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ORIGINAL ARTICLE

Posterolateral approaches to the thoracic spine for calcific disc herniation: is wider exposure always better?

Giuseppe Corazzelli[1] · Giulio Di Noto[2] · Antonio Ciardo[3] · Manuel Colangelo[1] · Sergio Corvino[1] · Settimio Leonetti[4] · Alessandro D'Elia[4] · Francesco Ricciardi[4] · Andrea Bocchino[1] · Sergio Paolini[4] · Vincenzo Esposito[4] · Gualtiero Innocenzi[4]

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Abstract

Objective To compare the costotransversectomy (CTV) and transpedicular (TP) approaches versus the transfacet (TF) approach for the surgical treatment of calcific thoracic spine herniations (cTDH), in terms of surgical and clinical outcomes.

Background Surgical approaches for cTDH are debated. Anterior approaches are recommended, while posterolateral approaches are preferred for non-calcific, paramedian, and lateral hernias. Currently, there is limited evidence about the superiority of a more invasive surgical approach, such as CTV or TP, over TF, a relatively less invasive approach, in terms of neurological outcome, pain, and surgical complications, for the treatment of cTDH.

Methods A retrospective, observational, monocentric study was conducted on patients who underwent posterolateral thoracic approaches for symptomatic cTDH, between 2010 and 2023, at our institute. Three groups were drafted, based on the surgical approach used: TF, TP, and CTV. All procedures were assisted by intraoperative CT scan, spinal neuronavigation, and intraoperative neuromonitoring. Analyzed factors include duration of surgery, amount of bone removal, intraoperative blood loss, CSF leak, need of instrumentation for iatrogenic instability, degree of disc herniation removal, myelopathy recovery. Afterwards, a statistical analysis was performed to investigate the bony resection of the superior posterior edge of the vertebral soma. The primary outcome was the partial or total herniation removal.

Results This study consecutively enrolled 65 patients who underwent posterolateral thoracic surgery for cTDH. The TF approach taking the least, and the CTV the longest time ($p < 0.01$). No statistical difference was observed between the three mentioned approaches, in terms of intraoperative blood loss, dural leakage, post-resection instrumentation, total herniation removal, or myelopathy recovery. An additional somatic bony resection was successful in achieving total herniation removal ($p < 0.01$), and the extent of bony resection was directly proportional to the extent of hernia removal ($p < 0.01$).

Conclusions No statistically significant differences were highlighted between the TP, TF, and CTV regarding the extent of cTDH removal, the postoperative complications, and the neurological improvement. The described somatic bone resection achieved significant total herniation removal and was directly proportional to the preop against postop anteroposterior diameter difference.

Keywords Thoracic disc herniation · Posterolateral approaches · Calcific thoracic spine herniations · Costotransversectomy · Surgical outcomes

Introduction

Thoracic disc herniation (TDH) is a rare condition, with an estimated incidence of 1 in 1,000,000 people [8]. Symptomatic thoracic hernias are amenable to surgical treatment. These approximate only 0.15% to 4% of the procedures for disc herniations. TDHs are calcific in 40% of cases and are defined as giant when involve 40% or more of the spinal canal [16].

The ascribable symptomatology is progressive myelopathy. Diagnosis is made by Magnetic Resonance Imaging (MRI), also showing the evidence of myelopathy. Given the invasiveness of neurosurgical approaches to the thoracic spine, surgical indication is granted to selected patients [5].

In time, anterior approaches to the thoracic spine have been described as the most suitable to visualize and remove

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the entirety of the herniation at the expense of increased surgical efforts and complication rates. Posterolateral approaches to the thoracic spine are feasible in several favorable conditions, such as the non-calcific consistency and the paramedian or lateral position of the thoracic herniation [4].

Noteworthy, in recent decades, spinal neurosurgery has adopted new technologies to support the surgeon in performing challenging procedures, such as intraoperative Computed Tomography (CT), spinal navigation, and motor and sensory evoked potentials in the lower extremities [14].

The most feared complications of posterolateral approaches are residual herniation, stationary or worsening myelopathy, CSF dural leak, and iatrogenic instability of the spine, resulting from the osteotomy of the intervertebral joints or the costal processes or the proximal portion of the rib [11].

Over time, anterior approaches to the thoracic spine have been progressively discontinued, in preference of posterolateral approaches tailored to the position and consistencies of thoracic hernias [1]. Nevertheless, there is limited evidence in the literature regarding the effective superiority of more invasive approaches on osteomuscular structures, such as costotransversectomy (CTV) and the transpedicular (TP) approaches, potentially destabilizing, over relatively less invasive approaches, transfacet (TF), sparing the costotransverse process and the ipsilateral pedicle.

In this setting, the aim of the present study is to compare CTV, TP and TF for the treatment of cTDH, from surgical, neuroradiological and clinical points of view, through a retrospective analysis of a monoinstitutional series of 65 patients.

Materials and methods

Selection criteria

In this retrospective, monocentric, observational study, clinical data were collected and analyzed from all the patients who received surgical procedures for calcific thoracic disc herniation (cTDH) between January 2013 and June 2023 at our Institution. The diagnostic criteria consisted of myelopathic cTDH and coherent thoracic spine MRI, confirming compression on the thoracic spinal cord. The surgical procedures were performed in the same single center and by the same surgical team, assuming uniform periprocedural management.

Patients were selected based on the following combined criteria:

- Clinical and radiological diagnosis of myelopathic cTDH.
- Availability and reliability of preoperative and 6-month postoperative neurological examination.
- Availability of preoperative and early postoperative thoracic column MRI and CT exams
- Accurate description of the surgical procedure and parameters (operative time, operative blood loss)
- Posterior-lateral approach to the thoracic spine (CTV, TP, or TF) (Fig. 1)
- Elective spinal surgery

At our institution, 96 (ninety-six) patients received thoracic discectomy procedures between the years 2013 and 2023. After screening of electronic records and clinical data, after removing patients who did not thoroughly observe (24 pts), or lost at follow-up (7 pts), we obtained the sample of the study. Hence, 65 (sixty-five) cTDH patients were enrolled. Electronic clinical charts, pre- and postoperative MRI (Fig. 2) and operative procedures were evaluated. Formerly, patients were divided into three groups, according to the selected approach: TP (n = 25, 38%), TF (n = 32, 49%), and CTV (n = 8, 12%). There was no selection of patients for approach, either dimensional or positional of the hernia, but rather a time evolution criterion. At our institution, it was observed that adopting CTV resulted in cruentation of the muscle and ribs, which did not offer effective surgical improvement. Therefore, at first CTV was the most used approach, especially, but not exclusively, adopted in the years 2013 to 2017, whereupon

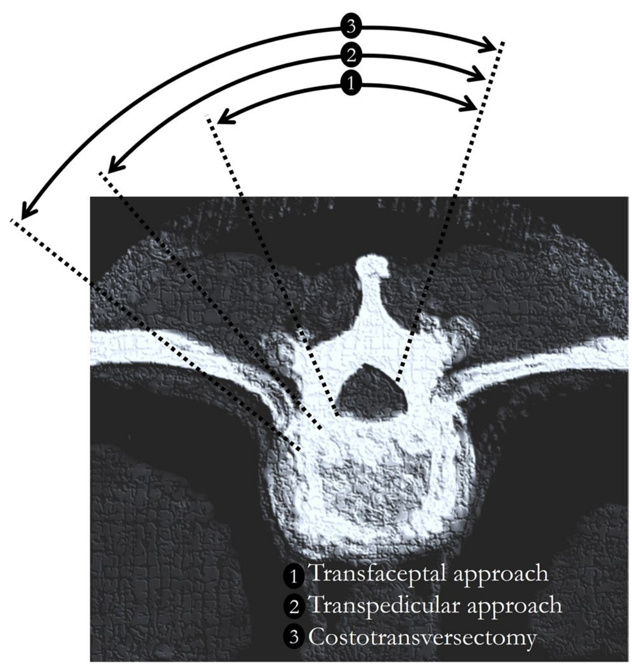

Fig. 1 CT axial section of the T11 vertebra, illustrative of the three surgical approaches examined in the study. 1. Transfacet approach, 2. Transpedicular approach, 3. Costotransversectomy

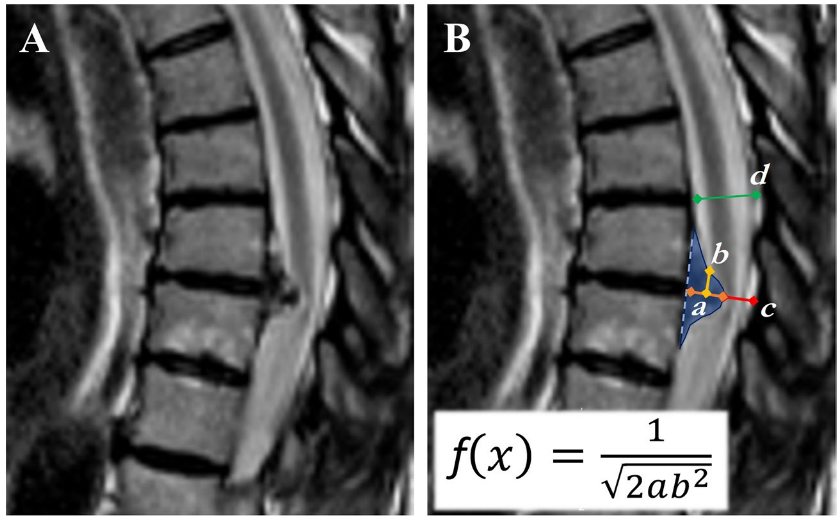

Fig. 2 Thoracic column MRI, sagittal T2w sequence. **A.** Median cTDH at T10-T11 level, at the slice of the maximum anteroposterior diameter, with compression on the spinal cord and subsequent myelopathy. **B.** Same sequence, illustrating the sagittal area drawing procedure. The formula for the area under the Gaussian curve is presented below. In detail, the mean (μ) of the Gaussian is line **a**, and the standard deviation (σ) is the line **b**. The compression ratio of the hernia on the spinal cord is calculated as the difference of the **d** and **c** lines

all the surgeons included in the study tended to adopt TP, between the years 2016 and 2021, then TF, particularly from 2019 onwards, depending on the reduced threat of instability and the same surgical vision, also implemented by intraoperative navigation, 45° endoscope and 3D-exoscope. In some surgical procedures, a minimal osteotomy was performed on the bony edges of the limiting bones, to create a chamber inside the vertebral soma, where the hernia could be scooped out, dissected after having reduced it to a final shell adherent to the ventral aspect of the dura, without dislocation of the spinal cord. Figure 3 illustrates the bone reaming process performed with the help of the Misonix. The details of this surgical technique were first described in this study [8]. Patients were divided according to the surgical procedure characterized or not by this minimal bone reaming.

All the patients gave written informed consent to the procedure and the reporting of each case.

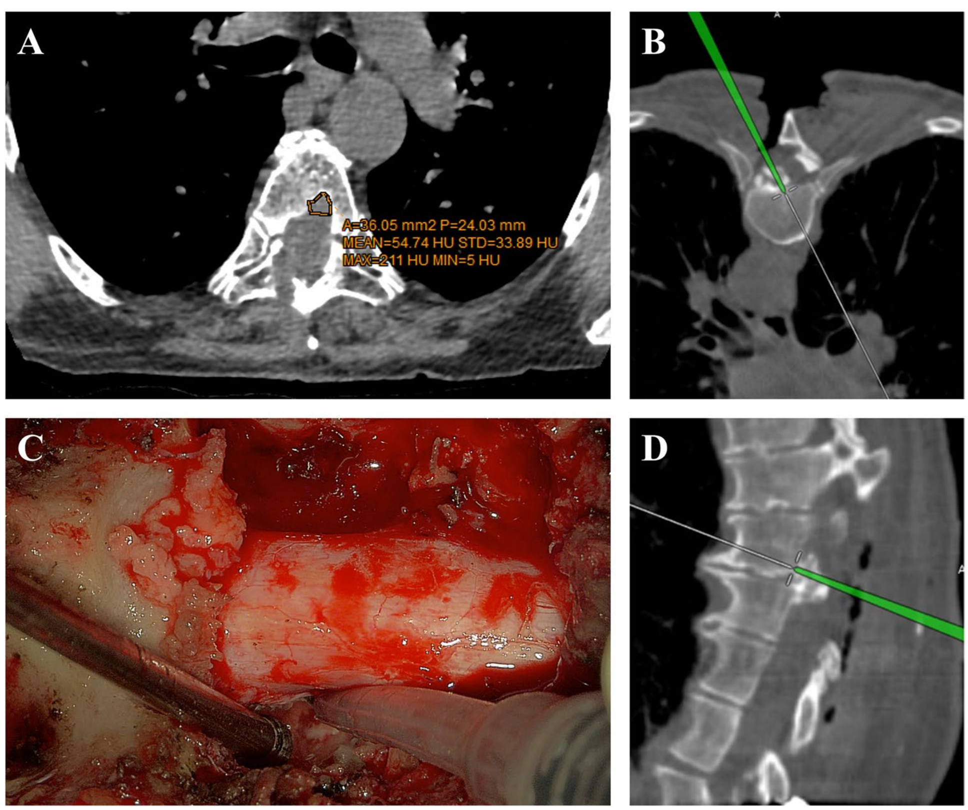

Fig. 3 Posterior-superior vertebral bone resection: **A**. Hand-drawn area of the bone resection performed on the super-posterior aspect of the T9 vertebra. **B**. Intraoperative CT, axial image, showing the complete excision of the cTDH. **C**. Magnified view at the 3D-exoscope (Orbeye) of bone resection with ultrasonic aspirator (Misonix). **D**. Intraoperative CT, sagittal image, showing the complete excision of the cTDH

Surgical procedures

The surgical procedure begins with a median incision made at the specific thoracic segment affected by the condition. This incision provides access to the area needing treatment. From there, a meticulous dissection ensues, involving the paravertebral muscles. For cases involving the costotransverse junction (CTV), dissection extends up to this point, while for cases involving the transverse process (TP and TF), dissection goes up to the respective anatomical landmarks.

Utilizing microscopic magnification for precision, a high-speed drill is employed to carefully remove the costotransverse process in cases involving CTV, as well as the inferoproximal portion of the overlying pedicle in cases of both CTV and TP involvement. Further drilling includes the medial third of the pedicle and the ipsilateral lamina for cases involving CTV, TP, and TF. These meticulous removals create the necessary space for subsequent steps.

Following this, the herniated disc or tissue causing the compression is meticulously identified and dissected away from the delicate thoracic dura mater. This step requires utmost precision to avoid any damage to the surrounding neural structures.

Finally, once the herniated tissue has been safely removed, any remaining fragments or protrusions are carefully addressed using a combination of high-speed drill and microrongeur techniques. Once the area is clear of any offending tissue, the surgical site is meticulously closed in layers to ensure proper healing and minimize the risk of post-operative complications [9, 15, 22].

All patients received surgery using a three-dimensional (3D) computed tomography navigation system (O-Arm CT scan—Medtronic), with Stealth Station System. Intraoperative monitoring of motor evoked potentials (MEPs) and somatosensory evoked potentials (SSEPs) were used to detect the incidence of spinal cord injuries. Electrophysiological surveying was done under basal conditions, at the patient's pronation, at the end of bone resection, several times during hernia dissection, at the end of resection, and at the end of closure. There were no aborted procedures due to decreased potentials. For any transient drop in MEPs and SSEPs, surgical maneuvers were abstained momentarily. Upon restoration of potentials, the procedure resumed.

Postprocedural secondary stabilization was chosen in three cases of 1-month increased range-of-movement at dynamic anteroposterior and lateral-lateral radiographic array.

For further clarification of the surgical approaches, we recommend consulting the work of Kshettry et al. [12], which provides anatomical comprehensive detailed insights into the methodological nuances, which may complement the textual descriptions provided in this manuscript.

Variables analyzed

Clinical variables included age, sex, and level involved, subdivided into the upper (T1-T4), middle (T5-T8), and lower thoracic spine (T9-T12), the position (median, paramedian left and right), and preoperative and 6-months postoperative Sunnybrook Cord Injury Scale (SCIS); radiological parameters were collected from pre, early and 6-month postoperative MRI and CT, and included the Anteroposterior diameter and the sagittal area of the calcific herniation, the compression grade on the dural sac, the postoperative extent of resection of the cTDH, and the area of the vertebral bone resection; the surgical parameters included the selected approach, intraoperative blood loss, operative time, dural leak, the use or not of the 45° endoscope, the use or less of the 3D exoscope system (OrbEye), need for post-resection instrumentation and the performance or not of the aforementioned bony resection.

MRI studies feature

All MRI studies were performed using a 1.5 T MR scanner and analyzed on a RadiAnt DICOM Viewer, Version 5 workstation. All MRI studies included T1- and T2-weighted images in sagittal and axial planes. The standard panel comprised of lumbar and sacral rachis. The matrix size measured 288 × 288, and the field of view spanned 200 × 1170 mm. The axial planes had a slice thickness of 4 mm and an interslice gap of 1 mm. Several measurements were performed on preoperative, intraoperative, and postoperative MRI and CT. Anteroposterior axial and sagittal diameter of the cTDH, the sagittal and axial area of the cTDH was calculated based on the Gaussian curve formula, as shown in Fig. 2, the volume was then calculated. The percentage of compression was determined, through the ratio of slices of higher hernia expression to a healthy level (Fig. 2B; C/D). These measurements were compared between the preoperative and the postoperative MRI and CT. Afterward, the procedures in which a minimal bony resection was performed at the superior-posterior corner of the vertebral body were further examined to collect the extent of bony removal in volume. The Regions of Interest (ROIs) were meticulously determined (Fig. 3). The initial drafting of the areas was conducted by one Author, and then revised and corrected by two others. To ensure accuracy, an experienced radiologist, not involved in the study, further reviewed and confirmed the ROI measurements [18].

Statistical analysis

Descriptive statistical analyses were performed adopting a non-parametric Kruskal–Wallis test for categorical and qualitative variables. To evaluate the variables over time, the two-way ANOVA test was used (Fig. 4). Concerning the bony resection analysis, Mann–Whitney test and linear univariate regression analysis were adopted (Fig. 5). The sample bony resection normal distribution was assessed using the Shapiro–Wilk test. Inter-rater reliability for MRI studies observers was assessed through the Cohen "Kappa". All statistical analyses were two-tailed, and α-error was set at p-value < 0.05. Data were aggregated in Microsoft Excel (version 14.2.5), and GraphPad software (version 10.01.01) performed the statistical analysis.

Results

Sixty-five patients (65 pts) were enrolled in this study as they matched the selection criteria. The sample included 34 females (52%) and 31 males (48%), with a mean age of 54.33 (± 13.16; range 21–82 years). The neurological onset was myelopathy in 73% of cases, back pain in 14% of cases, and intercostal neuralgia in 13%. The TP approach was performed in 25 patients, TF in 32, and CTV in 8. The sample showed a considerable prevalence of lower level cTDH (n = 43; 66%) compared to intermediate cTDH (n = 21; 32%) and upper cTDH (n = 1; 2%). Statistical descriptive analyses on the sample baseline characteristics are listed in Table 1.

25 procedures (38%) were performed using the 45° endoscope [19], and three procedures (4%) were performed under 3D exoscopic magnification throughout the surgery.

The preoperative size and the position of the hernias were homogeneous between the three groups (p = 0.23, and p = 0.15, respectively). The areas of residual hernias on the postoperative CTs were measured, not showing significant difference between the three approaches (p = 0.16). There was a substantial inter-rater agreement between Observer A and B (K 0.67; SE 0.094; 95CI 0.49–0.85), B and C (K 0.80; SE 0.083; 95CI 0.63–0.96), and A and C (K 0.66; SE 0.102; 95CI 0.467–0.865).

The three mentioned approaches did not show a significant difference in terms of intraoperative blood loss (p = 0.27), thoracic instrumentation (p = 0.86), complete

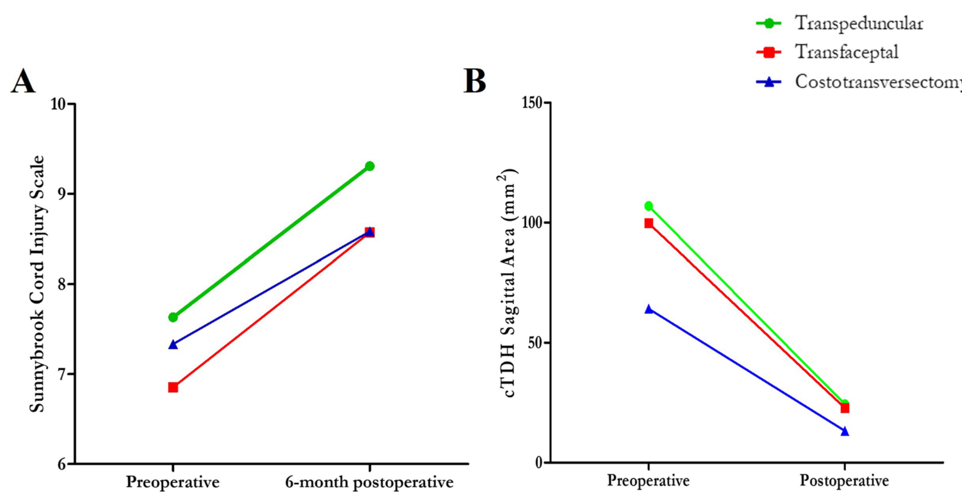

Fig. 4 **A**. Two-way ANOVA test comparing the Sunnybrook Cord Injury Scale preoperatively and 6 months postoperatively, between the three posterolateral thoracic spine approaches (p = 0.69). **B**. Two-way ANOVA test comparing the difference between pre and postoperative sagittal areas of the cTDH, between the three posterolateral approaches to the thoracic spine (p = 0.16)

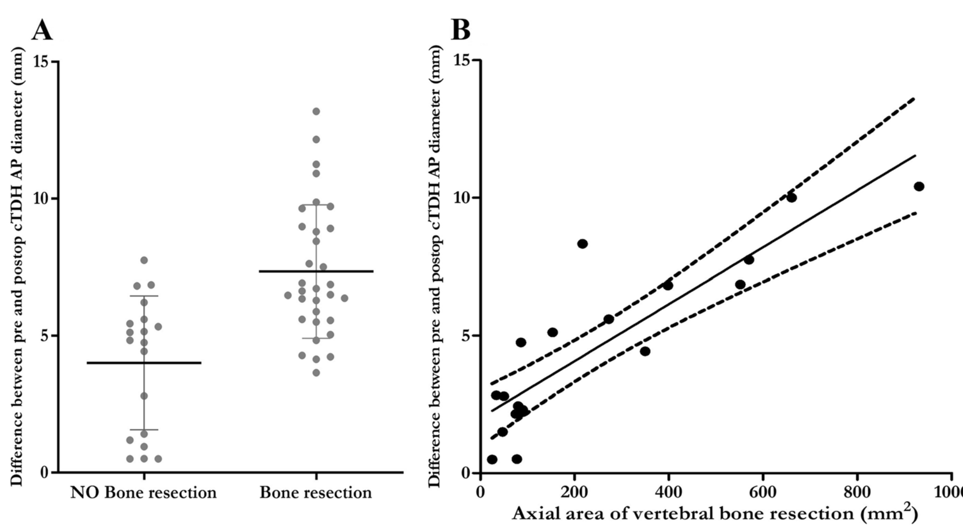

Fig. 5 **A**. Scatter dot-plot comparing the difference between pre and postoperative AP diameter between patients receiving or not vertebral bony resection of the posterosuperior edge of the lower vertebral soma. **B**. Statistical analysis on patients who received bony resection. Univariate linear regression analysis (p < 0.01; r square 0.76) showing significant direct proportionality between the extent of bone resection and the difference in cTDH AP diameter

Table 1 Sample's baseline characteristics. Descriptive statistical analyses of clinical, radiological, and surgical parameters

	Variables	Transpedicular (n = 25)	Transfacetal (n = 32)	Costotransversectomy (n = 8)	Kruskal–Wallis test
Clinical parameters	Age *	52.08 (± 8.86)	55.13 (± 15.50)	56.88 (± 15.24)	p = 0.86
	Sex ¥				
	Male	14 (56)	15 (47)	2 (25)	p = 0.15
	Female	11 (44)	17 (53)	6 (75)	
	Symptoms ¥				
	Myelopathy	19 (76)	24 (75)	5 (62)	p = 0.15
	Low back pain	3 (12)	5 (15)	1 (13)	
	Neuralgia	3 (12)	3 (10)	2 (25)	
	Preop SCIS *	7.71 (± 1.87)	6.84 (± 1.71)	7.0 (± 1,14)	p = 0.87
	6-months postop SCIS *	9.16 (± 0.91)	8.61 (± 2.39)	7.87 (± 1.96)	p = 0.18
Radiological parameters	Level involved ¥				
	Upper (T1-T4)	0	0	1	p = 0.76
	Middle (T5-T8)	8	10	3	
	Lower (T9-T12)	17	22	4	
	cTDH site ¥				
	Median	18 (72)	20 (62)	6 (75)	p = 0.15
	Paramedian	7 (28)	12 (38)	2 (25)	
	Preop cTDH Sag Area ‡	106.9 (± 44.06)	98.17 (± 51.40)	64.18 (± 26.18)	p = 0.23
	Postop cTDH Sag Area ‡	24.35 (± 30.99)	22.75 (± 39.01)	13.28 (± 25.29)	p = 0.13
Surgical parameters	Preop Hb #	14.35 (± 1.38)	14.61 (± 1.27)	12.72 (± 0.53)	p = 0.27
	POD1 Hb #	12.11 (± 1.31)	12.34 (± 1.52)	9.80 (± 1.16)	
	Intraoperative blood loss #	2.23 (± 0.96)	2.26 (± 0.93)	2.92 (± 0.81)	
	Operative times *	245.3 (± 79.29)	215.6 (± 68.16)	326.9(± 54.77)	**p < 0.01**
	Complete cTDH removal ¥	15 (60)	18 (56)	6 (75)	p = 0.13
	Thoracic instrumentations ¥	2 (8)	0 (0)	1 (12)	p = 0.86
	Thoracic dural leak ¥	8 (32)	4 (12)	1 (12)	p = 0.36
	Exoscope-assisted procedures	2	0	1	
	Intraoperative CT-assisted procedures	25 (100)	32 (100)	8 (100)	
	Spinal navigation-assisted procedures	25 (100)	32 (100)	8 (100)	
	SSEP and MEP-assisted procedures	25 (100)	32 (100)	8 (100)	
	45° Endoscope cTDH AP difference ¥ (†)	3 (5.83 ± 3.99)	17 (5.75 ± 3.54)	5 (6.24 ± 0.45)	**Kruskal–Wallis test**
	No- 45°endoscope cTDH AP difference ¥ (†)	22 (5.10 ± 3.75)	15 (5.43 ± 5.36)	3 (2.82 ± 1.91)	p = 0.45
	Mann–Whitney test	p = 0.89	p = 0.60	p = 0.39	
Bony resection analysis	**Bony resection – enhanced procedures**	**Yes (n = 30)**		**No (n = 35)**	**Kruskal–Wallis test**
	Transpedicular	10 (33)		15 (42)	p = 0.15
	Transfacetal	14 (47)		18 (51)	
	Costotransversectomy	6 (20)		2 (5)	
					Mann–Whitney test
	cTDH AP diam †	8.37 (± 2.55)		8.32 (± 3.38)	p = 0.96
	Postop cTDH AP diam †	4.0 (± 2.44)		6.33 (± 2.43)	**p < 0.01**
	Bony resection area ‡	250.4 (± 259.7)			

*The variable is expressed as mean ± standard deviation

¥The variable is expressed as Raw Frequency (percentage)

‡The variable is expressed in mm^2, as mean ± standard deviation

†The variable is expressed in mm, as mean ± standard deviation

#The variable is expressed in g/dL, as mean ± standard deviation cTDH removal (p = 0.13), and dural leakage rate (p = 0.36). Nevertheless, the three surgical approaches demonstrated the presence of statistical significance in terms of intraoperative time, with TF approach taking the least, and CTV the longest time (p < 0.01).

Post-procedural stabilization of the thoracic spine was required in only three cases (5%). However, the difference between the three surgical approaches was not significant (p = 0.86). Likewise, the incidence of CFS leak did not differ between the three approaches (p = 0.04).

Preoperative myelopathy was essentially homogeneous in the sample examined (p = 0.87). It was subsequently assessed six months after neurosurgical intervention and was not significantly different between the three different surgical approaches (p = 0.18). Two-Way ANOVA did not achieve significance in 6-month postoperative myelopathy recover between the three different approaches (p = 0.69) (Fig. 4A) and the cTDH area reduction (p = 0.16) (Fig. 4B). Nonetheless, all patients significantly improved their myelopathy in time, between preop and 6-month postoperative follow-up (p < 0.01). The analysis of the use of the 45° endoscope did not lead to a significant reduction in thoracic disc herniation in our series (Table 1; KW p = 0.45).

Concerning bony resection of the superior posterior edge of the vertebral soma, our analyses showed that patients who benefited from it showed a significant percentage of total hernia removal (p < 0.01) (Fig. 5A). Additionally, linear regression model showed the extent of bony resection proportionally correlating with the percentage of hernia removal (p < 0.01, R square 0.76) (Fig. 5B). Deductive statistical analyses performed on the sample are listed in Table 2.

Discussion

This study aimed to demonstrate the non-superiority, in terms of intraoperative complications, time, blood loss, and postoperative functional outcome, of more invasive approaches to the thoracic spine, such as CTV and TP, compared to the TF, which preserves the lateral two-thirds of the pedicle and the costotransverse process, in the surgery of cTDH. With this aim, an institutional case series of 65 consecutive patients operated for cTDH, between 2013 and 2023, were enrolled. Notably, this was the first study to assert the substantial homogeneity of the posterolateral approaches to the thoracic spine, in terms of postoperative complications, operative time and blood loss, and long-term functional outcome in myelopathic patients operated for cTDH. Myelopathy was assessed with the SCIS grading scale, a reproducible, reliable, and statistically valid index [3]. Moreover, our study represents the first evidence of 3D exoscopic magnification in cTDH surgery. In addition, the

Table 2 Deductive statistical analyses performed on the sample

Statistical analysis performed among the differences in patients' parameters between preoperative and 6-month follow-up						
Model	Transpedicular (n = 25)	Transfacetal (n = 32)	Costotransversectomy (n = 8)		Two-Ways ANOVA	
Difference between pre and postoperative SCIS *	1.45 (±1.39)	1.77 (±2.05)	0.87 (±1.55)		p = 0.69	
Difference between pre and postoperative cTDH Sag Area ‡	82.55 (±37.52)	75.42 (±45.20)	50.9 (±25.73)		p = 0.16	
Bony resection – enhanced procedures	**Yes (n = 30)**	**No (n = 35)**			**Mann–Whitney test**	
Difference between preop and postop cTDH AP diam †	4.37 (±2.49)	1.99 (±2.91)			**p < 0.01**	
Univariate linear regression analysis between the amount of bone resection and the anteroposterior diameter difference of cTDH						
		S-W normality test	R square	Std. error	F	F change (p-value)
Bony resection area ‡	250.4 (±259.7)	Yes (p = 0.19)	0.76	1.52	55.51	**p < 0.01**
Difference between preop and postop cTDH AP diam †	4.37 (±3.06)					

*The variable is expressed as mean ± standard deviation

¥The variable is expressed as Raw Frequency (percentage)

‡The variable is expressed in mm^2, as mean ± standard deviation

†The variable is expressed in mm, as mean ± standard deviation

#The variable is expressed in g/dL, as mean ± standard deviation use of technologies such as spinal navigation allows the overlapping of these approaches in terms of total resection of calcific hernia. Recently, the use of the 45° endoscope has been addressed as an aid for the neurosurgeon to reduce the amount of bone resection and increase visibility [17]. This was not reflected in our case series. Undoubtedly, adopting these recently introduced technologies has allowed the complete removal of 60% of cTDH, as well as a low incidence of intra- and post-operative complications. The descriptive variables of our sample were consistent with the existing literature [8]. Given the rarity of this pathology, it is difficult to draw unambiguous conclusions.

In this study, sampling and determination biases were reduced to minimum to assert the non-significant differences between the CTV, TP, and TF approaches. Remarkably, cTDH represents a rare pathology, with an estimated frequency of 1 per 1,000,000/year [6]. Specifically, surgical procedures in the thoracic spine account only for 0.15% to 4% of disc herniation surgeries [8]. Notably, in 75% of cases, the TDH location is below the T8 level [10]. The surgical indication is clear at severe refractory back pain, incoercible thoracic neuralgia, or neurological deficits, such as myelopathy or lower limb hyposthenia [14]. Respectively, myelopathy accounts for 70%, intractable radiculopathy for 24%, and back pain for 6% of surgical indications [2].

Historically, posterior laminectomy appears to be obsolete since it has demonstrated a 33% postoperative morbidity [11]. There is discordance in the literature on the superiority of anterior or posterolateral approaches to the thoracic spine, despite recent studies conclude the latter being associated with lower complication rates, better discharge rates, and functional outcomes [1, 8, 13, 21]. However, there is no accurate comparison between posterolateral approaches to the thoracic spine [20].

Our work stands as survey among posterolateral approaches to the thoracic spine. We believe that spinal surgery is evolving towards a progressively less invasive strategy with respect to osteomuscular structures [7]. Therefore, it is pertinent to opt for the least structural bone resection and least cruentation of the paravertebral musculature.

Furthermore, this study was the first to describe the surgical outcomes of minimal bony resection of the superoposterior edge of the inferior vertebral soma. The extent of bony resection on postoperative CT scans was measured. The diameter of residual cTDH was statistically lower in procedures where a bone resection was performed. In approaches where little exposure is provided, minimal bony removal of the vertebral soma may provide a larger working chamber to remove more herniary material. Data in the presented case series confirm this finding, with an effective direct proportionality between bone and herniation resection. This parameter is relative because the extent of thoracic hernia removal does not necessarily correlate with clinical improvement. However, the substantial radiological overlap is interesting, considering the difference in invasiveness between the three approaches.

Among the limitations existing in this study, the inaccuracy bias deriving from manual drawing of ROIs was minimized by the assessment between multiple professional figures, who checked and corrected the regions of interest. Nonetheless, a slight margin of error still exists, albeit minimal.

In addition, another important limitation concerns the relatively low sample size. Regrettably, unicomprehensive inferences may not be drawn from a limited patient population. Furthermore, the intrinsic limitation subsists in the retrospective nature of the present study. However, carrying out a prospective randomized surgical study on myelopathic pathology, in our opinion, would be unethical, as surgery is aimed at the best possible outcome for each patient. However, the sample included in the study is a relatively large one, considered the rarity of the pathology. Thoracic hernias are relatively uncommon. On the other hand, in view of the sample's homogeneity, and the uniformity with the described series in the literature, the difference between more invasive approaches, such as CTV and TP, and relatively less invasive approaches, such as TF, appears to be statistically insignificant for the cTDH management. In our opinion, however, further prospective studies are needed to evaluate the advantages and disadvantages of each posterolateral approach to the thoracic spine.

Conclusion

In our patient series, no statistically significant differences were found between the three different posterolateral thoracic spine approaches for cTDH, in terms of herniation removal, operative complications, blood loss, and postoperative functional outcomes. In less dural exposure approaches, a minimal vertebral body bone resection may provide a larger working chamber, with significant increase in the rate and proportion of herniation removed. This was the first study, to our knowledge, to depict this comparison. In our series, the simpler and less invasive technique has turned out not to be different from the other, more invasive approaches to the thoracic spine for cTDH. Further prospective studies are needed to firmly establish which technique is the optimal option for cTDH.

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Declarations

Ethics approval The ethical review process and approval by our ethics committee were not required for the present study because it is a retrospective study. Furthermore, the research data analysis does not affect the participants and their medical care. The study itself configures as a retrospective collection and analysis of clinical and surgical electronic data, available from the corresponding Author behind reasonable request.

Informed consent Informed consent was obtained from all participants in the study, both for the procedure and the publication of anonymized surgical and clinical material.

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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Authors and Affiliations

Giuseppe Corazzelli[1] · Giulio Di Noto[2] · Antonio Ciardo[3] · Manuel Colangelo[1] · Sergio Corvino[1] · Settimio Leonetti[4] · Alessandro D'Elia[4] · Francesco Ricciardi[4] · Andrea Bocchino[1] · Sergio Paolini[4] · Vincenzo Esposito[4] · Gualtiero Innocenzi[4]

✉ Giuseppe Corazzelli
GiuCoraz@gmail.com

[1] Division of Neurosurgery, Department of Neurosciences, Reproductive and Odontostomatological Sciences, "Federico II" University, Naples, Italy

[2] Division of Neurosurgery, Università Degli Studi Di Messina - Policlinico "G. Martino", Messina, Italy

[3] Division of Neurosurgery, Department of Human Neuroscience, University of Rome "Sapienza", Rome, Italy

[4] Department of Neurosurgery, IRCCS Neuromed, Pozzilli, IS, Italy