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The Gantry Crane Technique: A Novel Technique for Treating Severe Thoracic Spinal Stenosis and Myelopathy Caused by Ossification of the Ligamentum Flavum and Preliminary Clinical Results

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Abstract

Study Design: Retrospective single-arm study.

Objective: To propose a novel technique named the gantry crane technique for treating severe thoracic spinal stenosis and myelopathy caused by thoracic ossification of the ligamentum flavum (TOLF) and investigate its clinical results.

Methods: From June 2017 to January 2019, 18 patients presenting with severe spinal stenosis and myelopathy caused by TOLF were included in our study. All patients were treated with gantry crane technique, pre-operative JOA score, as well as 3 days-, 3 months-, 6 months-, 12 months-, 24 months after operation, and Hirabayashi recovery rate were reported. Pre- and post-operative image were utilized for the assessment of post-operative effect. Peri-operative complications were recorded to assess the safety of the gantry crane technique.

Results: The JOA score increased from 10.56 $\pm$ 3.76 preoperatively to 12.94 $\pm$ 3.33, 13.56 $\pm$ 3.48, 13.94 $\pm$ 3.32, 14.17 $\pm$ 3.70 and 14.06 $\pm$ 3.54 in 3 days, 3 months, 6 months, 12 months and 24 months after surgery, respectively. The post-operative JOA scores were improved with statistical significance at the level of $P < 0.05$. The recovery rate was (39.09 $\pm$ 33.85) %, (51.35 $\pm$ 42.60) %, (55.79 $\pm$ 36.10) %, (64.98 $\pm$ 29.24) % and (60.98 $\pm$ 35.96) % for 3 days, 3 months, 6 months, 12 months and 24 months after surgery, respectively. There were 2 cases of SSI (surgical site infection), 1 case of NI (neurovascular injury) and 1 case of cerebrospinal fluid (CSF) leakage.

Conclusions: This study highlights a safe and effective technique, the gantry crane technique, for treating severe thoracic spinal stenosis and myelopathy caused by TOLF.

Keywords

thoracic myelopath, ossification of ligamentum flavum, compression of spinal cord, gantry crane, surgical technique

Introduction

Thoracic ossification of the ligamentum flavum (TOLF), which was first described by Polgar in 1920, is a potential risk factor for thoracic spinal stenosis and myelopathy.[1,2] TOLF mostly occurs in lower thoracic spinal segments and is characterized by the replacement of the ligament tissue by pathological heterotopic ossification.[3] TOLF is the leading cause of thoracic spinal stenosis and myelopathy.[4,5] It was reported that TOLF has a relatively high occurrence in East Asia, especially in Japan and southern China (36% and 3.8% respectively).[6-8] More recently, reports of

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TOLF in other countries and areas, including North America, Middle East and Caribbean, have also been described.[9-11]

TOLF often develops insidiously and once patients present with neurological symptoms, surgical decompression is often necessary since conservative treatment has been proved ineffective.[12,13] On the whole, conventional surgical procedures for treating TOLF include en bloc laminectomy, fenestration, and laminoplasty.[14,15] These procedures are quite challenging because of relatively narrow caliber of thoracic segments and tenuous blood supply of spinal cord.[16] Moreover, clinical outcomes are often unsatisfactory because of direct manipulation of spinal canal.[17] It was reported that the standardized prevalence of cerebrospinal fluid (CSF) leakage is as high as 32% in these surgeries.[18] Thus, safe and effective surgical decompression is still a great challenge and is of great significance.[19,20]

To improve clinical outcomes and reduce the prevalence of postoperative complications, we investigated the gantry crane technique for treating severe thoracic spinal stenosis and myelopathy caused by ossification of the ligamentum flavum.

Materials and Methods

Study Design and Participants

This study was a single-center, retrospective, single-arm clinical study. From June 2017 to January 2019, patients presenting with severe spinal stenosis and myelopathy caused by TOLF, admitted to the Second Department of Spine Surgery at the Changzheng Hospital in Shanghai, were enrolled into our study. Patients were included in this study if they (1) were diagnosed with spinal stenosis and myelopathy due to TOLF with objective evidence; (2) had symptoms of spinal cord compression; (3) were willing and able to undergo surgery. Patients were excluded from this study if they (1) were complicated with severe hepatic and renal dysfunction, systemic infectious diseases, hematopoietic diseases and immune diseases; (2)were combined with malignant tumor, mental disease, cerebrovascular and respiratory diseases; (3) had incomplete information or the follow-up was lost; (4) were unable or unwilling to participate in the study. The study was approved by the Institutional Review Board and the Ethics Committee of Shanghai Changzheng Hospital (No. 2017SL040). Informed consents were obtained from all patients.

Collection of Evaluation Indicators

Patient demographics (age and sex), surgery time, intraoperative blood loss, and postoperative complications were recorded. Japanese Orthopaedic Association (JOA) score was used for the evaluation of pre- and post-operative neurological function. Preoperative JOA score, as well as 3 days-, 3 months-, 6 months-, 12 months-, 24 months after operation were reported. Postoperative recovery rate was referred to the Hirabayashi recovery rate, which was calculated as follows: Extent of improvement (%) = (postoperative JOA score-preoperative JOA score)/ (17-preoperative JOA score) $\times$ 100%. Plain X-ray and Computed Tomography (CT) were utilized to estimate the bone fusion and ossification position. The spinal cord compression and decompression was evaluated using Magnetic Resonance Imaging (MRI). Peri-operative complications, including pulmonary embolism (PE), neurological impairment (NI), cerebrospinal fluid (CSF) leakage, surgical site infection (SSI) were recorded to assess the safety of the gantry crane technique.

Surgical Technique

Bilateral lamina, spinous processes and transverse process were exposed using a standard posterior midline approach under general endotracheal anesthesia and prone position (Figures 1A, 2A, 3A). The spinous processes of involve segments were removed to facilitate further operation (Figures 1B, 2B, 4A). Two longitudinal osteotomy incisions were made at the junction of bilateral lamina and pedicle (Figures 1C, 4B). The longitudinal osteotomy incisions were made to the lateral of the base of the lamina and to the medial of the bilateral pedicles with the width of about 2 ~ 3 mm. Tunnels with 6 ~ 7 mm depth were made at the involved segments by drilling holes at 5 mm to the midline unilateral (Figures 1D, 4C). Then the suture anchor (TwinFix Ti 6.5, 2*#2) acting as the lifting installment was inserted into the tunnel (Figures 2C, 4D). Next, a transverse osteotomy incision connecting the lower end of the 2 longitudinal incisions was made (Figure 1E). Pedicle screws were placed bilaterally at involved segments (Figures 1F,2D). The screws were then affixed with 2 longitudinal rods and transverse connectors for further suspension (Figures 1G, 2E, 4E). Twined the sutures onto the transverse connectors stable the laminae temporarily. Next, a transverse osteotomy incision connecting the upper end of the 2 longitudinal incisions was made to isolate the laminae and ossified ligamentum flavum (Figures 1H, 4F).

After completely isolation of the laminae and ossified ligamentum flavum from other tissues, tightening of suture anchor was performed gradually to facilitate the posterior elevation of the laminae and ossified ligamentum flavum, and locked the buckle (Figures 2F, 3B). During the procedure, improved pulsation of the laminae and ossified ligamentum flavum along with the dura pulsation was observed, which indicates the decompression of spinal cord has been achieved (Figure 3C). The posterior elevation height of laminae and ossified ligamentum flavum can be affected by screw length, transverse connectors' position, and firmness of suture anchor. Then the posterior fusion was performed between bilateral transverse process. Finally, the incision was closed layer by layer with a drainage tube remained. No significant changes in neuroelectrophysiological monitoring indicators, including somatosensory evoked potentials (SSEPs) and motor evoked potentials (MEPs), were observed during the operation.

Statistical Analysis

Statistical analysis was performed using the Statistical Package for the Social Sciences (SPSS) version 26.0 (IBM Armonls, NY, USA). Numerical data is recorded as mean values $\pm$ standard deviation (SD). The unpaired 2-tailed Student t test

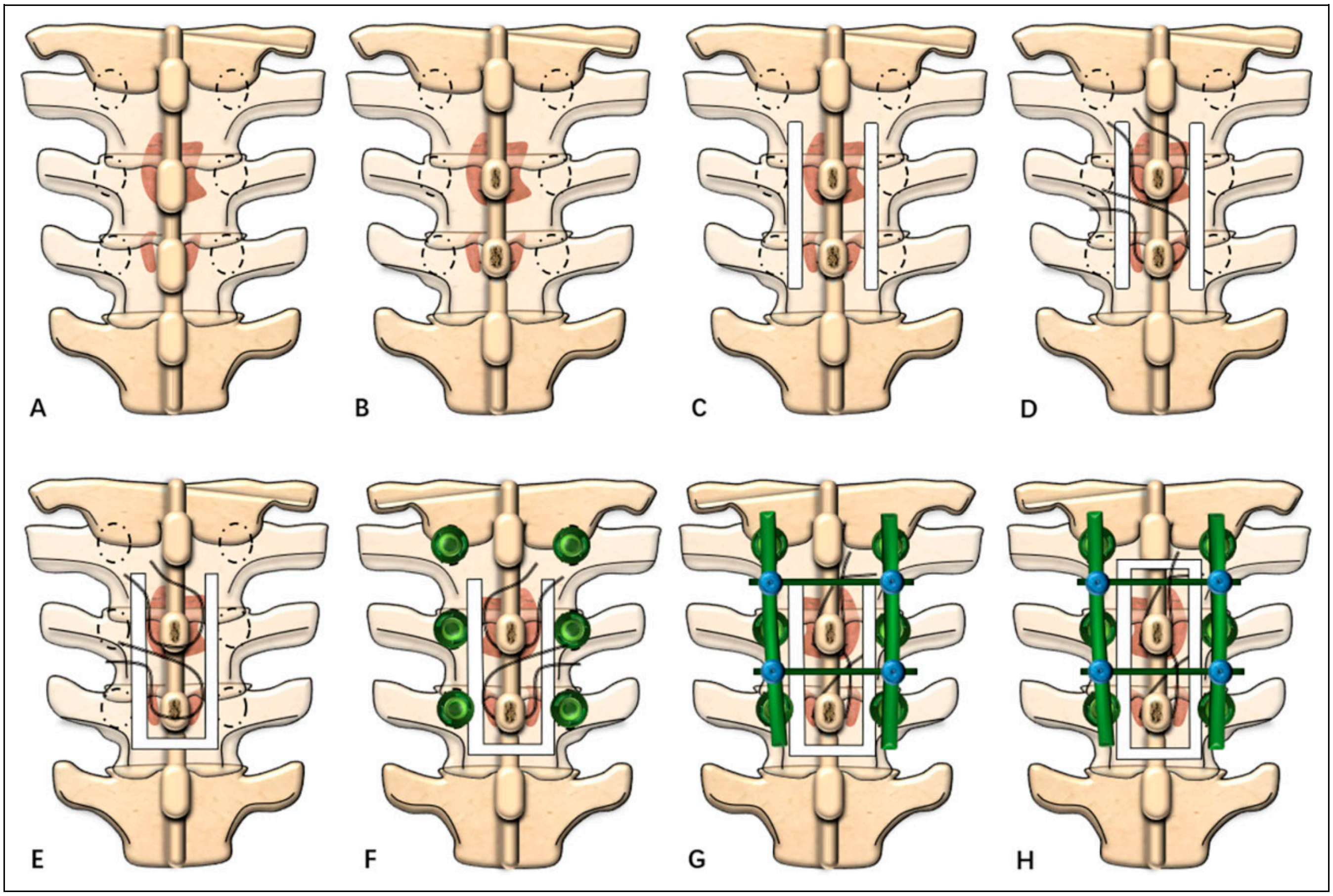

Figure 1. Description of the surgical procedure of the bridge crane technique. A, The exposure of bilateral lamina, spinous processes and transverse process. B, Removal of the spinous processes of involve segments. C, The longitudinal osteotomy incisions were made to the lateral of the base of the lamina and to the medial of the bilateral pedicles with the width of about 2 ~ 3 mm. D, Tunnels with 6 ~ 7 mm depth were made at the involved segments by drilling holes at 5 mm to the midline unilateral. E, One transverse osteotomy incision connecting the lower end of the 2 longitudinal incisions was made. F, Pedicle screws were placed bilaterally at involved segments. G, The screws were affixed with 2 longitudinal rods and transverse connectors for further suspension. H, Another transverse osteotomy incision connecting the upper end of the 2 longitudinal incisions was made to isolate the laminae and ossified ligamentum flavum.

or Mann-Whitney test were performed to compare the mean values or data distribution of continuous variables. One-way ANOVA was used to compare the mean values or data distribution of continuous variables. A 2-tailed P value of < 0.05 was considered statistically significant.

Results

General Outcomes

There were 12 males and 6 females, the mean $\pm$ SD of age was 60.67 years (range 46–75). The mean surgery time was 183 minutes (Standard deviation, 51.42 min; Range, 117-280 min), and the mean intraoperative blood loss was 561.67 ml (Standard deviation, 268.36 ml; Range 150-1250 ml) (Table 1).

Clinical Outcomes

During the 24 months of follow-up, remarkable improvement of patients' clinical manifestations was observed. The JOA score increased from 10.56 $\pm$ 3.76 (range 3-15) preoperatively to 12.94 $\pm$ 3.33 (range 5-17), 13.56 $\pm$ 3.48 (range 5-17), 13.94 $\pm$ 3.32 (range 5-17), 14.17 $\pm$ 3.70 (range 3-17) and 14.06 $\pm$ 3.54 (range 5-17) in 3 days, 3 months, 6 months, 12 months and 24 months after surgery, respectively (Figure 5). The post-operative JOA scores were improved with statistical significance at the level of $P < 0.05$. There was no statistically significant difference in JOA scores between 3 days, 3 months, 6 months, 12 months and 24 months after surgery ($P = 0.830$). The recovery rate was (39.09 $\pm$ 33.85) %, (51.35 $\pm$ 42.60) %, (55.79 $\pm$ 36.10) %, (64.98 $\pm$ 29.24) % and (60.98 $\pm$ 35.96) % for 3 days, 3 months, 6 months, 12 months and 24 months after surgery, respectively (Figure 6). No difference in recovery rate was witnessed between 3 days, 3 months, 6 months, 12 months and 24 months after surgery ($P = 0.239$).

All surgeries were performed successfully without any notable event during the operation. No mortality or pulmonary embolism (PE) were observed. However, we did find 2 cases of SSI (surgical site infection), 1 case of NI (neurovascular

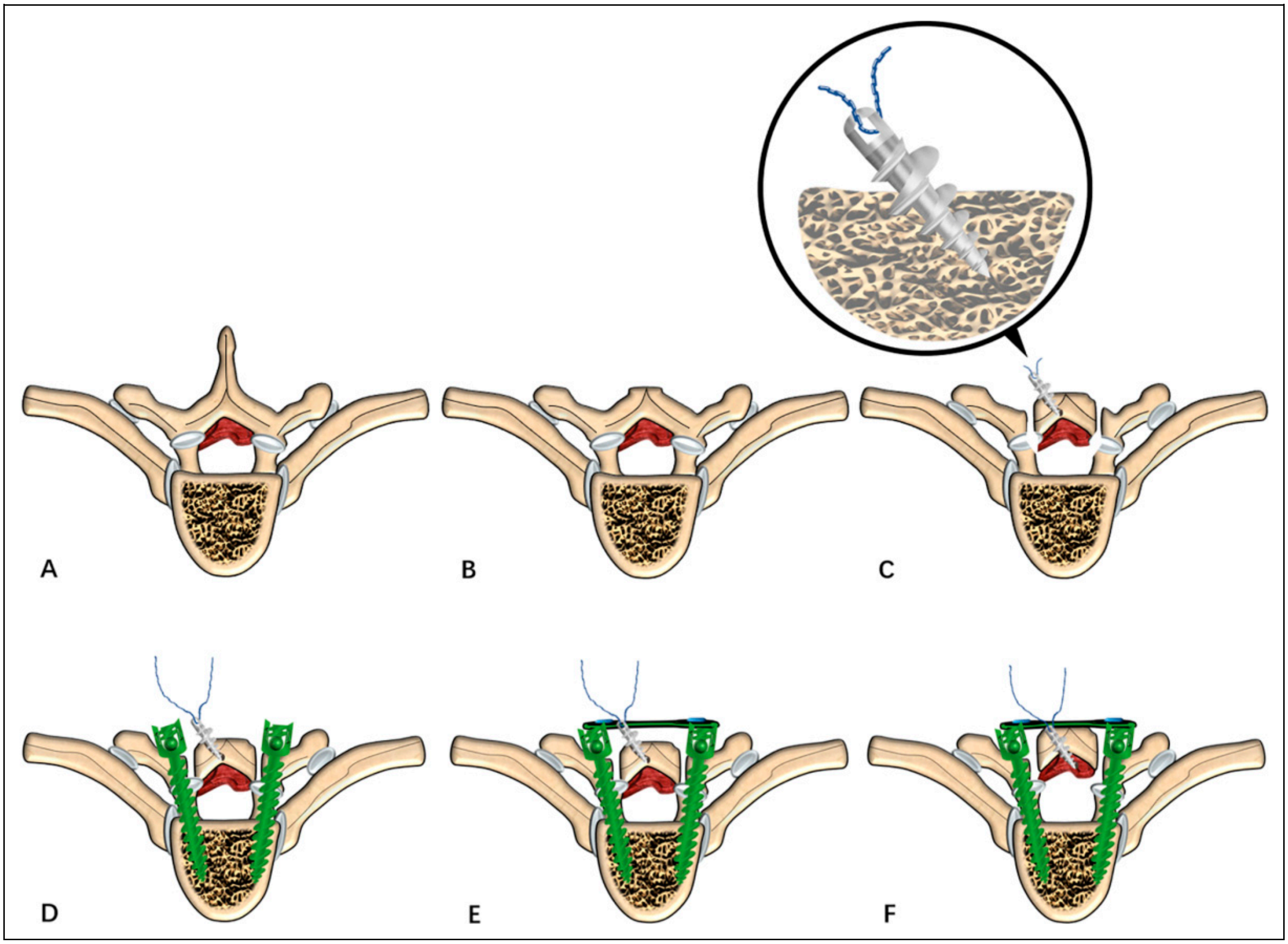

Figure 2. Demonstration of the procedure in an axial view. A, Bilateral lamina, spinous processes and transverse process were exposed using a standard posterior midline approach. B, Resection of the spinous processes of involve segments. C, The longitudinal osteotomy incisions and tunnels were made, then the suture anchor (TwinFix Ti 6.5, 2*#2) acting as the lifting installment was inserted into the tunnel. D, Placement of pedicle screws. E, After the affixation of pedicle screws to transverse connectors, the laminae and ossification was completely isolated from other tissues. F, Tightening of suture anchor was performed gradually to facilitate the posterior elevation of the laminae and ossified ligamentum flavum.

injury) and 1 case of cerebrospinal fluid (CSF) leakage. All cases of SSI were performed with 0.5% iodophor and 75% alcohol and all patients improved gradually. Patients with nerve damage were given oral Mecobalamin tablets (1 at a time, 3 times a day). No special treatment was performed for the patient with CSF leakage.

Radiological Outcomes

Preoperative and postoperative imaging results of typical case are as follows. Preoperative plain radiography revealed high-density mass projecting into the spinal canal at the level of the T4/T5 and T5/T6. Axial CT scan showed the ossified ligamentum flavum protruding into the spinal canal at T4/T5 and T5/T6, respectively. The sagittal and axial MRI demonstrated the compression at the level of T4/T5 and T5/T6, resulting in narrowing of the spinal canal (Figure 7). Postoperative plain radiography of the spine showed screws, rods and connectors were all in appropriate position. Sagittal CT showed the increased anterior and posterior diameter of spinal canal. Axial CT scanning demonstrated a sufficient decompression of the T4/T15. Sagittal MRI presented the decompression of the dura mater (Figure 8).

Discussion

TOLF mostly occurs at lower thoracic spinal segments and develops insidiously.[21] The clinical manifestations of patients with TOLF are relatively complex. Patients always present with back pain and numbness in the lower limbs during initial stage, and exhibit increased neural deficit symptoms as the progression of TOLF, including zonesthesia in the chest area, spastic paralysis in the lower limbs, sphincter dysfunction and sensory dysfunction in the saddle region.[22] Studies have shown that once patients with TOLF show clinical symptoms, spinal stenosis and spinal cord compression become increasingly

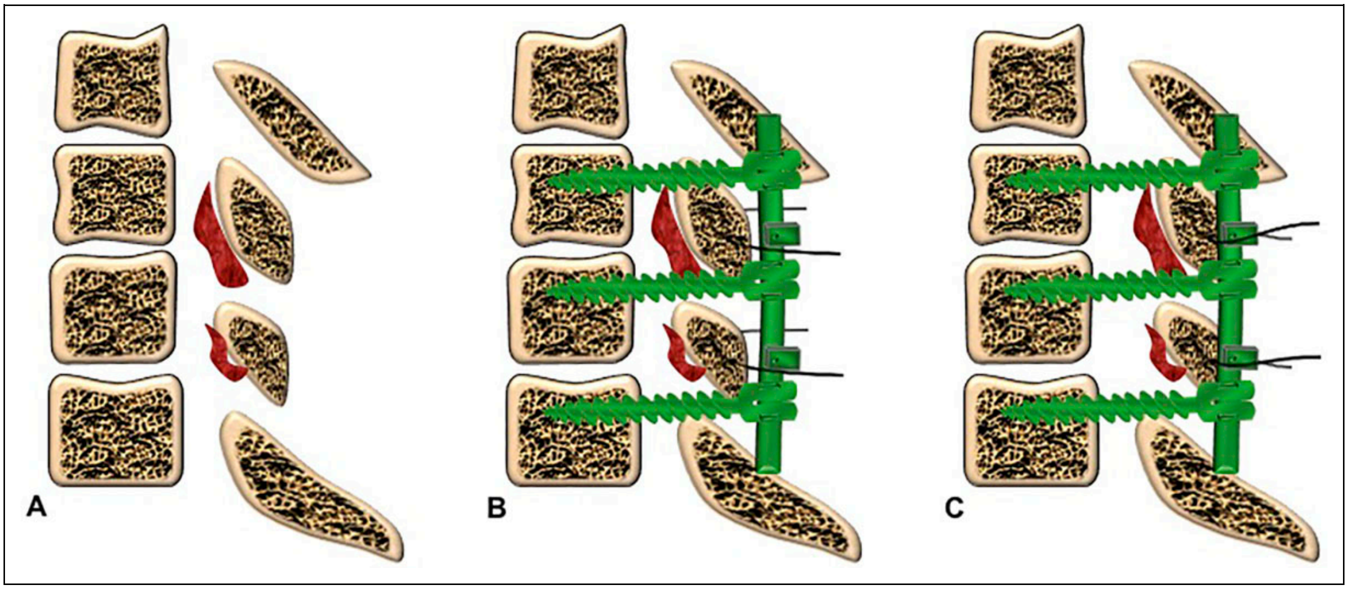

Figure 3. Illustration of the gantry technique procedure in a sagittal view. A, The spinous processes of involve segments were resected. B, Pedicle screws were placed bilaterally at involved segments and then were affixed with 2 longitudinal rods and transverse connectors for further suspension. C, Tightening of suture anchor was performed gradually to elevate the laminae and ossified ligamentum flavum.

Table 1. The Summary of the Pre- and Postoperative Clinical Data of the Patients.

Serial number	Sex	Age	Surgery time (min)	Intraoperative blood loss (ml)	Pre-JOA score	Post-JOA score (3d)	Post-JOA score (3 M)	Post-JOA score (6 M)	Post-JOA score (12 M)	Post-JOA score (24 M)	Recovery rate (%) (3d)	Recovery rate (%) (3M)	Recovery rate (%) (6M)	Recovery rate (%) (12M)	Recovery rate (%) (24 M)	Postoperative complications
1	F	46	226	800	9	16	16	16	16	17	87.50	87.5	87.5	87.5	100	N
2	M	53	217	150	11	11	11	12	12	11	0	0	16.67	16.67	0	N
3	F	61	148	1250	13	12	11	14	15	14	−25	−50	25	50	25	NI
4	F	69	222	400	9	12	12	15	16	15	37.50	37.5	75	87.5	75	N
5	M	64	280	350	3	8	8	8	9	8	35.71	35.71	35.71	42.86	35.71	N
6	M	56	135	700	6	9	10	10	9	9	27.27	36.36	36.36	27.27	27.27	N
7	M	55	268	460	4	5	5	5	3	5	7.69	7.69	7.69	7.69	7.69	CSF leak
8	F	68	117	880	14	16	16	17	16	16	66.67	66.67	100	66.67	66.67	N
9	M	66	142	300	9	13	15	15	15	15	50	75	75	75	75	N
10	M	57	157	460	14	15	17	17	17	17	33.33	100	100	100	100	N
11	M	58	127	580	14	17	17	17	17	17	100	100	100	100	100	SSI
12	M	64	158	670	11	15	16	15	15	15	66.67	83.33	66.67	66.67	66.67	N
13	M	57	216	350	13	15	15	16	15	16	50	50	75	50	75	N
14	F	75	255	400	15	15	15	15	16	15	0	0	0	50	0	SSI
15	M	72	147	480	12	16	17	17	15	17	80	100	100	60	100	N
16	M	50	144	650	15	16	17	15	17	17	50	100	0	100	100	N
17	M	56	178	880	6	10	12	13	15	13	36.36	54.55	63.64	81.82	63.64	N
18	F	65	157	350	12	12	14	14	17	16	0	40	40	100	80	N

N: not observed NI: neurovascular injury CSF: cerebrospinal fluids SSI: surgical site infection.

severe.[23] This requires prompt surgical decompression which often refers fenestration and laminectomy.

According to the characteristics of the most severe spinal stenosis and the continuity of ossification, Onishi et al.[24] divided TOLF into the following 5 types: lateral type, extended type, enlarged type, fused type and tuberous type. French-door laminectomy and fenestration are recommended when it comes to lateral, extended or enlarged type of TOLF. However, both of the 2 surgical procedures require longitudinal incisions, which is almost impossible not to injuring spinal cord or dura mater. En bloc laminectomy is indicated when TOLF is fused type or tuberous type, both of which are the common cause of severe thoracic spinal cord compression. However, en bloc laminectomy is quite a challenge for less-experienced spine surgeons since it is technically demanding. In addition, the high occurrence of early complications often leads to unsatisfactory results.[25] Direct manipulation of spinal canal can damage the stability of spine, which make it vulnerable to postoperative complications, such as dural tears or CSF leakage.[26]

The idea of gantry crane technique is to isolate and suspend the laminae and ossified ligamentum flavum to enlarge the space of spinal canal, as a result of decompression of spinal cord with less disturbance of spinal canal. The posterior elevation height of laminae and ossified ligamentum flavum, which

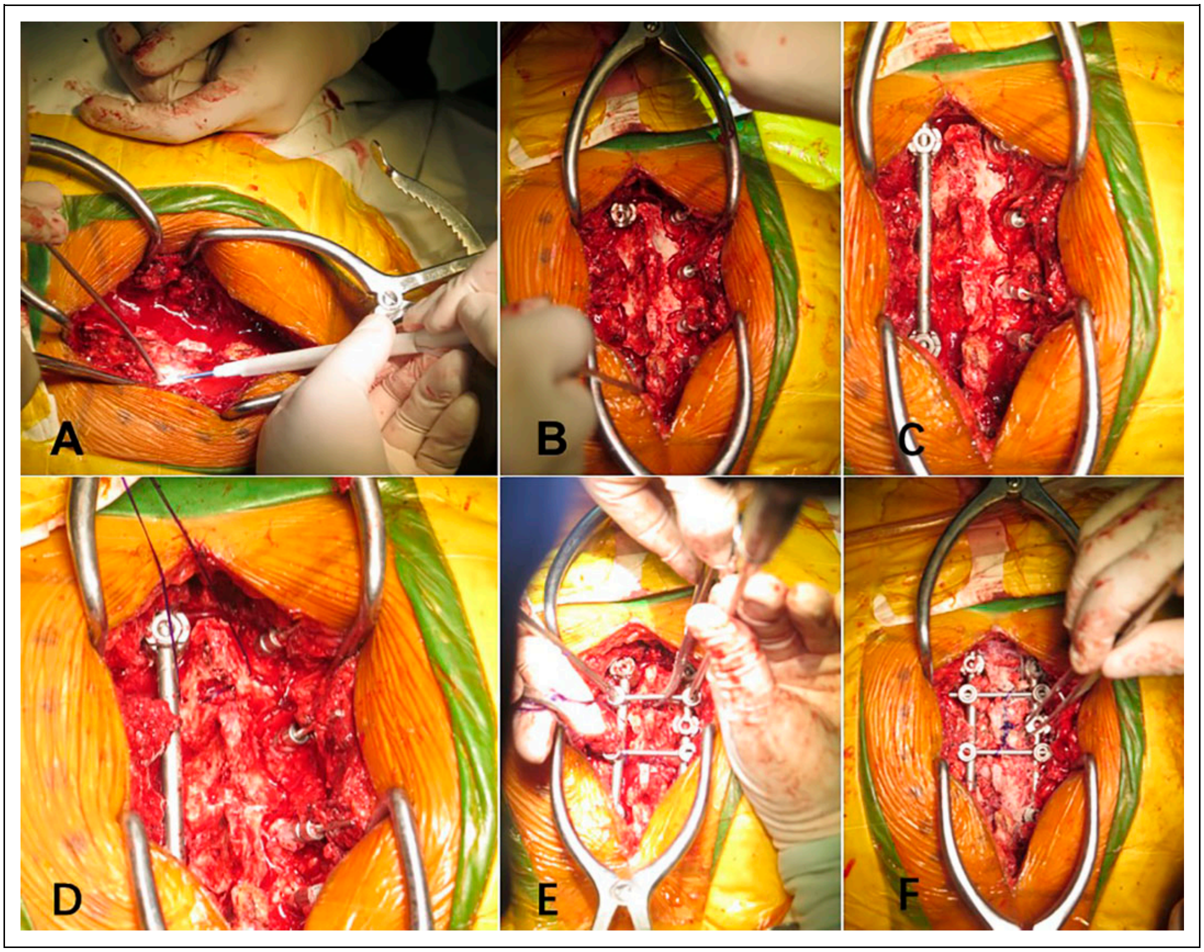

Figure 4. Representative images of intraoperative operation. A, The spinous processes of involve segments have been removed. B, Two longitudinal and the first transverse incisions have been made. C, Pedicle screws were placed bilaterally at involved segments. D, The suture anchor (TwinFix Ti 6.5, 2*#2) acting as the lifting installment was inserted into the tunnel. E, The screws were then affixed with 2 longitudinal rods and transverse connectors. F, Another transverse osteotomy incision was made and the laminae and ossified ligamentum flavum were isolated and elevated.

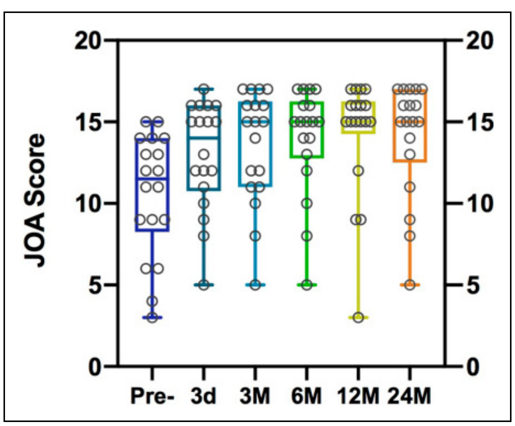

Figure 5. The JOA score increased from 10.56 $\pm$ 3.76 (range 3-15) preoperatively to 12.94 $\pm$ 3.33 (range 5-17), 13.56 $\pm$ 3.48 (range 5-17), 13.94 $\pm$ 3.32 (range 5-17), 14.17 $\pm$ 3.70 (range 3-17) and 14.06 $\pm$ 3.54 (range 5-17) in 3 days, 3 months, 6 months, 12 months and 24 months after surgery, respectively (Figure 4). The post-operative JOA scores were improved with statistical significance at the level of $P < 0.05$. There was no statistically significant difference in JOA scores between 3 days, 3 months, 6 months, 12 months and 24 months after surgery ($P = 0.830$).

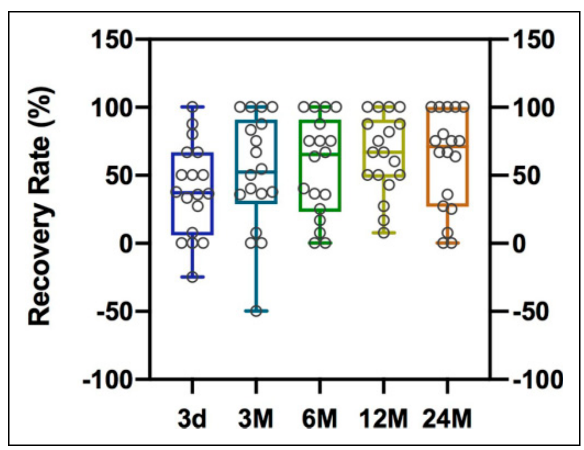

Figure 6. The recovery rate was (39.09 $\pm$ 33.85)%, (51.35 $\pm$ 42.60)%, (55.79 $\pm$ 36.10)%, (64.98 $\pm$ 29.24)% and (60.98 $\pm$ 35.96)% for 3 days, 3 months, 6 months, 12 months and 24 months after surgery, respectively (Figure 5). No difference in recovery rate was witnessed between 3 days, 3 months, 6 months, 12 months and 24 months after surgery ($P = 0.239$).

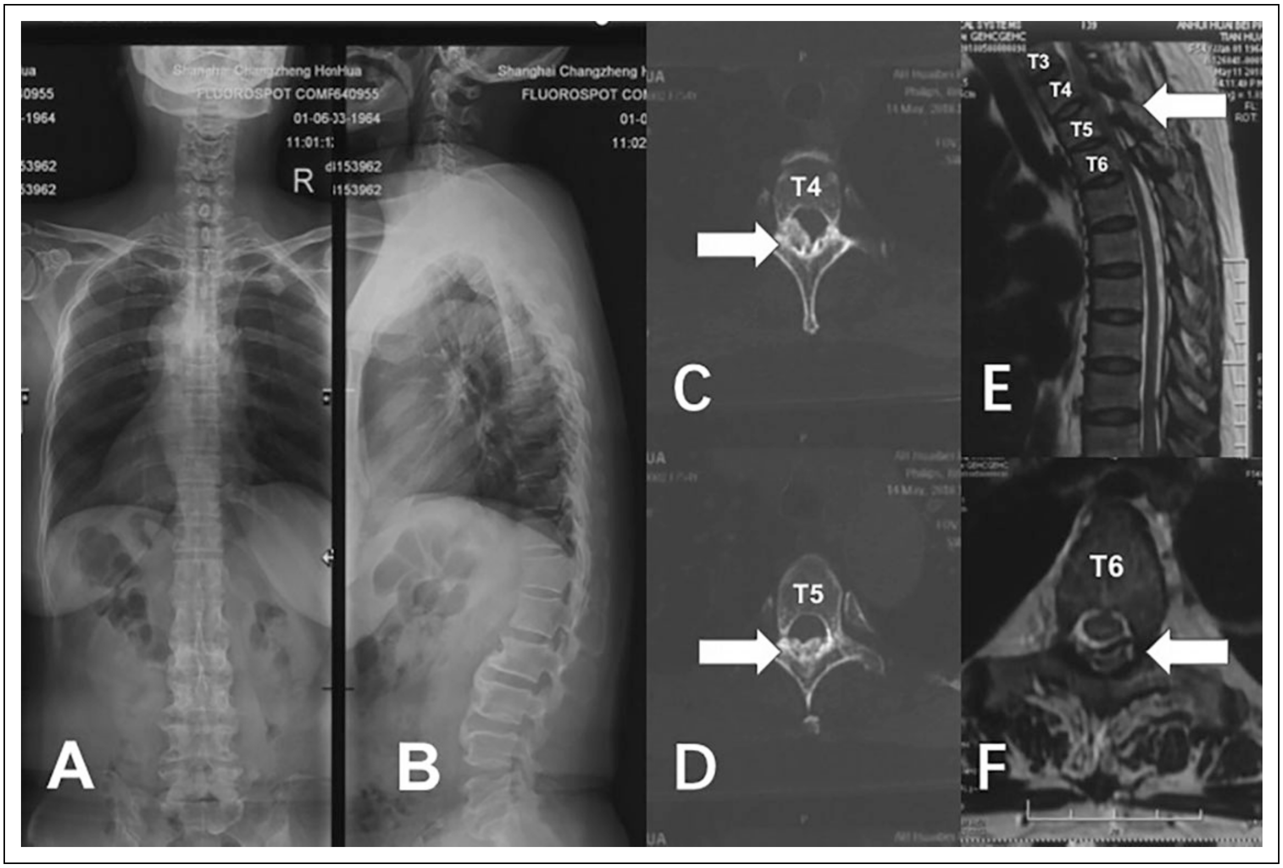

Figure 7. Preoperative imaging of the typical case. A and B, The plain radiography revealed high-density mass projecting into the spinal canal at the level of the T4/T5 and T5/T6. C and D, Axial CT scan showed the ossified ligamentum flavum protruding into the spinal canal at T4/T5 and T5/T6, respectively. E and F, The sagittal and axial MRI demonstrated the compression at the level of T4/T5 and T5/T6, resulting in narrowing of the spinal canal.

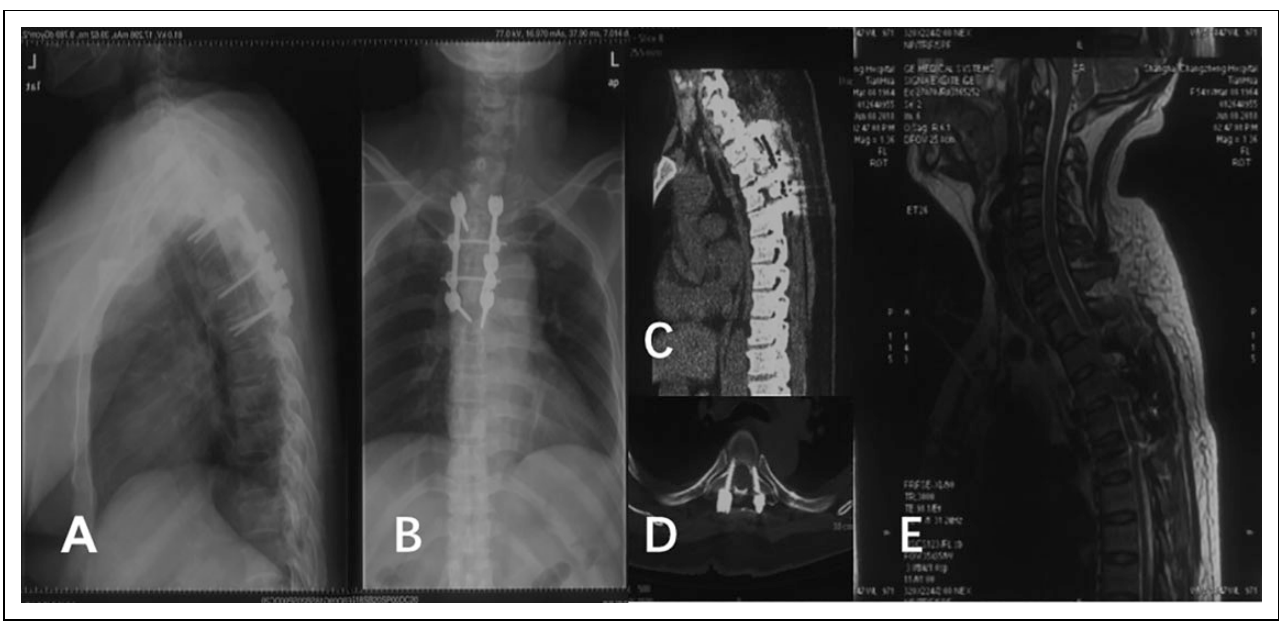

Figure 8. Imaging of the typical case after operation. A and B, Plain radiography of the spine showed screws, rods and connectors were all in appropriate position. C, Sagittal CT showed the increased anterior and posterior diameter of spinal canal. D, Axial CT scanning demonstrated a sufficient decompression of the T4/T15. E, Sagittal MRI presented the decompression of the dura.

are controllable, can be affected by screw length, transverse connectors' position, and firmness of suture anchor. The key factors to ensure the effect of surgery are complete dissociation and sufficient elevation of laminae and ossified ligamentum flavum. Our experience is that elevation of 102 mm can ensure adequate decompression and avoid dural tears caused by excessive lifting. The indicator of complete decompression is the laminae pulsation along with dura mater.

Postoperative complications are often the important factor compromising the effect of surgery. Hou et al.[27] reported that the most common complication in thoracic spine surgery for ossification of ligamentum flavum is CSF leak (69%), followed by neurological deterioration (21%), infection (5%), dehiscence (3%), deep venous thrombosis (DVT, 1%) and death (1%). The occurrence of dural adhesion, as reported, was 56% and 100% in the fused type and tuberous type, respectively.[28] Dural adhesion makes it unlikely for traditional procures to resect the ossified mass directly with dura mater and arachnoid membrane intact, leading to a result of high occurrence of CSF leak. Early neurological deterioration is not infrequent for traditional surgical procedures.[29] Higher occurrence of early neurological deterioration after laminectomy for thoracic spinal stenosis (14.5%), compared with that for cervical spinal stenosis (5.5%), was observed by Young et al.[30] The known causes of early neurological deficits are direct intraoperative spinal cord injury and postoperative epidural hematoma.[31,32] In addition, tenuous blood supply in thoracic spinal cord and narrow space of thoracic spinal canal also contributes to the early neurological deficits. However, the etiology of late neurological deterioration has not been elucidated clearly.[33,34] In our study, the common postoperative complications of the gantry crane technique for thoracic ossification of ligamentum flavum was SSI (11.1%, 2 in 18), followed by CSF leakage (5.6%, 1 in 18) and NI (5.6%, 1 in 18), which was the result of the indirect manipulation of ossified ligamentum flavum inside the spinal canal. The dura remains attach to the ossified ligamentum flavum throughout the isolation and suspension. Postoperative CT and MRI imaging revealed sufficient decompression of the spinal cord.

From the above discussion, the advantages of our new technique are as follows. Firstly, the isolation and ascension of laminae and ossified ligamentum flavum can enlarge the space of spinal canal without disturbing dural matter, as a result of less occurrence of postoperative complications. Secondly, symmetrical decompression with less damage to the stability of spine allows wider ranges of indications for the technique. Finally, the posterior elevation height of laminae and ossified ligamentum flavum are controllable, leading to precise treatment for each individual.

Limitations

The technique we proposed in this study has its own limitations. Firstly, we had a small number of patients with relatively shorter periods of follow-up at a single center, leading to the lack of judgment about the further clinical effects and safety of gantry crane technique, and limiting its generalizability to other centers that use different surgical approaches. However, we standardized the procedure of gantry technique used in this study as much as possible, and baseline characteristics of diagnosis were well balanced, so the preliminary clinical outcomes in this study supported the effectiveness and safety of this technique. The follow-up period was relatively short, which may attenuate the convincingness of this technique's long-term outcomes. Secondly, the laminae pulsation along with dura mater, which is the indicator of complete decompression, can't be monitored directly because the intactness of dural mater. Finally, the elevation is usually empirical and lacks in support of objective and accurate data. Thus, further studies on precise surgical indications and quantitative surgical procedures are till of great importance. Prospective double-blind multicenter study with larger sample size and longer follow-up are warranted to confirm our findings.

Conclusion

In summary, this study highlights a safe and effective technique, the gantry crane technique, for treating severe thoracic spinal stenosis and myelopathy caused by ossification of the ligamentum flavum. The novel idea of isolation and elevation of laminae and ossified ligamentum flavum to achieve directly decompression of spinal cord can significantly reduce the occurrence of tissue damage and postoperative complications. Further extension of the technique could be the study with larger sample size and longer follow-up time.

Authors' Note

Jian Zhu, Xi Luo, and Kaiqiang Sun are co-first authors. The manuscript submitted does not contain information about medical device(s)/drug(s).

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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