European Spine Journal (2019) 28:1322–1330
https://doi.org/10.1007/s00586-019-05923-4

ORIGINAL ARTICLE

Progressive decline in pulmonary function 5 years post-operatively in patients who underwent anterior instrumentation for surgical correction of adolescent idiopathic scoliosis

Burt Yaszay[1] · Pawel P. Jankowski[2] · Tracey P. Bastrom[1] · Baron Lonner[3] · Randal Betz[4] · Suken Shah[5] · Jahangir Asghar[6] · Firoz Miyanji[7] · Amer Samdani[8] · Peter O. Newton[1]

Received: 10 April 2018 / Revised: 17 January 2019 / Accepted: 12 February 2019 / Published online: 23 February 2019

Abstract

Purpose To evaluate changes in pulmonary function tests (PFT) at 5 years post-operatively in patients with adolescent idiopathic scoliosis (AIS) and to determine whether these changes are progressive or static after 2 years.

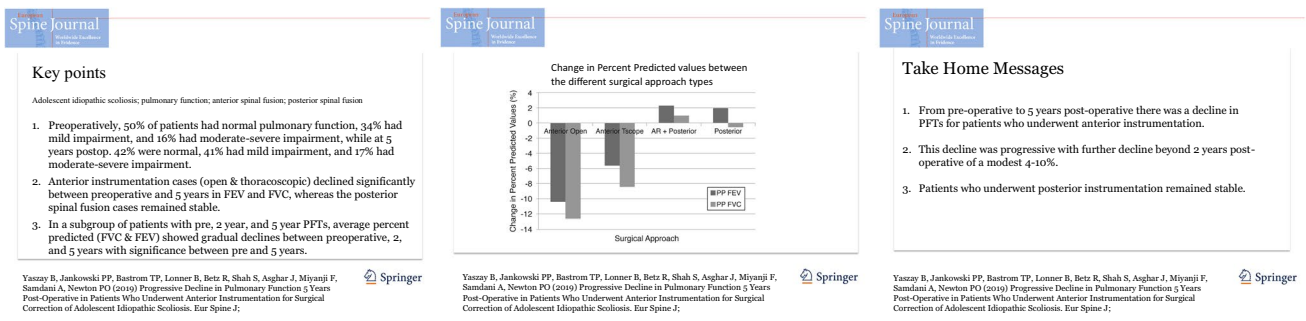
Methods AIS surgical patients with pre-operative and 5 year post-operative forced expiratory volume (FEV) and forced vital capacity (FVC) were included. The percentage of patients with pulmonary impairment at 5 years was calculated. Repeated measures ANOVA was used to evaluate changes between pre-operative PFT and 5 years post-operative PFT and to determine whether the changes differed between curve types and approach. A sub-analysis of patients with 2 year data was performed to determine whether PFT changes were static or progressive.

Results Two hundred and sixty-two patients had undergone pre-operative and 5 year post-operative PFTs. At 5 years, 42% were normal, 41% had mild impairment, and 17% had moderate-severe impairment. Overall, there was a decline in % predicted FVC ($p < 0.05$); FEV remained stable. There was no difference based on major curve type ($p > 0.05$). Anterior instrumentation cases declined significantly between pre-operative PFT and 5 years post-operative PFT (FEV: − 10% open, − 6% thoracoscopic; FVC: − 13% open, − 8% thoracoscopic) ($p \leq 0.02$). The posterior cases remained stable (2% FEV, $p = 0.7$; − 0.6% FVC, $p = 0.06$). A subgroup of 90 patients with 2 year post-operative PFTs demonstrated that changes were progressive between 2 and 5 years post-operatively. The average change in FVC from 2 to 5 years was significantly different between the anterior open (− 9%) and posterior-only (0.7%) groups ($p = 0.015$).

Conclusion In patients who underwent anterior instrumentation, PFTs declined from the pre-operative to the 5 years post-operative time point. There was a progressive decline of 4–10% beyond 2 years post-operatively. Patients who underwent posterior instrumentation remained stable.

Graphical abstract

These slides can be retrieved under Electronic Supplementary Material.



Keywords Pulmonary function · Adolescent idiopathic scoliosis · Anterior spinal fusion · Posterior spinal fusion

Extended author information available on the last page of the article

Introduction

Pulmonary function in patients with scoliosis has been shown to be effected by both patient characteristics and the surgical approach utilized to treat the spine deformity [1–8]. Patient characteristics such as curve location, the number of vertebrae in the curve, and curve rigidity have all been shown to be associated with pulmonary function [9–13]. Additionally, thoracic hypokyphosis and chest wall deformity have been shown to negatively impact pulmonary function [14]. In patients with adolescent idiopathic scoliosis (AIS), stiffness of the chest cage, reduction in the hemidiaphragmatic movement, and uneven distribution of inhaled air play a role in reduced pulmonary function [11].

It has been established that pulmonary function in patients with AIS is affected by the surgical approach [1–9, 15–22]. Anterior approaches, in particular, have been documented to negatively impact pulmonary function after surgery [16, 17, 19, 23] seemingly due to the violation of the chest wall, transection of the muscles, and other tissue planes that result in later intra- and extra-thoracic scarring [10, 13]. One study found that at 2 years post-operatively, the most significant predictors for pulmonary function in patients with AIS was pre-operative pulmonary function and surgical approach, specifically anterior approaches [13]. Longer-term follow-up has shown similar results.

The effects of open anterior surgical fusion (OASF) on pulmonary function tests (PFTs) have been documented at the 5-year mark and shown to have a negative impact on absolute FEV_1, percent predicted FEV_1, and percent predicted FVC [24]. In a 10-year follow-up analysis of the effects that different surgical approaches had on PFTs, Gitelman et al. showed that patients who underwent an anterior procedure (open anterior spinal fusion, combined anterior/posterior fusion, or thoracoplasty) had decreased PFTs at 10 years post-operatively as compared to pre-operatively [25]. This decline was not observed in a comparison cohort who underwent posterior-only procedures. Similarly, Sudo et al. reported that at an average of 15 years post-operatively, patients with Lenke 1 AIS curves had decreased percent predicted FVC and FEV_1 compared to baseline [26].

As has been shown, both the type of surgical intervention and the magnitude of the deformity have a vital influence on the extent of pulmonary function impairment and the long-term pulmonary status of AIS patients. The purpose of this study was to evaluate changes in PFTs at 5 years post-operatively and determine whether these changes are progressive or static after the 2 year mark.

Materials and methods

IRB approval was obtained for this study. A retrospective review of a multicenter prospective registry of patients with AIS who underwent surgical correction was conducted. To be included in the registry, patients had to be aged 10–21 years at the time of surgery and have a diagnosis of idiopathic scoliosis for which surgery was recommended to prevent progression or to correct trunk disfigurement. Patients with available data for forced expiratory volume (FEV) and forced vital capacity (FVC) at both the pre-operative and 5 year post-operative time points were included.

Pulmonary Function Tests

All patients in the study underwent pulmonary function tests (PFTs) for evaluating pulmonary volume prior to and after 5 years of surgery. The tests were performed with the patients standing. Each spirometry test was repeated 3 times, and the highest recording was selected. The PFT data were represented as an absolute value (best value) for FEV and FVC as well as percent predictive values normalized to age, weight, and height or arm span. There was no exclusion based on curve type. Pulmonary impairment was categorized using American Thoracic Society (ATS) guidelines for percent predicted values: $>80\%$ normal, ≤ 80 to $>65\%$ mild, ≤ 65 to $\geq 50\%$ moderate, $<50\%$ severe impairment [27].

Statistical analysis

Overall average change in between PFTs pre-operatively and 5 years post-operatively was performed using repeated measures ANOVA. Following this, between-subjects repeated measures ANOVAs were performed to determine whether changes differed between curve types and approach [posterior (PSF), anterior open, anterior thoracoscopic, PSF + open/thoracoscopic anterior release].

Descriptive statistics for the percentage of patients with pulmonary impairment at 5 years were calculated. A subanalysis of patients who also had 2 year PFT data available was performed to determine whether PFT changes were static or progressive over the 5 year period. Alpha was set at $p \leq 0.05$, and all analyses were performed utilizing SPSS v.12 (SPSS Inc., Chicago, IL).

Table 1 Overall cohort change in PFT values from pre-operative PFT to 5 years post-operative PFT

	FEV best value (L)	FEV % predicted	FVC best value (L)	FVC % predicted
Pre-op	2.5 ± 0.6	80.5 ± 15	2.9 ± 0.7	86.5 ± 15
5 year	2.7 ± 0.6	79.2 ± 14	3.3 ± 0.8	82.7 ± 14
p value	**≤ 0.001**	0.16	**≤ 0.001**	**≤ 0.001**

Bold values represent statistical significance

Table 2 Within-group comparison of changes from pre-operative PFT to 5 years post-operative PFT for each curve group

	FEV best value			FEV % predicted			FVC best value			FVC % predicted		
	Pre-op	5 year	*p* value	Pre-op	5 year	*p* value	Pre-op	5 year	*p* value	Pre-op	5 year	*p* value
Primary thoracic (Lenke 1–4)	2.5 0.6	2.7 ± 0.7	**≤ 0.001**	79 ± 15	79 ± 14	0.76	2.9 ± 0.7	3.2 ± 0.8	**≤ 0.001**	85 ± 15	82 ± 14	**0.005**
Primary thora-columbar (Lenke 5–6)	2.8 ± 0.7	2.8 ± 0.5	0.89	87 ± 15	82 ± 12	**0.02**	3.3 ± 0.6	3.7 ± 0.7	**0.04**	94 ± 10	88 ± 13	**≤ 0.001**

Bold values represent statistical significance

Results

There were 262 patients with pre-operative and 5 year post-operative PFT data. Average age at surgery was 14.8 ± 1.8 years (range 11–20 years) with the majority being female ($n = 217$, 82.8%). There were 213 patients with primary thoracic curves (Lenke 1–4) and 48 patients with primary thoracolumbar/lumbar curves (Lenke 5–6). The distribution of treatment approaches were as follows: PSF and instrumentation ($n = 165$), anterior instrumentation via an open approach ($n = 48$), anterior instrumentation via thoracoscopic approach ($n = 35$), and PSF/instrumentation with anterior release ($n = 14$; 1 open approach, 13 thoracoscopic). Within the patients with primary thoracic curves, there were 60 (28%) anterior fusion/instrumentation cases and 153 (72%) PSF cases. In the thoracolumbar/lumbar group, there were 22 (46%) anterior and 26 (54%) PSF procedures.

For the entire cohort, percent predicted FEV was not significantly changed from pre-operative PFT to 5 years post-operative PFT ($p > 0.05$). The percent predicted FVC values, however, demonstrated a significant decline from pre-operative PFT to 5 years post-operative PFT ($p \leq 0.001$, Table 1). Both FEV and FVC best values (rate and volume) increased significantly between the two time points ($p \leq 0.001$). Pre-operatively, 50% were normal, 34% had mild impairment, and 16% had moderate-severe impairment, while at 5 years post-operatively, 42% were normal, 41% had mild impairment, and 17% had moderate-severe impairment ($p \leq 0.001$).

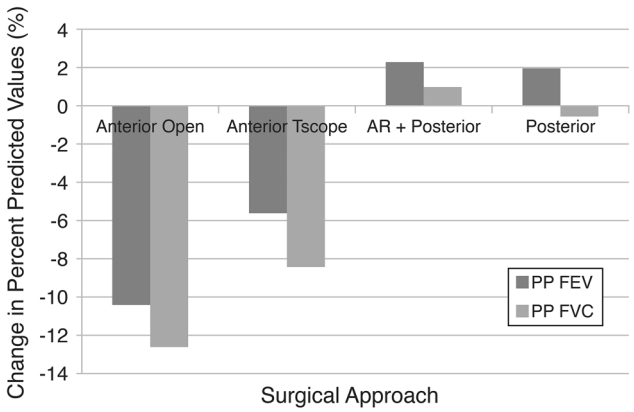


Fig. 1 Change in percent predicted values between the different surgical approach types

Repeated measures ANOVA demonstrated no significant difference in pattern of change over time based on major curve for percent predicted values (Lenke 1–4 vs 5–6, $p > 0.05$). However for best values, Lenke 1–4 curves demonstrated more impairment pre-operatively with a subsequent larger increase over time as compared to Lenke 5–6 ($p = 0.002$ FEV, $p = 0.012$ FVC). Within-group analysis of each Lenke type for all PFT data is seen in Table 2.

Repeated measures ANOVA demonstrated significantly different patterns of change from pre-operative PFT to 5 years post-operative PFT between the different approaches for all four PFT variables (all $p \leq 0.001$, Fig. 1). Anterior instrumentation cases (open and

thoracoscopic) declined significantly between pre-operative PFT and 5 years post-operative PFT in FEV (− 10% open $p \leq 0.001$, − 6% thoracoscopic $p = 0.02$) and FVC (− 13% open $p \leq 0.001$, − 8% thoracoscopic $p = 0.002$), whereas the PSF cases remained stable (2% FEV $p = 0.7$, − 0.6% FVC $p = 0.06$). The PSF + anterior release cases demonstrated a nonsignificant increase (2% FEV $p = 0.7$, 1% FVC $p = 0.06$). Within-group analysis of each approach for all PFT data is seen in Table 3. Best values increased significantly for the PSF and PSF + anterior release cases from pre-operative PFT to 5 years post-operative PFT, with no significant changes noted for the anterior instrumentation groups (Fig. 2). Conversely, percent predicted values decrease significantly for the anterior instrumentation groups over time, with no significant changes noted for the posterior groups.

A subgroup of 90 patients with 2 year post-operative PFTs had similar findings. Within this subgroup, there were 73 primary thoracic curves [25 (34%) anterior, 48 (66%) posterior] and 17 primary thoracolumbar/lumbar curves [12 (71%) anterior, 5 (29%) posterior]. Average percent predicted FVC and FEV showed gradual declines between pre-operative PFT, 2 years post-operative PFT, and 5 years post-operative PFT—with significance between pre-operative PFT and 5 years post-operative PFT ($p < 0.05$)(Table 4). The best values for FEV showed no significant change over the three time points ($p = 0.11$). The best values for FVC were significantly greater at the 5 year time point as compared to the pre-operatively and 2 year time points ($p < 0.05$). The percentage of patients who improved, worsened, or had no change in ATS pulmonary function impairment level can be found in Table 5.

There were no significant differences in changes over the three time periods based on curve type for all four PFT variables (Best Value FEV $p = 0.59$, Best Value FVC $p = 0.43$, % Predicted FEV $p = 0.34$, % Predicted FVC $p = 0.69$). FEV percent predicted between 2 and 5 years was not significantly different based on approach ($p = 0.41$)(Table 6); there was a 4% decline in the anterior open group ($n = 19$), 3.5% decline in the anterior thoracoscopic group ($n = 18$), 4% increase in the PSF + anterior release group ($n = 7$), and a 2% decline in the PSF only group ($n = 46$) (Fig. 3). There was a significant difference in change between 2 and 5 years in percent predicted FVC (Table 7) (Fig. 4), with a 9.6% decline in the anterior open group, 4.8% decline in the anterior thoracoscopic group, 3% increase in the PSF + anterior release group, and a 0.7% increase in the PSF only group ($p = 0.015$). There was no significant difference in change from 2 to 5 years based on approach for either of the best values (FEV $p = 0.37$, FVC $p = 0.71$) (Tables 6, 7).

Table 3 Within-group comparison of changes from pre-operative PFT to 5 years post-operative PFT for each surgical approach

	FEV Best Value			FEV % Predicted			FVC Best Value			FVC % predicted		
	Pre-op	5 year	*p* value	Pre-op	5 year	*p* value	Pre-op	5 year	*p* value	Pre-op	5 year	*p* value
Anterior open ($n = 48$)	2.6 ± 0.8	2.5 ± 0.5	0.65	84 ± 19	73 ± 14	**≤ 0.001**	2.9 ± 0.6	2.9 ± 0.6	0.86	88 ± 17	76 ± 16	**≤ 0.001**
Anterior thoracoscopic ($n = 35$)	2.5 ± 0.6	2.5 ± 0.5	0.85	81 ± 15	75 ± 13	**0.015**	2.9 ± 0.7	2.9 ± 0.6	0.98	88 ± 17	79 ± 15	**0.002**
Posterior + Anterior release ($n = 14$)	2.1 ± 0.6	2.5 ± 0.8	**0.004**	73 ± 11	75 ± 12	0.45	2.6 ± 0.7	3.0 ± 0.9	**0.003**	80 ± 13	81 ± 8	0.83
Posterior ($n = 165$)	2.5 ± 0.6	2.9 ± 0.6	**≤ 0.001**	80 ± 14	82 ± 13	0.06	2.9 ± 0.7	3.4 ± 0.8	**≤ 0.001**	86 ± 15	85 ± 12	0.57

Bold values represent statistical significance

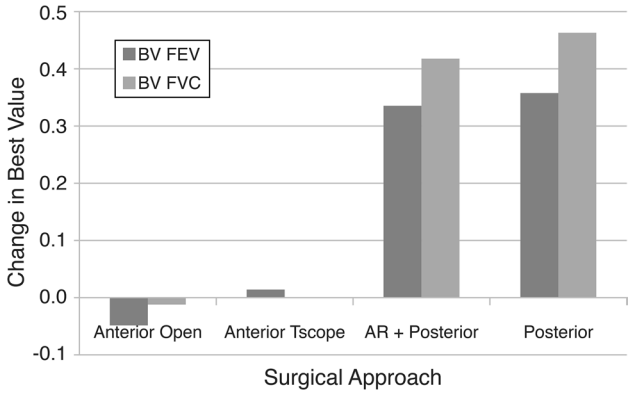


Fig. 2 Change in best values for the different surgical approach types

have on pulmonary function. Previous studies have shown that the reduction in PFTs for AIS patients possesses a strong correlation with the magnitude of the thoracic curve [2, 7, 28], decreased thoracic kyphosis [28], and the surgical approach utilized [1–9, 15–22]. The negative impact of open anterior instrumented fusion on PFTs in the short term has been well documented in the literature. Graham and colleagues found that in patients with AIS who underwent anterior spinal fusion and instrumentation with thoracotomy, the FVC, FEV1, and TLC values were within 95% of baseline by the 2-year follow-up visit, but were still statistically less than what was observed pre-operatively [16]. Prior work has shown that AIS patients who undergo anterior approaches (open or thoracoscopic) may regain similar pulmonary function at 2 years as they had at baseline, but that this improvement is not as great as that seen in patients who underwent PSF and did not have any violation of their chest cavity [6, 11, 12, 17].

Table 4 Change in PFT values from pre-operative PFT to 2 years to 5 years post-operative PFTs

	FEV best value (L)	FEV % predicted	FVC best value (L)	FVC % predicted
Pre-op	2.48 ± 0.6	81 ± 16*	2.98 ± 0.7*	87 ± 16*
2 year	2.56 ± 0.6	77 ± 14	3.07 ± 0.7¥	83 ± 15
5 year	2.58 ± 0.6	75 ± 13*	3.15 ± 0.7*¥	81 ± 13*
p value	0.10	***0.004**	***¥0.008**	***0.004**

Bold values represent statistical significance

*, ¥ correspond to the values within each column that were found to have statistically significant differences

Table 5 Percentage of patients with pre-operative, 2 year post-operative, and 5 year post-operative PFTs ($N = 90$) who changed pulmonary function impairment levels

Change in impairment level	Pre-operative to 2 years (%)	2 years to 5 years (%)	Pre-operative to 5 years (%)
Improved	7	9	45
No change	80	78	36
Worsened	13	13	19

In our study, we found that the percent predicted FEV and FVC significantly declined between pre-operative PFT and 5 years post-operative PFT for the anterior instrumented cases, both open and thoracoscopic, while the posterior cases with or without an anterior release remained stable. A recently published meta-analysis by Lee et al. showed that posterior approach without thoracoplasty resulted in mild to moderate increases in PFTs 2 and 6 years post-operatively [11]. When compared head to head against anterior spinal fusion and VAT at 2 years post-operatively, PSF resulted

Table 6 Within-group comparison of FEV values between pre-operative, 2 years post-operative, and 5 years post-operative PFTs for each surgical approach

	FEV best value				FEV % predicted			
	Pre-operative	2 year	5 year	*p* value	Pre-operative	2 year	5 year	*p* value
Anterior open ($n = 19$)	2.6 ± 0.7	2.5 ± 0.7	2.6 ± 0.6	0.72	85 ± 20	78 ± 19	73 ± 14	0.15
Anterior thoracoscopic ($n = 18$)	2.5 ± 0.6	2.5 ± 0.5	2.4 ± 0.6	0.55	84 ± 18	78 ± 15	75 ± 13	0.05
Posterior + anterior release ($n = 7$)	1.9 ± 0.6	2.1 ± 0.5	2.2 ± 0.6	0.15	71 ± 12	69 ± 8	72 ± 9	0.26
Posterior ($n = 46$)	2.5 ± 0.5	2.7 ± 0.5	2.7 ± 0.6	**0.02**	79 ± 12	78 ± 13	76 ± 12	0.62

Bold values represent statistical significance

Discussion

One of the many goals of surgically correcting AIS is to halt and improve any negative effects the deformity may

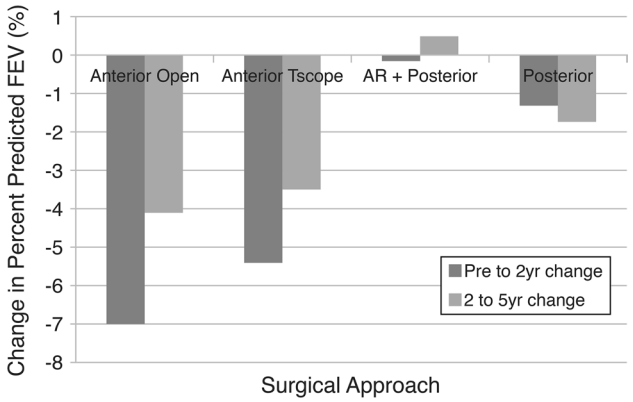


Fig. 3 Change in percent predicted FEV for the different surgical approach types

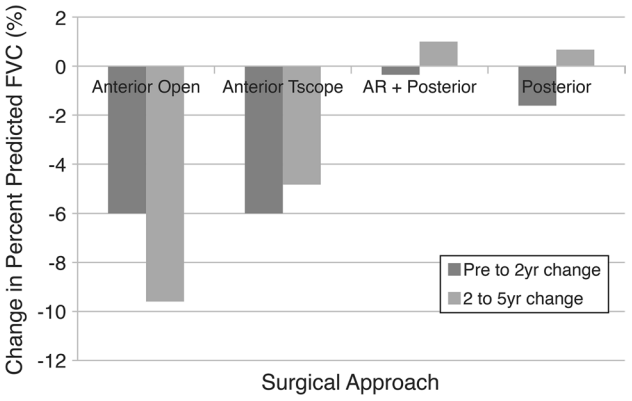


Fig. 4 Change in percent predicted FVC for the different approach types

in moderate to large improvements in PFTs. Lee and colleagues also found that VAT led to decreased PFTs at the 2 year post-operative mark compared to posterior fusion. Furthermore, VAT did not lead to better PFT results when compared to open anterior instrumentation approaches with thoracotomy [11]. In their analysis of four studies, ASR with PSF had no decrease in PFT outcome measures at 2 years after surgery. Likewise, no significant difference was found in absolute PFT values when comparing prior to surgery and 5 and 6 years post-surgery [11].

When comparing the pattern of change from pre-operative PFT to 5 years post-operative PFT based on major curve type (Lenke 1–4 vs. 5–6) for percent predicted FEV and FVC, we found no significant differences. When the same analysis was run for best values, Lenke 1–4 curves displayed a larger increase over time compared to the Lenke 5–6 group. One possible explanation for this is that the majority of Lenke 1–4 curves (72%) were corrected via posterior approach instead of through an anterior approach, whereas only 54% of the Lenke 5–6 curves were corrected through a posterior approach.

From pre-operative to 5 years post-operative, the different surgical approaches demonstrated significantly different patterns of change in regards to the four recorded PFT variables. The percent predicted FEV and FVC significantly declined between pre-operative PFT and 5 years post-operative PFT for the anterior instrumented cases, both open and thoracoscopic, while the posterior cases with or without an anterior release remained stable. This finding is in line with prior studies that analyzed these effects at the 2 year, 5 year, 10 year, and up to 15 year post-operative time points [9, 12, 13, 24–26]. Tis and colleagues demonstrated that OASF had a statistically significant negative impact on FEV_1, percent predicted FEV_1 and percent predicted FVC at 5 years post-surgery when compared to baseline [24]. In a 15 year average follow-up analysis of 25 AIS patients with Lenke 1 curves treated through OASF, the results demonstrated a significantly decreased mean percent predicted FVC and FEV_1 at long-term follow-up compared to baseline [26]. However, in that study the authors note that clinically no patients had complaints related to pulmonary function.

In the subgroup of 90 patients with pre-operative, 2 year post-operative, and 5 year post-operative PFTs, there were similar findings for 2 year PFTs as those previously reported in the literature [6, 11, 16, 17]. The average percent predicted FVC and FEV both displayed a gradual decline between pre-operative PFT and 2 years post-operative PFT. In our study, however, the difference between the pre-operative values

Table 7 Within-group comparison of FVC values pre-operative, 2 years post-operative, and 5 years post-operative PFT for each surgical approach

	FVC best value				FVC % predicted			
	Pre-operative	2 year	5 year	*p* value	Pre-operative	2 year	5 year	*p* value
Anterior open ($n=19$)	3.1 ± 0.7	3.0 ± 0.7	3.1 ± 0.7	0.3	91 ± 18	86 ± 16	76 ± 15	**0.01**
Anterior thoracoscopic ($n=18$)	2.9 ± 0.8	2.9 ± 0.6	2.9 ± 0.6	0.62	90 ± 20	84 ± 19	79 ± 12	**0.02**
Posterior + anterior Release ($n=7$)	2.5 ± 0.7	2.7 ± 0.8	2.8 ± 0.9	0.12	82 ± 12	78 ± 4	80 ± 5	0.74
Posterior ($n=46$)	2.9 ± 0.7	3.2 ± 0.7	3.3 ± 0.7	**≤0.001**	84 ± 14	83 ± 13	84 ± 12	0.59

Bold values represent statistical significance

became statistically significant at the 5 year mark. When the comparison was made between the 2 and 5 year time points, we found there to be a further decline in PFTs. FEV percent predicted between 2 and 5 years showed a decline except for the posterior + anterior release group; this difference, however, was not statistically significant. The difference in percent predicted FVC between the different surgical approaches was statistically significant with greater progressive decline in the anterior instrumentation groups.

Limitations of this study include that the data were collected at different sites introducing heterogeneity in the pulmonary function testing, lack of data to correlate the clinical significance of the findings in relation to decreasing PFT values, and a smaller number of patients who underwent anterior surgical correction in relation to posterior correction. Even with these limitations, significant differences were found. More importantly, this study demonstrates a progressive loss between PFTs 2 years post-operatively and 5 years post-operatively. Although it was beyond the scope of the current study, future studies would benefit from evaluating how this decline in pulmonary function clinically impacts the patients. Similarly, future studies will also provide insight into how the correction of the three-dimensional deformity influences long-term lung function [28, 29].

Conclusions

Although pulmonary function remains an important outcome following AIS surgical correction, it is one of the many variables that determine whether the procedure was successful. Many factors must be considered when choosing the "best" approach for a particular patient with AIS. The results of this study will hopefully provide further useful information for the scoliosis surgeon when the pros and cons are being weighed to decide on the best approach to treat a particular curve type.

Acknowledgements This study was supported in part by grants to the Setting Scoliosis Straight Foundation in support of Harms Study Group research from DePuy Synthes Spine, EOS imaging, K2M, Medtronic, NuVasive and Zimmer Biomet. Harms Study Group Investigators: Aaron Buckland, MD; New York University Amer Samdani, MD; Shriners Hospitals for Children—Philadelphia Amit Jain, MD; Johns Hopkins Hospital Baron Lonner, MD; Mount Sinai Hospital Benjamin Roye, MD; Columbia University Burt Yaszay, MD; Rady Children's Hospital Chris Reilly, MD; BC Children's Hospital Daniel Hedequist, MD; Boston Children's Hospital Daniel Sucato, MD; Texas Scottish Rite Hospital David Clements, MD; Cooper Bone & Joint Institute New Jersey Firoz Miyanji, MD; BC Children's Hospital Harry Shufflebarger, MD; Nicklaus Children's Hospital Jack Flynn, MD; Children's Hospital of Philadelphia Jahangir Asghar, MD; Cantor Spine Institute Jean Marc Mac Thiong, MD; CHU Sainte-Justine Joshua Pahys, MD; Shriners Hospitals for Children—Philadelphia Juergen Harms, MD; Klinikum Karlsbad-Langensteinbach, Karlsbad Keith Bachmann, MD; University of Virginia Larry Lenke, MD; Columbia University Mark Abel, MD; University of Virginia Michael Glotzbecker, MD; Boston Children's Hospital Michael Kelly, MD; Washington University Michael Vitale, MD; Columbia University Michelle Marks, PT, MA; Setting Scoliosis Straight Foundation Munish Gupta, MD; Washington University Nicholas Fletcher, MD; Emory University Patrick Cahill, MD; Children's Hospital of Philadelphia Paul Sponseller, MD; Johns Hopkins Hospital Peter Gabos, MD: Nemours/Alfred I. duPont Hospital for Children Peter Newton, MD; Rady Children's Hospital Peter Sturm, MD; Cincinnati Children's Hospital Randal Betz, MD; Institute for Spine & Scoliosis Ron Lehman, MD; Columbia University Stefan Parent, MD: CHU Sainte-Justine Stephen George, MD; Nicklaus Children's Hospital Steven Hwang, MD; Shriners Hospitals for Children—Philadelphia Suken Shah, MD; Nemours/Alfred I. duPont Hospital for Children Tom Errico, MD; Nicklaus Children's Hospital Vidyadhar Upasani, MD; Rady Children's Hospital.

Compliance with ethical standards

Conflict of interest All authors report grants to their institutions from the Setting Scoliosis Straight Foundation during the conduct of this study. The following conflicts of interest exist outside of the submitted work: Dr. Yaszay received grants and personal fees from K2M, grants and personal fees from DePuy Synthes Spine, personal fees from Nuvasive, personal fees from Medtronic, personal fees from Orthopediatrics, personal fees from Stryker, personal fees from Globus, grants from Setting Scoliosis Straight Foundation, and has a patent with K2M with royalties paid. Dr. Lonner reports received grants from Setting Scoliosis Straight Foundation, personal fees from DePuy Synthes Spine, personal fees from K2M, personal fees from Paradigm Spine, personal fees from Spine Search, personal fees from Ethicon, non-financial support from Spine Deformity Journal, grants from John and Marcella Fox Fund Grant, grants from OREF, personal fees from Zimmer Biomet, and personal fees from Apifix. Dr. Betz received personal fees and other from Abyrx, other from Advanced Vertebral Solutions, personal fees and other from ApiFix, personal fees from DePuy Synthes Spine, other from Electrocore, personal fees from Globus Medical, other from Medovex, personal fees from Medtronic, other from MiMedx, other from Orthobond, personal fees and other from SpineGuard, other from SpineMedica, personal fees from Thieme Medical Publishers, personal fees from Zimmer Biomet, and has an immediate family member who is an employee of DePuy Synthes Spine. Dr. Shah received personal fees from DePuy Synthes Spine and K2M. Dr. Asghar received personal fees and non-financial support from Omega innovative Technologies, and personal fees from Life Spine and Globus Medical. Dr. Samdani received personal fees from DePuy Synthes Spine, personal fees from Ethicon, personal fees from Globus Medical, personal fees from Misonix, personal fees from Stryker, personal fees from Zimmer Biomet, other from Setting Scoliosis Straight Foundation, other from Scoliosis Research Society, and other from Children's Spine Study Group. Dr. Newton received grants and other from Setting Scoliosis Straight Foundation, other from Rady Children's Specialists, grants, personal fees and non-financial support from DePuy Synthes Spine, grants and other from SRS, grants from EOS imaging, personal fees from Thieme Publishing, grants from NuVasive, other from Electrocore, personal fees from Cubist, other from International Pediatric Orthopedic Think Tank, grants, non-financial support and other from Orthopediatrics, grants, personal fees and non-financial support from K2M, grants and non-financial support from Alphatech, and has the following patents: Anchoring systems and methods for correcting spinal deformities (8540754) with royalties paid to DePuy Synthes Spine, a patent Low profile spinal tethering systems (8123749) licensed to DePuy Spine, Inc., a patent Screw placement guide (7981117) licensed to DePuy Spine, Inc., a patent Compressor for use in minimally invasive surgery (7189244) licensed to DePuy Spine, Inc., and a patent Posterior spinal fixation pending to K2M.

References

1. Aaro S, Ohlund C (1984) Scoliosis and pulmonary function. Spine 9:220–222
2. Kearon C, Viviani GR, Kirkley A, Killian KJ (1993) Factors determining pulmonary function in adolescent idiopathic thoracic scoliosis. Am Rev Respir Dis 148:288–294. https://doi.org/10.1164/ajrccm/148.2.288
3. Leong JC, Lu WW, Luk KD, Karlberg EM (1999) Kinematics of the chest cage and spine during breathing in healthy individuals and in patients with adolescent idiopathic scoliosis. Spine 24:1310–1315
4. Upadhyay SS, Mullaji AB, Luk KD, Leong JC (1995) Relation of spinal and thoracic cage deformities and their flexibilities with altered pulmonary functions in adolescent idiopathic scoliosis. Spine 20:2415–2420
5. Vedantam R, Crawford AH (1997) The role of preoperative pulmonary function tests in patients with adolescent idiopathic scoliosis undergoing posterior spinal fusion. Spine 22:2731–2734
6. Vedantam R, Lenke LG, Bridwell KH, Haas J, Linville DA (2000) A prospective evaluation of pulmonary function in patients with adolescent idiopathic scoliosis relative to the surgical approach used for spinal arthrodesis. Spine 25:82–90
7. Weinstein SL, Zavala DC, Ponseti IV (1981) Idiopathic scoliosis: long-term follow-up and prognosis in untreated patients. J Bone Joint Surg Am 63:702–712
8. Wood KB, Schendel MJ, Dekutoski MB, Boachie-Adjei O, Heithoff KH (1996) Thoracic volume changes in scoliosis surgery. Spine 21:718–723
9. Gagnon S, Jodoin A, Martin R (1989) Pulmonary function test study and after spinal fusion in young idiopathic scoliosis. Spine 14:486–490
10. Kim YJ, Lenke LG, Bridwell KH, Cheh G, Sides B, Whorton J (2008) Prospective pulmonary function comparison of anterior spinal fusion in adolescent idiopathic scoliosis: thoracotomy versus thoracoabdominal approach. Spine 33:1055–1060. https://doi.org/10.1097/brs.0b013e31816fc3a5
11. Lee AC, Feger MA, Singla A, Abel MF (2016) Effect of surgical approach on pulmonary function in adolescent idiopathic scoliosis patients: a systemic review and meta-analysis. Spine 41:E1343–E1355. https://doi.org/10.1097/brs.0000000000001619
12. Lenke LG, Newton PO, Marks MC, Blanke KM, Sides B, Kim YJ, Bridwell KH (2004) Prospective pulmonary function comparison of open versus endoscopic anterior fusion combined with posterior fusion in adolescent idiopathic scoliosis. Spine 29:2055–2060
13. Newton PO, Perry A, Bastrom TP, Lenke LG, Betz RR, Clements D, D'Andrea L (2007) Predictors of change in postoperative pulmonary function in adolescent idiopathic scoliosis: a prospective study of 254 patients. Spine 32:1875–1882. https://doi.org/10.1097/brs.0b013e31811eab09
14. Wang X, Dockery DW, Wypij D, Gold DR, Speizer FE, Ware JH, Ferris BG Jr (1993) Pulmonary function growth velocity in children 6 to 18 years of age. Am Rev Respir Dis 148:1502–1508. https://doi.org/10.1164/ajrccm/148.6_Pt_1.1502
15. Chen SH, Huang TJ, Lee YY, Hsu RW (2002) Pulmonary function after thoracoplasty in adolescent idiopathic scoliosis. Clin Orthop Relat Res 399:152–161
16. Graham EJ, Lenke LG, Lowe TG, Betz RR, Bridwell KH, Kong Y, Blanke K (2000) Prospective pulmonary function evaluation following open thoracotomy for anterior spinal fusion in adolescent idiopathic scoliosis. Spine 25:2319–2325
17. Kim YJ, Lenke LG, Bridwell KH, Kim KL, Steger-May K (2005) Pulmonary function in adolescent idiopathic scoliosis relative to the surgical procedure. J Bone Joint Surg Am 87:1534–1541. https://doi.org/10.2106/JBJS.C.00978
18. Kinnear WJ, Kinnear GC, Watson L, Webb JK, Johnston ID (1992) Pulmonary function after spinal surgery for idiopathic scoliosis. Spine 17:708–713
19. Kumano K, Tsuyama N (1982) Pulmonary function before and after surgical correction of scoliosis. J Bone Joint Surg Am 64:242–248
20. Lenke LG, Bridwell KH, Blanke K, Baldus C (1995) Analysis of pulmonary function and chest cage dimension changes after thoracoplasty in idiopathic scoliosis. Spine 20:1343–1350
21. Newton PO, Faro FD, Gollogly S, Betz RR, Lenke LG, Lowe TG (2005) Results of preoperative pulmonary function testing of adolescents with idiopathic scoliosis. A study of six hundred and thirty-one patients. J Bone Joint Surg Am 87:1937–1946. https://doi.org/10.2106/JBJS.D.02209
22. Redding G, Song K, Inscore S, Effmann E, Campbell R (2008) Lung function asymmetry in children with congenital and infantile scoliosis. Spine J 8:639–644. https://doi.org/10.1016/j.spine.2007.04.020
23. Betz RR, Harms J, Clements DH 3rd, Lenke LG, Lowe TG, Shufflebarger HL, Jeszenszky D, Beele B (1999) Comparison of anterior and posterior instrumentation for correction of adolescent thoracic idiopathic scoliosis. Spine 24:225–239
24. Tis JE, O'Brien MF, Newton PO, Lenke LG, Clements DH, Harms J, Betz RR (2010) Adolescent idiopathic scoliosis treated with open instrumented anterior spinal fusion: five-year follow-up. Spine 35:64–70. https://doi.org/10.1097/BRS.0b013e3181c4af52
25. Gitelman Y, Lenke LG, Bridwell KH, Auerbach JD, Sides BA (2011) Pulmonary function in adolescent idiopathic scoliosis relative to the surgical procedure: a 10-year follow-up analysis. Spine 36:1665–1672. https://doi.org/10.1097/BRS.0b013e31821bcf4c
26. Sudo H, Ito M, Kaneda K, Shono Y, Takahata M, Abumi K (2013) Long-term outcomes of anterior spinal fusion for treating thoracic adolescent idiopathic scoliosis curves: average 15-year follow-up analysis. Spine 38:819–826. https://doi.org/10.1097/BRS.0b013e31827ddc60
27. Murray J, Nadel J (2000) Textbook of respiratory medicine. Saunders, Philadelphia
28. Yaszay B, Bastrom TP, Bartley CE, Parent S, Newton PO (2017) The effects of the three-dimensional deformity of adolescent idiopathic scoliosis on pulmonary function. Eur Spine J 26:1658–1664. https://doi.org/10.1007/s00586-016-4694-y
29. Udupa JK, Tong Y, Capraro A, McDonough JM, Mayer OH, Ho S, Wileyto P, Torigian DA, Campbell RM Jr (2018) Understanding respiratory restrictions as a function of the scoliotic spinal curve in thoracic insufficiency syndrome: a 4D dynamic MR imaging study. J Pediatr Orthop 10:15–20. https://doi.org/10.1097/bpo.0000000000001258

Affiliations

Burt Yaszay[1] · Pawel P. Jankowski[2] · Tracey P. Bastrom[1] · Baron Lonner[3] · Randal Betz[4] · Suken Shah[5] · Jahangir Asghar[6] · Firoz Miyanji[7] · Amer Samdani[8] · Peter O. Newton[1]

✉ Burt Yaszay
byaszay.rady@gmail.com

1 Rady Children's Hospital, 3020 Children's Way, MC5062, San Diego, CA 92123, USA

2 New York University, New York, NY, USA

3 Mount Sinai Hospital, New York, NY, USA

4 The Institute for Spine and Scoliosis, Lawrenceville, NJ, USA

5 Alfred I. duPont Hospital for Children, Wilmington, DE, USA

6 Nicklaus Children's Hospital, Miami, FL, USA

7 British Columbia Children's Hospital, Vancouver, BC, Canada

8 Shriners Hospitals for Children, Philadelphia, PA, USA