European Spine Journal (2025) 34:2750–2761
https://doi.org/10.1007/s00586-025-08654-x

ORIGINAL ARTICLE

Two to five years pulmonary functions after thoracic, thoracolumbar and bilateral vertebral body tethering surgery

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Received: 19 May 2024 / Revised: 5 December 2024 / Accepted: 4 January 2025 / Published online: 14 March 2025

Abstract

Purpose Adolescent Idiopathic Scoliosis negatively impacts chest wall development. Bracing and fusion surgery have shown varied effects on pulmonary outcomes. Vertebral Body Tethering presents a growth-sparing alternative that might mitigate these effects by reducing biomechanical disruptions. Aim was to evaluate changes in pulmonary functions during the course of the follow-up after VBT surgery.

Methods Retrospective cohort study including patients who underwent Thoracic, Thoracolumbar and Bilateral VBT surgery with a minimum 24 months follow-up. Forced Vital Capacity (FVC%), Forced Expiratory Volume in the first second (FEV1%) and FEV1/FVC ratio were evaluated at multiple time points. Four groups were formed using main curve location and surgical technique. Analyses of variance were used to assess changes over time.

Results 81 consecutive patients (76F, 5 M; 12.5 ± 1.6 years) with a mean follow-up 53.4 (24–105) months were included. Preoperatively, the median Sanders was 3 (1–7) and the median Risser was 0 (− 1—5). The mean MT curve of 50.8º ± 11.0º was corrected to 26.0º ± 7.3º at 6 weeks, which was modulated to 22.4º ± 13.4º. FVC%, FEV1%, and FEV1/FVC showed significant improvements over time for the entire cohort up to 2–3 years ($p < 0.0005$) where the curve type and surgical technique influenced improvement patterns. For patients with longer follow-up, values at 4–6 years did not differ from those at 2–3 years ($p > 0.05$, for all comparisons).

Conclusions Thoracoscopic VBT surgery led to consistent increases in FVC%, FEV1%, and FEV1/FVC values across the entire cohort, which were sustained at longer follow-up in a subset of patients. Surgeries on thoracic curves showed more pronounced improvements compared to thoracolumbar curves.

Key points Pulmonary function test results (FVC%, FEV1% and FEV1/FVC) improved following VBT surgery for AIS patients.

Thoracic and thoracolumbar surgery for thoracic curves, and bilateral surgery resulted in more pronounced FVC% and FEV1% improvements.

Improvement in FVC% and FEV1% values started earlier after Thoracic VBT.

Thoracolumbar surgery for thoracolumbar curves displayed significant improvement only in FEV1/FVC results, as they had better preoperative pulmonary functions.

Observed improvements in FVC%, FEV1% and FEV1/FVC were preserved at 4–6 and 7–8 years follow-up in a subset of patients, averaging a mean duration of 48.7 months for the whole cohort.

Keywords Adolescent idiopathic scoliosis · Thoracoscopic vertebral body tethering · Pulmonary function tests · Growth modulation

Introduction

Normative data studies have emphasized the importance of puberty within the adolescence period regarding the development of the chest wall and lungs [1, 2]. Adolescent

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idiopathic scoliosis (AIS) has been shown to impair pulmonary functions, as the period of rapid curve progression coincides with peak growth [3, 4]. Although pulmonary functions were shown to increase after bracing, fusion surgery has been associated with further impairment [5], in addition to other undesirable effects such as loss of mobility and growth limitation.

Vertebral Body Tethering (VBT) is a relatively new, growth- and mobility-friendly alternative to spinal fusion [6], which can be expected to preserve thoracic growth and have a protective and/or corrective effect on pulmonary functions by minimizing insult to chest biomechanics. Nonetheless, the anterior surgical approach raised concerns regarding the pulmonary outcomes. Although, early pulmonary complications were demonstrated to be low [7, 8], limited studies in the literature have reported heterogeneous pulmonary function test results, given different maturity stages [8, 9] of patients and various surgical approaches [8–10].

The aim of the study was to evaluate the changes in pulmonary function test results during the course of the follow-up after thoracic, thoracolumbar and bilateral VBT surgery.

Materials and methods

Patients

A retrospective cohort study was conducted in an ethics board approved single-center prospectively recorded data set of consecutive patients. Follow-up time points were 6 weeks, 3, 6, 12, 18 and 24 months; every 6 months until skeletal maturity and annually thereafter. Patients who were (1) diagnosed with AIS, (2) had undergone VBT surgery for main thoracic, thoracolumbar or both curves and (3) were operated at least 24 months before the date of data query were included. Patients who (1) did not have a preoperative and/or (2) 12 months follow-up and/or (3) at least 24 months follow-up pulmonary function test results were excluded.

Demographic, perioperative and radiographic data

Demographic data included age at surgery, gender, ethnicity and menarche status. Growth related data included Modified Risser score, Sanders Simplified Skeletal Maturity Staging and clinical standing height measurements. Follow-up height gain was calculated using pre-discharge measurements to eliminate the surgical correction related gain.

Perioperative data included surgical technique, operative time, estimated blood loss, length of hospital stay, upper and lower instrumented vertebrae and the number of levels tethered. Radiographic data included curve types, proximal thoracic (PT), main thoracic (MT), and thoracolumbar/lumbar (TL/L) Cobb angles, and thoracic kyphosis and lumbar lordosis. A negative sign was assigned to an overcorrected curve. Pulmonary, mechanical and curve behavior complications, readmissions and reoperations were noted. Broken tethers were indicated by ≥ 6° increase of angulation between adjacent screws between any two postoperative radiographs [11].

Outcome data

Forced Vital Capacity (FVC), percent predicted FVC (FVC%), Forced Expiratory Volume in the first second (FEV1), percent predicted FEV1 (FEV1%) and FEV1/FVC ratio was recorded as the Pulmonary Function Tests (PFT) preoperatively and yearly at each postoperative follow-up time point. Data collected in 2 and 3 years, and 4, 5 and 6 years, and 7 and 8 years were merged for statistical analyses. If a patient had more than one data available for a time period, the most recent data was included in the study.

Impairment in pulmonary functions were categorized based on FEV1% values, in accordance with the American Thoracic Society guidelines, where 70–99% denotes mild, and 6–69%, 50–59%, 35–49% and < 35% denote moderate, moderate-severe, severe and very severe impairments [12], respectively. In accordance with the previous literature, a 10% variation in percent predicted values was determined as the threshold for significance [13] and preoperative and 2–3 years follow-up results were compared.

Surgical technique & perioperative pulmonary management

Thoracic, thoracolumbar and bilateral surgeries were performed under neurophysiological monitoring. Thoracoscopic and retroperitoneal approaches were performed by thoracic and vascular access surgeons, respectively. T4 to L1 vertebrae were instrumented using 3 visualization ports and 3 or 4 working ports. Pleura was dissected off the lateral aspect of the vertebral bodies anterior to the rib heads sequentially along the length of the curve. Retroperitoneal approach was used to instrument L2, L3 and L4 vertebrae. Non-divided diaphragm approach, which involves a blunt dissection that does not require a suture repair during closure, was used to transfer the tether from the retroperitoneal region to the thoracic cage or vice versa.

For both approaches, segmental vessels were identified, coagulated and divided. Care was taken to protect the intervertebral discs. Following the instrumentation and tether placement, set screws on each screw were tightened one by one while achieving correction through both tensioning of the tether and translation of the spine. At the end of the procedures, a chest tube and/or a retroperitoneal drain were placed. No diaphragm repair was performed. Bilateral surgeries were applied as same-day two-stage surgeries.

The postoperative recovery management comprised Triflo exercises initiated by a senior respiratory therapist on day one and the patients were encouraged to continue working on these exercises hourly during hospitalization. Chest tubes were removed once the 24 h output decreased below 100 ml. Breathing home-exercises were advised for another 2 months following discharge.

Statistical analysis

Quantitative variables were expressed as mean and standard deviation or median and range, and categorical variables as percentages. SPSS 20.0 (Chicago, Illinois, USA) was used for analysis. A p value of <0.05 was considered significant.

Four groups were formed in regards to main curve location (thoracic and thoracolumbar/lumbar) and surgical technique (thoracic, thoracolumbar and bilateral) as:

- Thoracic–Thoracic: Lenke 1 & 2 curves that underwent Thoracic VBT
- Thoracic–Thoracolumbar: Lenke 1Ar & 2Ar curves that underwent Thoracolumbar VBT
- Thoracolumbar–Thoracolumbar: Lenke 5 curves that underwent Thoracolumbar VBT
- Thoracic/Thoracolumbar–Bilateral: 1C, 3C & 6C curves that underwent Bilateral VBT

Preoperative height measurements and growth parameters were compared among groups using one-way analysis of variance (ANOVA) and Kruskal–Wallis tests, respectively. Distributions of complications among groups were compared using Fisher Exact test. PFT changes over time were analyzed for the whole cohort and for each group using Repeated Measures ANOVA and Freidman test using the percent predicted values instead of absolute values to account for age, gender, height and race. As patients who had 4–6 and 7–8 years PFT evaluations predominantly underwent thoracic surgery, the effect of thoracoscopic VBT over time on PFTs were compared in general using one-way repeated measures ANOVA without further analyzing according to groups. For both analyses, if the assumption of sphericity was violated, as assessed by Mauchly's test of sphericity, a Greenhouse–Geisser correction was applied. Post hoc analyses were performed with a Bonferroni adjustment.

Results

Study size

At the day of the query, our dataset comprised 165 VBT patients, 119 of whom were potentially eligible according to the inclusion criteria. Two patients (1.7%) were lost to follow-up, 3 (2.5%) did not have a preoperative PFT, 15 (12.6%) did not have PFT results at 12 months follow-up and 18 (15.1%) did not have a PFT at or later than 24 months follow-up, resulting in 81 (68.1%) patients being included for analysis. The mean follow-up duration was 53.4 (24–105) months.

Descriptive data

The mean age at surgery was 12.5 ± 1.6 (9.5–16.5) years. Seventy-six (93.8%) patients were female, among whom, 46 (60.5%) were premenarchal, while the rest were, on average, 9.8 ± 9.7 (1–48) months postmenarchal. All patients were Caucasians. Curve types and perioperative details are given in Table 1.

Preoperatively, the mean standing height was 155.8 ± 8.3 (130–178), the median modified Risser score was 0 (− 1 to 5) and the median Sanders stage was 3 (1–7). Preoperative height measurements, modified Risser scores and Sanders stages were similar among groups ($p = 0.571$, $p = 0.229$, $p = 0.131$, respectively).

Preoperative, bending and follow-up maximum Cobb angles for PT, MT and TL/L curves and sagittal measurements are detailed in Table 2. During the course of the follow-up, patients grew 7.4 ± 5.5 cm on average (0.5–25). At the latest follow-up, the median modified Risser score was 5 (4–5) and the median Sanders stage was 8 (7–8). Details of height measurements and skeletal maturity indicators are given in Table 2.

Six (7.4%) patients experienced pulmonary complications, while 14, 34 and 5 experienced overcorrections, tether breakages and implant complications, respectively. Pulmonary, mechanical and curve behavior complications were similar among groups ($p > 0.05$, for all comparisons). Details are given in Table 3. One patient (1.2%) had a readmission due to pleural effusion and was treated with intense pulmonary rehabilitation without the need for a reintervention. Two patients (2.5%) were converted to fusion.

Results of the outcome data

Details of the pulmonary function test results for the whole cohort are given in Table 4. The mean latest PFT timing was 48.7 (20.8–104.7) months. Of note, as per the inclusion/exclusion criteria, for the first three time points, the data was available for the whole cohort (55 Thoracic, 15 Thoracolumbar, 11 Bilateral), while the data at 4 to 6 years follow-up was only present in 47 (34 Thoracic, 8 Thoracolumbar, 5 Bilateral) cases, and the data at 7 to 8 years follow-up was only present in 9 (7 Thoracic, 1 Thoracolumbar, 1 Bilateral).

Repeated measures ANOVA results revealed that FVC%, FEV1% and FEV1/FVC values improved over time

Table 1 Perioperative details and curve types

	Patient cohort ($n=81$)
Surgical technique, n (%)	
Thoracic	55 (67.9%)
Thoracolumbar	15 (18.5%)
Bilateral	11 (13.6%)
Surgical time, min, mean ± SD (range)	310 ± 134 (125–650)
Estimated blood loss, ml, mean ± SD (range)	104 ± 72 (15–400)
Length of Hospital stay, days, mean ± SD (range)	4.8 ± 1.4 (3–9)
UIV location, n (%)	
T4	3 (3.7%)
T5	46 (56.8%)
T6	21 (25.9%)
T7	3 (3.7%)
T8	1 (1.2%)
T9	1 (1.2%)
T10	4 (5.0%)
T11	2 (2.5%)
LIV Location, n (%)	
T11	17 (21.0%)
T12	23 (28.4%)
L1	15 (18.5%)
L2	3 (3.7%)
L3	19 (23.4%)
L4	4 (5.0%)
Levels tethered, median (Range)	8 (5–12)
Lenke classification, n (%)	
1A	21 (25.9%)
1Ar	15 (18.5%)
1B	12 (14.8%)
1C	14 (17.3%)
2Ar	1 (1.2%)
2A	4 (5.0%)
2B	3 (3.7%)
3C	1 (1.2%)
5C	8 (9.9%)
6C	2 (2.5%)

n: number; %: percentage; min: minutes; ml: milliliters; SD: Standard Deviation

for the whole cohort ($p < 0.0005$, for all comparisons), however, as detailed in Table 5 and Fig. 1, the main curve location and the surgical technique affected the improvement pattern. FVC%, FEV1%, and FEV1/FVC values improved in Thoracic–Thoracic ($p < 0.0005$, $p < 0.0005$ and $p = 0.003$, respectively) and Thoracic/Thoracolumbar–Bilateral groups ($p = 0.039$, $p = 0.011$ and $p = 0.023$, respectively). In the Thoracic–Thoracolumbar group, only improvements in FVC% and FEV1% reached statistical significance ($p = 0.012$ and $p = 0.016$, respectively), while in the Thoracolumbar–Thoracolumbar group, only improvement in FEV1/ FVC reached statistical significance ($p = 0.030$).

At the 2–3 years follow-up, 3 (3.7%) patients experienced a decrease of ≥ 10% in FEV1% values, while 38 (46.9%) were stable within ± 10% change, and 27 (33.3%), 8 (9.9%) and 5 (6.2%) patients experienced an increase of 10–19%, 20–29% and ≥ 30%, respectively. Details of pulmonary function impairment categories are given in Table 6.

Comparable to the analysis in the whole cohort, repeated measures ANOVA results revealed that FVC%, FEV1% and FEV1/FVC values improved over time for the 47 patients who had 4–6 years PFT results. Details are given in Table 7 and Fig. 2. Notably, values at 4–6 years did not differ from those at 2–3 years ($p > 0.05$, for all comparisons). Similarly, for the 9 patients who had 7–8 years PFT results available, values at 7–8 years did not differ from those at 4–6 years ($p > 0.05$, for all comparisons).

Discussion

This study demonstrates increases in pulmonary function outcomes following VBT surgery for AIS patients. Notably, the main curve location (thoracic and thoracolumbar/lumbar) and the surgical technique (thoracic, thoracolumbar, or bilateral) influenced the pattern of improvement. The improvements observed in FVC%, FEV1% and FEV1/FVC values were maintained for a mean duration of 48.7 months in 81 patients.

Scoliosis results in asymmetrical and impaired chest wall development with decreased lung capacity, limited chest wall movement, and overall stiffness of the chest cage and the spine. This results in mechanical inefficiency and restrictive ventilation which results in preexisting pulmonary dysfunction in AIS patients [14, 15]. The intricate relationship between spine and thoracic growth necessitates comprehensive management strategies, which not only prioritizes spinal deformity correction but also ensures optimal respiratory function.

The gold standard fusion surgery has potential side effects such as decreased thoracic growth and increased chest wall stiffness that affects chest biomechanics and interferes with the expected age-related increase in chest dimensions. Accordingly, it was demonstrated that, any type of thoracic cage disruption leads to a significant decline in the percent predicted values of pulmonary functions 5 years following surgery [16]. Compared to posterior fusion, anterior spinal fusion (ASF) has been associated with more pronounced decreases in pulmonary function [17]. Plus, anterior spinal fusion was reported to lead to various pulmonary complications such as pneumothorax, chylothorax, effusion, pneumonia, atelectasis, post-thoracotomy syndrome, and visceral injury [18, 19]. Yet, the effects of ASF on pulmonary

Table 2 Preoperative and follow-up maximum Cobb angle measurements and growth parameters

	Pre-operative	Bending	6 weeks	12 months	24 months	Latest Follow-up
Curve measurements						
PT, Degree						
Mean ± SD	27.3 ± 8.9	11.2 ± 8.0	19.1 ± 7.0	16.7 ± 7.5	15.9 ± 7.9	16.2 ± 8.3
Min–Max	2–46	− 18–30	5–38	3–39	1–41	2–41
MT, Degree						
Mean ± SD	50.8 ± 11.0	17.3 ± 9.3	26.0 ± 7.3	21.7 ± 9.0	19.2 ± 11.6	22.4 ± 13.4
Min–Max	24–77	0–40	10–42	− 5–40	− 16–41	− 24–52
TL/L, Degree						
Mean ± SD	35.2 ± 10.8	0.6 ± 13.9	18.5 ± 9.0	14.8 ± 10.2	12.7 ± 11.7	14.9 ± 15.0
Min–Max	12–64	− 32–59	− 3–39	− 12–43	− 18–43	− 46–59
Kyphosis, Degree						
Mean ± SD	28.7 ± 11.2	n/a	28.7 ± 10.2	30.4 ± 9.5	31.1 ± 10.3	32.1 ± 9.8
Min–Max	2–59		3–55	4–55	4–58	5–58
Lordosis, Degree						
Mean ± SD	58.0 ± 10.9	n/a	55.0 ± 9.8	56.8 ± 8.8	56.2 ± 8.6	56.7 ± 8.9
Min–Max	35–91		35–90	37–88	33–80	37–80
Growth parameters						
Standing height, cm						
Mean ± SD	155.8 ± 8.3	n/a	157.0 ± 8.3	160.4 ± 7.2	162.4 ± 6.9	164.4 ± 6.8
Range	130–178		133–181	143–186	147–189	151–189
Modified risser score						
Median	0	n/a	0	3	4	5
Range	− 1–5		− 1–5	− 1–5	0–5	4–5
Sanders stage						
Median	3	n/a	n/a	6	7	8
Range	1–7			2–8	2–8	7–8

PT: Proximal Thoracic; MT: Main Thoracic; TL/L: Thoracolumbar/Lumbar; SD: Standard Deviation; Min: minimum; Max: maximum; n/a: not applicable

function were shown to be associated with the surgical technique [20]. Patients undergoing ASF with both thoracoscopy or thoracotomy were reported to have significant declines in pulmonary functions, where a greater and persistent deficit was observed in 1 and 2 year postoperative pulmonary function in patients who undergo thoracotomy [20, 21]. Other studies have shown return to preoperative baseline values by second year [22], and even an improvement in pulmonary capacity beyond preoperative levels with thoracoscopic ASF [23].

VBT, a fusionless treatment option for AIS, can theoretically be expected to have better outcomes in terms of postoperative pulmonary functions compared to ASF due to its biomechanical advantages. When performed as a thoracoscopic surgery, VBT was reported to lead to improved perioperative outcomes, decreased pain and morbidity [24]; however, the reported pulmonary function test results after VBT have been widely variable [10, 25, 26].

This study reports a 7.4% pulmonary complication rate which is comparable to the reported rates that vary between 3 and 12% [8, 10, 25, 27]. Notably, no deterioration in FEV1% categories was observed in our cohort. Furthermore, the sustained improvement in pulmonary function tests indicate that thoracoscopic VBT might not adversely affect respiratory functions contrary to previous concerns. In comparison, while some series reported no improvement or decline in all three surgical techniques [8, 9, 26], others have observed a reduction in percent predictions [10]. We speculate that there are three main reasons explaining the differences between our results and that of the previous literature. First, the use of open thoracotomy approach [8–10] may have influenced the results similarly to the abovementioned anterior fusion literature. Second, the difference in the remaining growth potential between the cohorts, as evident by > 2 years mean difference in age at surgery [8, 9], may have an effect. In the current study that includes a relatively younger cohort, the anticipated peak-growth related increase in pulmonary function more commonly coincided with curve modulation, while in relatively older cohorts, this time period more commonly overlapped with the natural history of scoliotic curve progression. Third, reporting on a small percent of potentially eligible patients who were non-consecutively enrolled

Table 3 Pulmonary, mechanical and curve behavior complications

	Total $n=81$	Main Curve & Surgical Technique Thoracic–Thoracic $n=55$	Thoracic–Thoracolumbar $n=7$	Thoracolumbar–Thoracolumbar n = 8	Thoracic / Thoracolumbar–Bilateral $n=11$	*p*
	n (%)	*n* (%)	*n* (%)	*n* (%)	*n* (%)	
Pulmonary complications	6 (7.4%)	4 (7.3%)	1 (14.3%)	0 (0.0%)	1 (9.1%)	0.615
Atelectasis	*3 (3.7%)*	*3 (5.5%)*	*0 (0.0%)*	*0 (0.0%)*	*0 (0.0%)*	
Lobar atelectasis	*1 (1.2%)*	*0 (0.0%)*	*0 (0.0%)*	*0 (0.0%)*	*1 (9.1%)*	
Pleural effusion	*2 (2.5%)*	*1 (1.8%)*	*1 (14.3%)*	*0 (0.0%)*	*0 (0.0%)*	
Overcorrections	14 (17.3%)	8 (14.5%)	2 (28.6%)	1 (12.5%)	3 (27.3%)	0.481
Thoracic *	*3 (3.7%)*	*2 (3.6%)*	*0 (0.0%)*	*1 (12.5%)*	*0 (0.0%)*	
Lumbar †	*8 (9.9%)*	*4 (7.3%)*	*1 (14.3%)*	*0 (0.0%)*	*3 (27.3%)*	
Both §	*3 (3.7%)*	*2 (3.6%)*	*1 (14.3%)*	*0 (0.0%)*	*0 (0.0%)*	
Tether breakages ¥						
Thoracic *	*21 (25.9%)*	*16 (29.1%)*	*3 (42.9%)*	*1 (12.5%)*	*1 (9.1%)*	0.341
Lumbar †	*14 (53.8%)*‡	n/a	*2 (28.6%)*	*3 (37.5%)*	*9 (81.8%)*	0.061‡
Implant complications	5 (7.1%)	4 (8.5%)	1 (25.0%)	0 (0.0%)	0 (0.0%)	0.402
UIV loosening and/or migration	*4 (5.0%)*	*3 (5.5%)*	*1 (14.3%)*	*0 (0.0%)*	*0 (0.0%)*	
LIV loosening and/or migration	*1 (1.2%)*	*1 (1.8%)*	*0 (0.0%)*	*0 (0.0%)*	*0 (0.0%)*	

UIV: Upper Instrumented Vertebra; LIV: Lower Instrumented Vertebra; n/a: not applicable

* Complications recorded between T4-L1

† Complications recorded between L1-L4

§ Complications that occurred in both thoracic and lumbar regions

¥ A total of 34 patients experiences tether breakages, where 1 patient undergoing bilateral surgery experienced breakages in both regions

‡ Comparison performed among 3 groups, total $n=26$

Table 4 Preoperative and follow-up pulmonary function test results

	Preoperative ($n=81$)	1 year* ($n=81$)	2–3 years* ($n=81$)	4–6 years* ($n=47$)	7–8 years* ($n=9$)
FVC, ml					
Mean ± SD	2535.4 ± 539.7	2774.0 ± 490.6	3159.3 ± 476.0	3362.1 ± 546.2	3683.3 ± 695.4
Min–Max	1400–3850	1820–4300	2150–4940	1950–4660	2680–5010
FVC%, percentage					
Mean ± SD	83.3 ± 12.9	86.5 ± 12.8	91.6 ± 13.6	93.4 ± 13.3	92.2 ± 9.3
Min–Max	53–118	57–124	64–123	67–124	83–110
FEV1, ml					
Mean ± SD	2143.3 ± 432.5	2437.7 ± 423.3	2727.2 ± 353.7	2929.1 ± 445.1	3184.4 ± 617.2
Min–Max	1230–2950	1480–3980	1930–3540	1650–4100	2410–4450
FEV1%, percentage					
Mean ± SD	82.9 ± 12.3	87.9 ± 13.5	93.2 ± 13.4	95.4 ± 13.2	91.9 ± 9.3
Min–Max	59–111	56–143	65–129	71–130	78–104
FEV1/FVC, ratio					
Mean ± SD	84.9 ± 5.7	87.0 ± 6.5	87.2 ± 6.5	87.4 ± 5.8	86.6 ± 5.1
Min–Max	68.1–99.5	68.0–99.2	68.4–98.5	75.5–99.6	80.1–94.2

FVC: Forced Vital Capacity; FEV1: Forced Expiratory Volume in the first second; SD: Standard Deviation; Min: minimum; Max: maximum

* The mean timing of PFT data at 1–year visit was 12.3 (10.2–14.9) months, while at 2–3 years, 4–6 years and 7–8 years it was 29.7 (20.8–40.0), 59.4 (46.6–79.7) and 92.2 (81.8–104.7) months, respectively

Table 5 PFT results for different curve types and surgical techniques and the whole cohort

Main Curve & Surgical Technique	*n*	Preoperative Mean ± SD Median (Min–Max)	1 year Mean ± SD Median (Min–Max)	2–3 years Mean ± SD Median (Min–Max)	*p*
FVC%					
Whole Cohort	81	83.3 ± 13.0	86.5 ± 12.8	91.6 ± 13.6	< 0.0005*
		84 (53–118)	85 (57–124)	91 (64–123)	
Thoracic—Thoracic	55	82.4 ± 12.6	87.2 ± 12.3	91.6 ± 12.6	< 0.0005*
		82 (53–118)	86 (65–124)	91 (67–117)	
Thoracic—Thoracolumbar	7	83.6 ± 12.8	83.0 ± 13.5	92.7 ± 13.5	0.012**
		87 (61–98)	83 (57–98)	97 (64–103)	
Thoracolumbar—Thoracolumbar	8	88.9 ± 18.2	89.5 ± 17.7	93.1 ± 20.2	0.446
		91.5 (57–117)	89.5 (60–116)	87 (65–123)	
Thoracic/Thoracolumbar—Bilateral	11	83.8 ± 11.4	83.1 ± 11.9	89.7 ± 14.8	0.039**
		85 (61–97)	84 (59–98)	90 (64–110)	
FEV1%					
Whole Cohort	81	82.9 ± 12.3	87.9 ± 13.5	93.2 ± 13.4	< 0.0005†
		82 (59–111)	86 (56–143)	93 (65–129)	
Thoracic—Thoracic	55	81.5 ± 11.2	87.5 ± 12.8	92.5 ± 12.0	< 0.0005†
		81 (60–110)	86 (68–143)	93 (70–129)	
Thoracic—Thoracolumbar	7	85.9 ± 13.2	87.7 ± 13.9	96.4 ± 15.3	0.016††
		86 (65–107)	87 (62–105)	100 (65–112)	
Thoracolumbar—Thoracolumbar	8	90.0 ± 16.3	92.3 ± 16.9	94.5 ± 16.3	0.687
		91 (66–111)	86.5 (67–119)	88.5 (75–116)	
Thoracic/Thoracolumbar—Bilateral	11	82.9 ± 13.7	86.5 ± 15.4	93.7 ± 18.3	0.011††
		82 (59–107)	87 (56–105)	94 (68–114)	
FEV1/FVC					
Whole Cohort	81	84.9 ± 5.7	87.0 ± 6.5	87.3 ± 6.5	< 0.0005§
		84.9 (68.1–99.5)	87.2 (68.0–99.2)	88.1 (68.4–98.5)	
Thoracic—Thoracic	55	84.5 ± 6.1	85.9 ± 6.7	86.6 ± 6.9	0.003§
		83.9 (68.1–99.5)	85.6 (68.0–98.3)	87.0 (68.4–98.5)	
Thoracic—Thoracolumbar	7	87.7 ± 4.3	90.7 ± 5.2	88.7 ± 5.5	0.156
		87.4 (79.5–91.8)	91.8 (82.4–96.9)	89.8 (78.8–95.9)	
Thoracolumbar—Thoracolumbar	8	86.3 ± 5.0	89.3 ± 4.0	88.8 ± 5.0	0.030§§
		86.4 (80.9–94.3)	89.8 (82.5–94.8)	88.8 (81.0–94.7)	
Thoracic/Thoracolumbar—Bilateral	11	84.1 ± 4.8	88.4 ± 6.5	88.6 ± 6.5	0.023§§
		84.5 (78.0–93.3)	89.3 (77.5–99.2)	88.8 (75.3–96.9)	

FVC: Forced Vital Capacity; FEV1: Forced Expiratory Volume in the first second (FEV1), SD: Standard Deviation; min: minimum; max: maximum

[*] *p* values in Post hoc tests between preoperative and 1 year, preoperative and 2–3 years and 1 year and 2–3 years for the whole cohort were $p = 0.016$, $p < 0.0005$ and $p < 0.0005$ respectively; and for Thoracic curves that underwent Thoracic Surgery were $p = 0.002$, $p < 0.0005$ and $p < 0.0005$, respectively according to Repeated Measures ANOVA analysis

[**] *p* values in Post hoc tests between preoperative and 1 year, preoperative and 2–3 years and 1 year and 2–3 years for Thoracic curves that underwent Thoracolumbar Surgery were $p = 0.855$, $p = 0.184$ and $p = 0.010$, respectively; and for Bilateral Surgery were $p = 1.000$, $p = 0.264$ and $p = 0.043$, respectively according to Freidman test

[†] *p* values in Post hoc tests between preoperative and 1 year, preoperative and 2–3 years and 1 year and 2–3 years for the whole cohort were $p < 0.0005$, $p < 0.0005$ and $p < 0.0005$ respectively; and for Thoracic curves that underwent Thoracic Surgery were $p < 0.0005$, $p < 0.0005$ and $p < 0.0005$, respectively according to Repeated Measures ANOVA analysis

[††] *p* values in Post hoc tests between preoperative and 1 year, preoperative and 2–3 years and 1 year and 2–3 years for Thoracic curves that underwent Thoracolumbar Surgery were $p = 0.687$, $p = 0.326$ and $p = 0.015$, respectively; and for Bilateral Surgery were $p = 1.000$, $p = 0.023$ and $p = 0.043$, respectively according to Freidman test

[§] *p* values in Post hoc tests between preoperative and 1 year, preoperative and 2–3 years and 1 year and 2–3 years for the whole cohort were $p < 0.0005$, $p < 0.0005$ and $p = 1.000$ respectively; and for Thoracic curves that underwent Thoracic Surgery were $p = 0.076$, $p = 0.005$ and $p = 0.610$, respectively according to Repeated Measures ANOVA analysis

[§§] *p* values in Post hoc tests between preoperative and 1 year, preoperative and 2–3 years and 1 year and 2–3 years for Thoracolumbar curves that underwent Thoracolumbar Surgery were $p = 0.043$, $p = 0.101$ and $p = 1.000$, respectively; and for Bilateral Surgery were $p = 0.210$, $p = 0.023$ and $p = 1.000$, respectively according to Freidman test

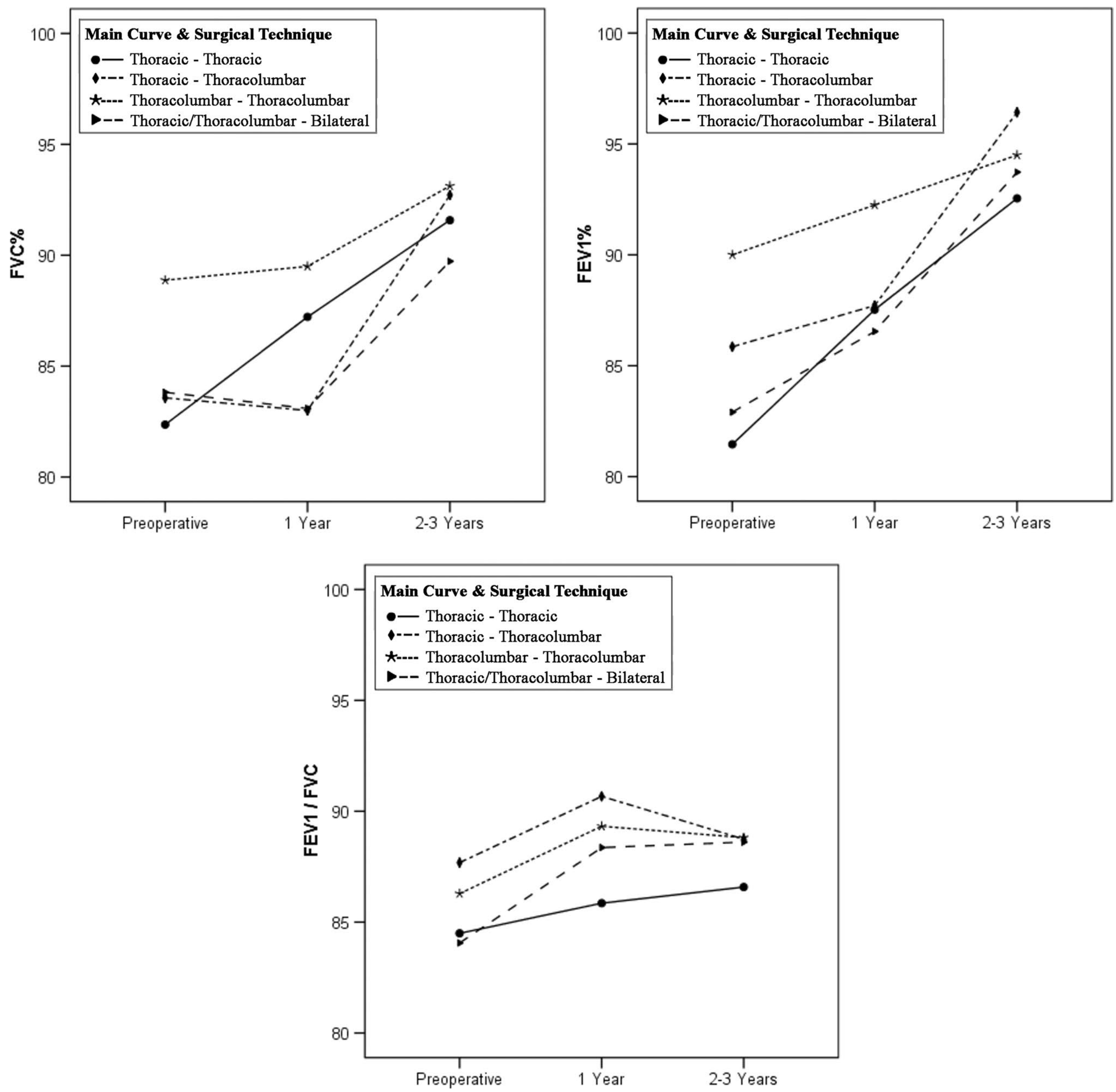

Fig. 1 FVC%, FEV1% and FEV1/FVC results for different curve types and surgical techniques for the whole cohort

and inconsistent timeframe for the PFTs [10, 26] may limit the interpretation of the reported results.

PFTs improved from preoperative to the first-year as well as from the first-year to years 2–3 after Thoracic VBT for thoracic curves. In comparison, in other curve types and surgical techniques, there was no improvement from preoperative to the first-year. The observation of differences in improvement patterns of FVC%, FEV1% and FEV1/FVC values among groups, where post-hoc analyses showed earlier improvement in thoracic VBTs compared to thoracolumbar and bilateral cases, suggests that diaphragm involvement may impact the results. This aligns with Hwang et al. [26] study, which observed an impact on PFTs when surgery extends below T12. Additionally, the observed consistent improvement in FVC% and FEV1% in thoracic or thoracolumbar surgeries for the main thoracic curves and in bilateral surgery, in comparison to preservation of these values in the thoracolumbar curves undergoing thoracolumbar surgery, could potentially be attributed to the ceiling effect, given the better preoperative pulmonary function values in thoracolumbar curves. This may be due to the apex being located

Table 6 Crosstabulation of preoperative vs 2–3 years impairment in pulmonary functions based on FEV1% values, in accordance with the American Thoracic Society guidelines

Preoperative	Postoperative 2–3 years follow-up				Total
	No impairment, *n* (%)	Mildly impaired, *n* (%)	Moderately impaired, *n* (%)	Moderate-severely impaired, *n* (%)	
No impairment, *n* (%)	9*	0§	0§	0§	9 (11.1%)
Mildly impaired, *n* (%)	18†	41*	0§	0§	59 (72.9%)
Moderately impaired, *n* (%)	0†	10†	2*	0§	12 (14.8%)
Moderate-severely impaired, *n* (%)	0†	1†	0†	0*	1 (1.2%)
Total, *n* (%)	27 (33.3%)	52 (64.2%)	2 (2.5%)	0 (0.0%)	81 (100%)

n: number; %: percentage

[*] 52 (64.2%) patients remained in the same category

[†] 28 (34.6%) patients improved by one category and 1 patient (1.2%) improved by two categories

[§] No patients experienced a worsening in category

Table 7 PFT results of the 47 patients who had 4–6 years evaluations

	Preoperative Mean ± SD Median (Min–Max)	1 year Mean ± SD Median (Min–Max)	2–3 years Mean ± SD Median (Min–Max)	4–6 years Mean ± SD Median (Min–Max)	*p*
FVC%	83.0 ± 13.2	86.9 ± 13.7	91.8 ± 14.2	93.4 ± 13.3	< 0.0005
	85 (53–117)	87 (59–124)	92 (65–121)	94 (67–124)	
FEV1%	83.4 ± 12.1	89.5 ± 14.5	94.7 ± 13.8	95.4 ± 13.2	0.004
	83 (60–111)	87 (56–143)	95 (68–129)	93 (71–130)	
FEV1/FVC	85.8 ± 4.6	88.2 ± 5.4	88.1 ± 5.3	87.5 ± 5.8	< 0.0005
	86.1 (76.4–95.5)	87.9 (77.3–99.2)	87.8 (74.0–98.5)	87.2 (75.5–99.6)	

FVC: Forced Vital Capacity; FEV1: Forced Expiratory Volume in the first second (FEV1)

lower than the thoracic cavity, resulting in less impact on respiratory capacity to begin with, hence less room for improvement.

To the best of our knowledge, the current study has the longest follow-up duration with pulmonary function data on each timeframe on consecutive AIS patients who underwent VBT surgery. The study's findings on pulmonary complications and PFT results underscore the procedure's potential in preserving chest biomechanics. However, the reported variation in FEV1% changes warrants studies in larger cohorts to reach more definitive conclusions.

Limitations of the study

The retrospective nature of the analyses and the limited number of patients forms the main limitations. The uneven distribution of the 81 patients across the four groups represents another limitation. Nevertheless, these results demonstrate the real-life situation, ultimately representing patients coming to our practice, which requires different VBT approaches similar to other studies in the literature. Effects of various pulmonary, mechanical and curve behavior complications on pulmonary functions could not be analyzed due to the paucity of such complications within the groups. Moreover, the 4–6 years follow-up data mostly had measurements from patients who underwent thoracic VBT surgery. Thus, we were unable to make a comparison of PFT after VBT surgery according to curve and surgical type at longer follow-up. Since the difference in PFT values between surgery groups follow a similar trend until the years 2–3, it can be estimated that the trend will not shift in longer follow-up. Future studies with a larger cohort are warranted.

Conclusions

Thoracoscopic VBT surgery on 81 AIS patients resulted in an increase in FVC%, FEV1% and FEV1/FVC values until 2–3 years, which were preserved at 4–6 and 7–8 years follow-up in a subset of patients. Having better respiratory functions

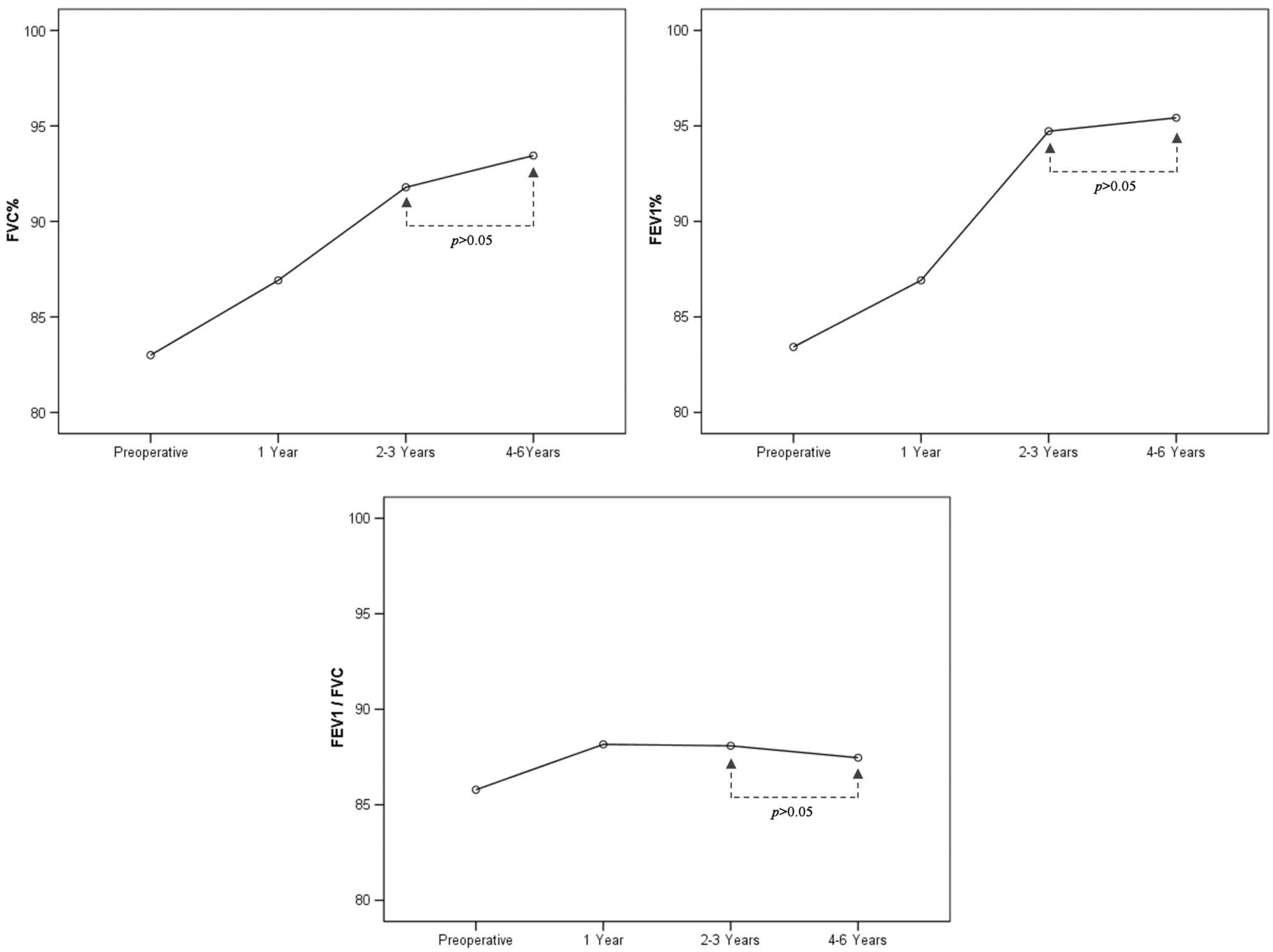

Fig. 2 Comparison of FVC%, FEV1% and FEV1/FVC results over time for the 47 patients who had 4–6 years evaluations

preoperatively, thoracolumbar curves that underwent thoracolumbar surgery displayed significant improvement only in FEV1/FVC results. In comparison, thoracic and thoracolumbar surgery for thoracic curves, and bilateral surgery resulted in more pronounced FVC% and FEV1% improvement, where improvement after Thoracic VBT started earlier. This designates the need for further studies to thoroughly understand the factors affecting pulmonary functions.

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK).

Conflict of interest Ahmet Alanay declares Royalties with Highridge, Consultancy with Highridge and Globus Medical, and Grants with Medtronic and Depuy Synthes. Caglar Yilgor declares Consultancy with Medtronic. All remaining authors do not have any competing interests to declare.

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