	D	E	98	98	172	172	Improved/ no
4	Lt ventral at C2	11	E	E	E	100	100	174	174	Stable/no
5	Rt ventral at C2-C3	9	E	D	E	100	90	218	218	Stable/no
6	Rt ventral at C7	3	E	E	E	100	100	224	224	Stable/no
7	Lt ventral at T7	9	A	A	A	50	50	136	136	Stable/no
8	Lt ventral at C6	8	E	E	E	100	100	216	216	Stable/no
9	Rt ventral at T6-T7	82	E	E	E	100	100	206	206	Stable/no
10	Rt ventral at C6	6	D	D	D	80	80	212	212	Stable/no

[a] Lt, left; Rt, right; C, cervical; T, thoracic.; Preop, preoperative; Postop, postoperative; A-E Frankel grades preoperative and postoperative and during follow-up; Motor score: motor function assessment comprised key muscle functions testing of 10 paired myotomes using the ASIA classification scale; Sensory score: sum of segmental light touch and pinprick classifications using the ASIA classification scale.

TABLE 4. Intraoperative Neurophysiological Monitoringchanges, superficial sensory function, dorsal column function and motor function pre- and postoperativelyof the patients[a]

Patient No.	Surgical Approach	EP Changes	Superficial Sensory Function		Dorsal Column Function		Motor Function	
			Preop	Postop	Preop	Postop	Preop	Postop
1	ADREZotomy	Unchanged	Bihypesthesia below T4 level	No deficit	Bi LEdysfunction	No deficit	Lt LE weakness	No deficit
2	ADREZotomy	Bi LE tcMEPdecreased more than 80% SEP unchanged	Intact	Intact	Intact	Intact	Rt UE weakness	Improved
3	ADREZotomy	Unchanged	Rt hypesthesia a below T4 level	No deficit	Intact	Intact	Lt weakness	No deficit
4	ADREZotomy	Unchanged	Lt hypesthesia a below C5 level	No deficit	Intact	Intact	Intact	Intact
5	Incision through abnormal surface, ADREZotomy	Rt tcMEPloss SEP unchanged	Rt C3-C5 hypesthesia	No deficit	Intact	Intact	Intact	Transient motor deficit
6	ADREZotomy	LtUE tcMEPdecreased more than 80% SEP unchanged	Intact	Intact	Intact	Intact	Intact	Intact
7	ADREZotomy	Unchanged	No function below T7	No deficit	No function below T7	No deficit	Bi LE no function	No deficit
8	ADREZotomy	RtUE tcMEP decreased more than 80% SEP unchanged	Lt C5-C8 hypesthesia	No deficit	Intact	Intact	Intact	Intact
9	ADREZotomy	Unchanged	Lt LE hypesthesia	No deficit	Intact	Intact	Intact	Intact
10	ADREZotomy	RtUE tcMEP decreased more than 80% RtLE tcMEP decreased more than 50% SEP unchanged	Bi C6-C7, L5 hypesthesia	No deficit	Intact	Intact	Bi UE, LE weakness	No deficit

[a]No, number; EP, evoked potential; tcMEP, trans-cranial motor-evoked potential; SEP, somatosensory evoked potential; Bi, bilateral; Lt, left; Rt, right; LE, lower extremity; UE, upper extremity.

TABLE 5.Neurological status of patients prior to surgery, at immediate postoperative assessment, and at long-term follow-up[a]

Frankel Grade	Preop (%)	Immediate Postop (%)	Follow-up (%)[a]
A	1 (10.0)	1 (10.0)	1 (10.0)
B	0 (0.0)	0 (0.0)	0 (0.0)
C	0 (0.0)	0 (0.0)	0 (0.0)
D	4 (40.0)	4 (40.0)	2 (20.0)
E	5 (50.0)	5 (50.0)	7 (70.0)
total	10 (100.0)	10 (100.0)	10 (100.0)

[a]The mean follow-up duration was 17.3 months.