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'Short Bars Crossed' to Remodel the Entire Chest Wall in Children and Adolescents with Pectus Excavatum☆

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Background: The cross-bar technique of minimally invasive pectus excavatum (PE) correction remains underreported, which is especially true of pediatric patients. We therefore reviewed the experience of a Turkish and an Austrian center. An additional novelty characterizing both pediatric cohorts was the use of short bars.

Methods: In a retrospective study, pediatric PE corrections involving 'short bars crossed' were analyzed for complications and intra-/postoperative outcomes. Cases with two or three bars were included, given that a horizontal third bar was placed whenever considered useful for upper-chest elevation. All bars were fitted with a single stabilizer near the surgical entry point. In the Austrian center, intercostal nerve cryoablation was used for pain management. Descriptive statistics are presented.

Results: Seventy-eight patients ≤18 years old were evaluable at the Turkish (n = 56) and Austrian (n = 22) centers. Total median values were 16.2 (IQR: 15.1–17.4) years for age and 4.60 (IQR: 3.50–6.11) for Haller index. Ten mild or moderate complications (12.8%) were observed, including just one revision requirement due to bar migration (1.28%). Intercostal nerve cryoablation (n = 13) was associated with longer surgical procedures at 150 (IQR: 137–171) versus 80 (IQR: 60–100) minutes but with shorter hospital stays, given an IQR of 3–4 days versus 4–5 days.

Conclusion: 'Short bars crossed'—with a single stabilizer in a ventral position close to the surgical entry point—ensure a wide distribution of forces, protect against bar migration, are safe and effective, and offer stability at an age characterized by growth and physical activity.

Level of Evidence: IV.

1. Introduction

Pectus excavatum (PE) is a common congenital deformity of the chest wall that occurs in approximately 1 out of 300–400 individuals, with a male-to-female predominance of about 4:1 to 5:1 [1–4]. While treatment with a vacuum bell can yield acceptable results in mild to moderate deformities, more severe cases will often require surgical correction for functionally and cosmetically adequate outcomes [5,6].

The surgical concept known as 'minimally invasive repair of pectus excavatum' (MIRPE) was first described by Nuss et al. in 1998 [7]. Gaining wide popularity and acceptance among specialized surgeons, MIRPE has superseded previous techniques of open surgery for PE over the years [8–12]. As this development has resulted in a growing number of patients, surgeons were increasingly faced with more complex deformities that required modifications to the default MIRPE technique. These modifications have predominantly focused on the number, configuration, and length of bars implanted into the pectus.

One novelty that attracted surgeons' attention was the use of two 'short bars crossed', as first reported by Pilegaard and Licht [13,14]. Shorter bars have proven to offer high stability, require fewer stabilizers, and facilitate insertion and removal by minimizing the distances between the incisions and the chest entry/exit points. Their use does not increase complication rates [14,15] and can help to prevent depression of the lateral chest wall, thus further

Abbreviations: CWD, chest wall deformity; HI, Haller index; INC, intercostal nerve cryoablation; MIRPE, minimally invasive repair of pectus excavatum; PE, pectus excavatum.

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minimizing developmental risks such as thoracic growth restriction.

More importantly, the approach of implanting two shorter bars in a crosswise fashion at the deepest point of sternal excavation will optimize elevation of the chest by ensuring that its entire wall is fully covered, thus facilitating remodeling of the entire chest wall as an essential treatment objective in severe cases of chest wall deformity (CWD) [15,16].

'Short bars crossed' also make for high stability of the bar configuration, thus meeting a major requirement for use particularly in children and adolescents, whose chest wall is still more flexible than in adults. Also, this age group typically engages in high levels of physical activity, and stability of the bar configuration becomes even more important as physical appearance and fitness become a major part of life during puberty.

Few studies are currently available on the use of 'short bars crossed', and most of these patients have been adults [17,18]. Hence, we designed a study to report on the experience collected with this specific technique of MIRPE at two specialized centers, specifically in children and adolescents with severe CWD-type deformities due to pectus excavatum.

2. Methods

2.1. Study design

The investigation was performed retrospectively across two centers: the Marmara University Istanbul in Turkey (Department of Thoracic Surgery) and the Medical University of Vienna in Austria (University Clinic of Pediatric Surgery). Approval of the study protocol was obtained from both institutional review boards (Turkish center: IRB #09.2023.331; Austrian center: EK #2078/2023).

2.2. Study population

Any children and adolescents ≤18 years old who had been treated by MIRPE using 'short bars crossed' were eligible for inclusion. The medical documentation systems of both centers were thoroughly reviewed to this end, covering the periods of 08/2005–09/2023 at the Turkish (n = 1089) and 01/2012–11/2023 at the Austrian (n = 445) center. A total of 78 patients were ultimately included (Turkish cohort: n = 56; Austrian cohort: n = 22). The indication for surgery in all patients was based on a comprehensive assessment of clinical symptoms, the anatomical severity of the deformity and the Haller index.

Both centers have adopted the short bar technique as a routine procedure for all patients. While standard MIRPE with a single bar or multiple parallel bars is adequate for most CWDs in children or adolescents, more complex cases will often require additional structural support to achieve remodeling of the entire chest wall. Accordingly, two 'short bars crossed' had usually been selected in the presence of a morphological PE subtype characterized by *(i)* rib flare; *(ii)* one deep focal depression; *(iii)* a short sternum; or *(iv)* a Grand Canyon-style depression and short sternum (Fig. 1).

2.3. Data collection

For each patient, data were collected about demographic variables, number of bars used, perioperative complications, length of hospital stay, and postoperative details. Pre- and postoperative photographs had been systematically taken and archived. Specific information collected about each PE scenario included the type of deformity and Haller index (HI) scores.

Preoperative assessment of PE patients in the Austrian study cohort consisted of CT or MRI scans. Additional diagnostics included cardiopulmonary function via echocardiography, electrocardiograms, and spirometry to measure forced vital capacity or forced expiratory volume, as well as a 48-h epicutaneous test for metal allergies. In the Turkish cohort, preoperative CT scans had taken place in patients with cardiopulmonary problems, relevant syndromes or anomalies, or previous pectus surgery. Success of the procedures and satisfaction with their outcomes were verified based on the surgeons' postoperative assessment of complete chest wall remodeling and the patients' feedback during outpatient follow-ups (1, 6, and 18 months after surgery).

2.4. Surgical technique

Under general anesthesia with single-lumen endotracheal intubation, the patient is positioned supine, towards the right side of the table, with the right arm positioned above and slightly in front of the head, while the surgeon stands on the right side. A surgical skin marker was used to indicate the deepest point of sternal depression, as well as the surgical entry and exit points, then fitting a malleable template to the morphology of the chest wall for the purpose of shaping the medical-steel bars (Hipokrat®; Hipokrat A.Ş., Izmir, Turkey). Bar length was considered ideal when the structure extended bilaterally over one rib pair. The bar endings were custom-bent for anatomical fitting. In alignment with the anterior axillary line, 2–3 cm vertical incisions were performed bilaterally, and subcutaneous and submuscular pockets were created to accommodate the stabilizer for either bar.

Another incision (3–5 mm) along the right posterior axillary line was created for the thoracoscope, maintaining a capnothorax of 10–12 mmHg. In 13 cases treated at the Austrian center, sternum elevation was preceded by intercostal nerve cryoablation (INC) bilaterally. The cryoablation probe (CryoICE; AtriCure, Mason, OH, USA) was inserted on both sides, and its tip was applied at −70 °C

Fig. 1. A number of distinct PE deformities call for the cross-bar technique: (A) rib flare; (B) one deep focal depression; (C) short sternum; and (D) Grand Canyon type with short sternum.

for 2 min to the neurovascular bundles beneath the ribs from the 3rd to 7th intercostal spaces [19–22]. An introducer was then inserted through the right incision for mediastinal dissection. Intrathoracic vision, and thus the safety of bar placement, was greatly improved by our routine use of a vacuum bell at this point to instantly elevate the sternum. Also, the surgeons continuously visualized the introducer tip during dissection and utilized additional devices (Ligasure Maryland; Medtronic, Minneapolis, MN, USA) or a laparoscopic endokittner as needed.

2.5. Bar and stabilizer placement

The rationale of strategically crossing two bars at the deepest point of the excavation is to simultaneously elevate the sternum along with the entire anterior chest wall while, at the same time, applying downward pressure on any flared ribs via the lower ends of the crossed bars. The orientation of the first bar was from the right upper to the left lower chest, while the second bar extended from the right lower to the left upper chest through the same mediastinal tunnel. The bars are situated submuscularly at their cranial ends and subcutaneously at their caudal ends. The caudal entry-exit points are chosen very deep in the thoracic cage near the diaphragm, with the intention of creating a maximal steep cross to effectively bridge and lift the entire deformity cross-wise. As this technical refinement has not been previously described in the literature, we propose characterizing it as “TTC – Total Thoracic Cross,” as introduced by Prof. Mustafa Yüksel. In situations where two bars crossed would have been insufficient to elevate the upper chest region, a third bar was placed horizontally on top. This horizontal bar was placed prior to the crossed bars for immediate and adequate elevation of the sternum.

Each bar was fitted with a single stabilizer close to the surgical entry point. Firm interlocking of both components was ensured by *(i)* a sliding mechanism for placing the stabilizer over the bar and *(ii)* two custom-bent kinks along the bar. The first kink was introduced with a bender in the process of anatomical bar shaping (as dictated by the malleable template) and served as a stop as the stabilizer was being slid over the bar. Once this stop was reached, the second kink was introduced with a bender for firm fixation.

Unlike the two default lateral stabilizers used with long bars extending horizontally from one mid-axillary line to the other, this single stabilizer faces ventrally to avoid any upward/downward slipping of the bar effectively. Also, bilateral stabilizers are bound to unload the entire force coming from the bar onto the sternum, whereas a single stabilizer close to a ventral entry point can distribute this force over a wider area. The idea of the cross-bar technique is to take full advantage of this principle by further enlarging this area via the oblique orientations of both bars to lift even depressions in anterolateral regions.

2.6. Postoperative considerations

After the implant procedure had been completed and the induced pneumothorax resolved via positive end-expiratory pressure and a suction catheter, postoperative analgesia was provided by intercostal nerve cryoablation, followed by 1–2 days of patient-controlled analgesia in the Austrian cohort, and by intravenous patient-controlled analgesia for 3 days, followed by oral analgesics, in the Turkish cohort.

2.7. Bar removal and complications

The bars are typically removed after 3 years. Regarding the risk profile for the removal of multiple bars, including cross-bar bars, our previous experience indicates that it does not significantly differ from that of the classic MIRPE. However, we have not yet collected precise data on this in our patient cohort. Notably, with the removal of multiple bars, there is inherently a higher overall risk simply because the removal procedure is performed multiple times.

2.8. Statistical analysis

No statistical tests were performed, given no adequate statistical basis for outcome variables to be compared across studies, and subsamples too small for useful within-study comparisons. Hence, descriptive statistics are used throughout, with mean values and standard deviations being listed for information but not discussed in detail. All discussion of data is, therefore, based on median values and interquartile ranges.

3. Results

Of 78 children and adolescents ≤18 years old (median age: 16.2 years; IQR: 15.1–17.4) included, 73 were male (93.6%) and 5 female (6.41%). All had been treated with ‘short bars crossed’ by themselves (n = 42; 53.8%; males: n = 39; females: n = 3) or with a third bar horizontally on top (n = 36; 46.2%; males: n = 34; females: n = 2). Given 56 patients at the Turkish and 22 at the Austrian center, two bars had been used more commonly at the former (n = 37; 66.1%) and three bars more commonly at the latter (n = 17; 77.3%).

An overview of patient data is provided in Table 1. Median age was very similar among the patients treated either with two (16.4 years; IQR: 15.0–17.4) or with three (16.0 years; IQR: 15.2–17.5) bars. Since the HI score was not available in 4 cases, values are presented based on 74 patients. Figure 2 illustrates representative pre- and postoperative photographs and radiographs from our series.

Table 2 lists all adverse events. A total of 10 mild or moderate complications (12.8%) were observed, notably including just one revision requirement due to bar migration (1.28%). There were no events of a fatal or life-threatening nature.

As apparent from Table 3, intercostal nerve cryoablation was associated with median durations of surgery up by 90 min, given 80 min (IQR: 60–100) based on 65 cases versus 150 min (IQR: 137–171) minutes based on 13 cases.

Table 4 indicates that patients receiving or not receiving cryoablation were discharged from the hospital after a median of 4 days. Note, however, the different IQRs involved of 3–4 or 4–5 days, given the low resolution of this variable (entire days). Also, a difference of 5 days (IQR: 4.25–5) versus 4 days (IQR: 3.25–4.75) is seen for the three-bar technique. The figures for the two-bar technique, while pointing in the same direction, are based on a very small case number involving cryoablation (n = 3).

4. Discussion

Over the past two decades, the original Nuss procedure has become a benchmark for treating a multitude of PE deformities [19,20]. Despite being widely used, however, the default technique of implanting one long bar, extending from one mid-axillary line to the other, clearly runs up against limitations of case-specific morphology [7]. In particular, less-than-ideal outcomes have been reported in complex (e.g. asymmetric, combined, or multiple-rib) CWDs among older patients with more rigid chests [15,21–24]. Also, the standard configuration of a single bar supported by lateral stabilizers is prone to bar migration. Events of this type, alongside other complications of varying severity, account for complication

Table 1
Patient age and Haller index scores at the time of surgery.

	Two or three bars		Two bars		Three bars	
	Age (yrs) (n = 78)	HI (n = 74)	Age (yrs) (n = 42)	HI (n = 42)	Age (yrs) (n = 36)	HI (n = 32)
Median	16.2	4.60	16.4	4.45	16.0	5.25
IQR	15.1–17.4	3.50–6.11	15.0–17.4	3.48–5.68	15.2–17.5	4.25–7.58
Range	6.69–18.9	2.00–13.40	6.69–18.9	2.00–12.8	12.6–18.8	3.00–13.40
Mean ± SD	16.0 ± 1.89	5.32 ± 2.35	15.9 ± 2.13	4.88 ± 2.23	16.1 ± 1.55	6.86 ± 5.43

HI = Haller index; IQR = interquartile range; SD = standard deviation.

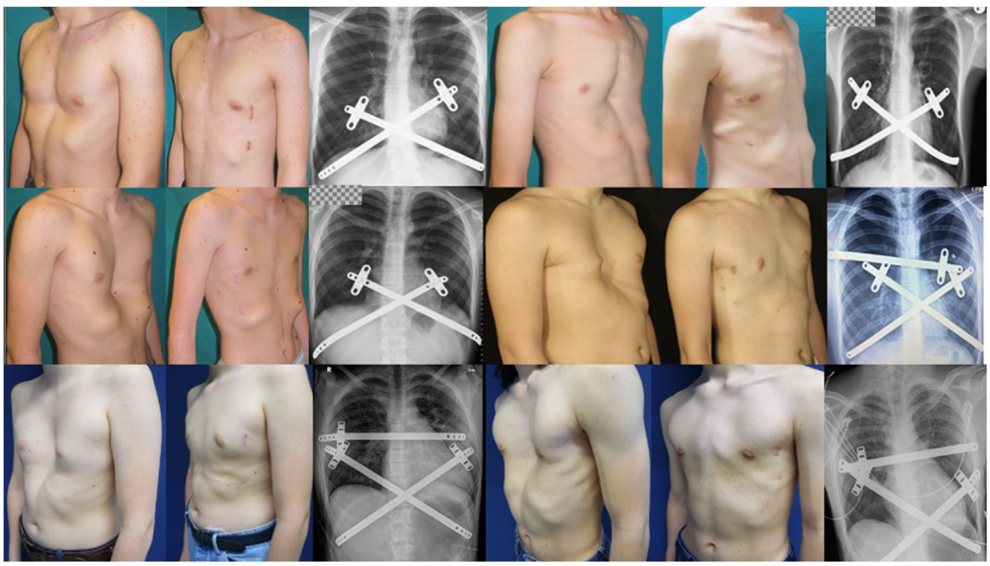

Fig. 2. Pre- and postoperative photographs and radiographs illustrating a number of distinct PE deformities (also see Fig. 1) and how they had been treated with 'short bars crossed' either by themselves or with a third bar placed horizontally on top.

Table 2
Intra- and postoperative complications.

Total, n	10	12.8%
Intraoperative		
Lung injury, n	1	1.28%
Pneumothorax, n	1	1.28%
Early postoperative		
Pleural effusion, n	1	1.28%
Wound infection, n	1	1.28%
Revision due to incisional infection, n	1	1.28%
Late postoperative		
Seroma, n	1	1.28%
Allergic exanthema, n	1	1.28%
Pleural effusion due to physical strain, n	1	1.28%
Bar revision (mouth tip of bar correction), n	1	1.28%
Revision due to bar migration, n	1	1.28%

rates documented for this technique over a range of 2%–20% [25–30].

Growing insights into the intricacies of CWDs have led surgeons to acknowledge a need for adjustments to the traditional Nuss approach. That being said, detailed reports on technical improvements in children and adolescents remain sparse, and treatment methods may differ among pediatric and thoracic surgeons. In addition to the fact that intraoperative risks to the heart have been eliminated by routinely using thoracoscopy and elevating the sternum, recent improvements in addressing complex CWDs by corrective surgery have focused on bar positioning, elevating the entire chest wall, reducing bar migration, and minimizing severe complications [26,27,31–34].

Shorter bars and multiple bar configurations have greatly improved stabilization while enabling adequate correction even of

Table 3
Durations of the surgical procedures.

	Two or three bars			Two bars			Three bars		
	Total (n = 78)	INC no (n = 65)	INC yes (n = 13)	Total (n = 42)	INC no (n = 39)	INC yes (n = 3)	Total (n = 36)	INC no (n = 26)	INC yes (n = 10)
Median (min)	90	80	150	60	60	142	125	100	164
IQR (min)	60–141	60–100	137–171	60–90	60–85	138–146	90–163	87–149	139–175
Range (min)	60–222	60–222	115–184	60–189	60–189	134–150	60–222	60–222	115–184
Mean ± SD (min)	103 ± 44	94 ± 41	152 ± 22	82 ± 33	77 ± 29	142 ± 7	129 ± 42	118 ± 43	155 ± 24

INC = intercostal nerve cryoablation; IQR = interquartile range; SD = standard deviation.

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Table 4
Periods of hospitalization.

	Two or three bars			Two bars			Three bars		
	Total (n = 78)	INC no (n = 65)	INC yes (n = 13)	Total (n = 42)	INC no (n = 39)	INC yes (n = 3)	Total (n = 36)	INC no (n = 26)	INC yes (n = 10)
Median (d)	4	4	4	4	4	3	5	5	4
IQR (d)	4–5	4–5	3–4	3–4	3–4.5	3–3	4–5	4.25–5	3.25–4.75
Range (d)	2–8	2–8	3–8	2–8	2–8	3–3	3–8	4–8	3–8
Mean ± SD (d)	4.41 ± 1.26	4.46 ± 1.18	4.15 ± 1.56	3.98 ± 1.10	4.05 ± 1.11	3.00 ± 0.00	4.92 ± 1.23	5.08 ± 1.00	4.50 ± 1.63

INC = intercostal nerve cryoablation; IQR = interquartile range; SD = standard deviation.

severe CWDs [15,24,32,35–39]. Pilegaard and Licht [13] pioneered these advancements as, in 2008, they first reported their experience with shorter bars and stabilizers closer to the thoracic entry point, which they found to considerably reduce the risk of bar migration. This benefit is particularly useful in children and adolescents, in that bar configurations characterized by higher stability are helpful in avoiding growth-related thoracic constrictions ("sandglass" deformities) and will not interfere with the high levels of physical activity typical of this age.

More recently, Pilegaard [14] reported on a second cohort, this time also incorporating the use of two 'short bars crossed' at the deepest point of the sternal depression, which offered the best support even under short excavations. This "cross-bar technique" was then developed further by Park [15,32], who advocated its use in patients with various severe deformities and added a third bar horizontally on top for complete remodeling of the entire chest wall, departing somewhat from Pilegaard's method by using longer bars and interconnecting them bilaterally via bridge plates.

The first clinical case of 'short bars crossed' with a third bar placed horizontally on top should be credited to the co-author of this study, Prof. Yüksel (Fig. 3). Ermerak and Yüksel [18] have recently published what, to date, is the most comprehensive study of benefits offered by 'short bars crossed'. Observing significant improvements in specific CWD subtypes (uni-/bilateral rib flare, single focal depression), they found this technique to be effective in reducing bar migration and in dealing with anatomical challenges (e.g. a short sternum, a sternum descending steeply as far cranially as the clavicle, or Grand Canyon-style deformities) by including a third bar horizontally on top for optimal repair.

Despite the potential of these innovative modifications to the original Nuss procedure, notably with regard to bar stability and interventional safety, the technique of two 'short bars crossed' has not been widely adopted [13,18,29]. Possible explanations for this hesitancy include a lack of clinical data, surgeons holding on to their preferred techniques, or accessibility problems keeping them from finding out about the details of the technique.

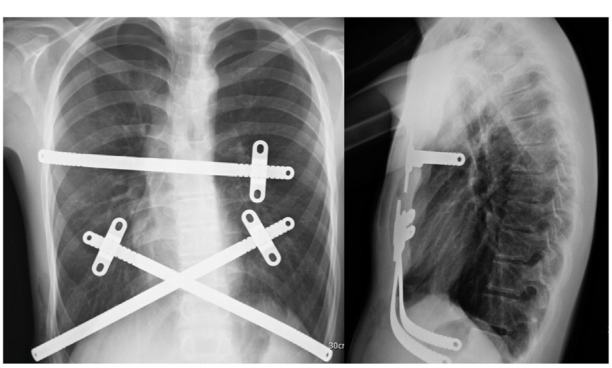

Fig. 3. Radiographic views from 2017, illustrating the first documented case of a patient treated by 'short bars crossed' with a third bar placed horizontally on top. (Source: Turkish center of the present study.)

The present report introduces the concept of 'short bars crossed' specifically to children and adolescents ≤18 years. In our study we have observed only one bar migration (1,28%), but no flipping or rotation. Short bars, as such, address the common, and potentially severe, complication of bar migration by offering much better stability than the longer bars used in the traditional Nuss procedure, which is on record as involving a ≈15% rate of bar flipping [40]. A single stabilizer as used in our series (see *Study Design and Methods*), will prevent slipping of the bar, thus almost invariably eliminating the need for sutures and reducing the need for more implant components seen with other techniques [41].

In effect, this short-bar technique further minimizes the invasiveness of an already minimally invasive procedure, and it allows for multiple bars to be placed either in parallel or crosswise. Parallel short bars may be useful when, due to a wider chest wall depression, the midline area needs to be covered more extensively, and a single bar is deemed inadequate for this purpose. Even the parallel-bar technique, however, runs up against limitations in extreme cases of CWD—whether characterized by pronounced asymmetry, a short sternum, rib flare, or one deep focal depression.

This is where the cross-bar technique comes in [42]. Crossing two bars right at the deepest point of excavation will increase the central force of elevation, keep the bars securely in place, and expand lateral coverage to below the sternal tip. Lower-rib flare, which characterizes many cases of severe CWD (and has been suggested as a potential sequela of previous PE repair with bars [43]), can also be effectively managed for most cases in this fashion via the lower ends of the crossed bars applying downward pressure to the flared ribs. The fact that this neither involves any additional steps nor makes the procedure more invasive constitutes a notable advantage over alternative methods of correcting rib flare [43].

Inserting the crossed bars becomes even safer by routinely using a vacuum bell for instant elevation of the sternum, which will greatly improve intrathoracic vision and eliminates the need for invasive techniques affecting the sternum, like crane lifting [39]. In cases where the upper chest wall was depressed, with the sternum descending steeply already at the rather superior level of the clavicle, liberal use was made of a third horizontal bar, thus making sure that the entire chest wall would ultimately be corrected. Even this third bar, being inserted through the existing incisions, does not add invasiveness to the surgical procedure and is safe and effective without increasing complication rates, as shown both in the present study and the literature [32,44].

Whether or not a third bar is used in specific situations, two 'short bars crossed' offer a force distribution capable of remodeling the entire chest wall in the absence of extra invasiveness. Both bars can be safely placed and configured to repair even extreme pectus deformities while, at the same time, retaining all the advantages of a minimally invasive procedure. Interfering neither with high levels of physical activity nor with ongoing thoracic growth, this technique is exceptionally well suited for pediatric use.

We observed durations of surgery similar to traditional methods, suggesting that the 'short bars crossed' technique is as efficient as it is safe. Overall, the patients remained hospitalized for similarly long as patients treated with two parallel bars, although the median in-hospital stays were found to be noticeably longer based on the subgroup whose treatment involved a third bar (5 days; IQR: 4–5) versus two (4 days; IQR: 3–4).

This difference is put into perspective when intercostal nerve cryoablation comes into play, which apparently reduced hospitalization for the three-bar technique from 5 (IQR: 4.25–5) to 4 days (IQR: 3.25–4.75; see Table 4), underscoring the benefits to be gained by this intraoperative step with a view to postoperative pain management and mobilization. This finding would imply—as a crucial implication to be considered by surgeons, pediatric patients, and family members—that even the more complex procedures involving a third bar are not automatically tantamount to greater postoperative discomfort.

Our data do not support concerns that the cross-bar technique might increase the risk of complications like, for instance, pleural effusion [45]. Hence, our report on children and adolescents could be an important step toward establishing this combined short-bar/cross-bar approach as a safe and effective treatment modality in its own right, with the potential of setting a new standard for PE correction in pediatric thoracic surgery.

We routinely employ short bars in all patients and specifically utilize the short bars crossed technique for those whose deformities meet the specified morphological inclusion criteria.

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Declaration of competing interest

The authors have no conflicts of interest to disclose.

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