Spine

SPINE Volume 38, Number 22, pp 1920-1926
©2013, Lippincott Williams & Wilkins

DEFORMITY

Should Postoperative Pulmonary Function Be a Criterion That Affects Upper Instrumented Vertebra Selection in Adolescent Idiopathic Scoliosis Surgery?

Satoru Demura, MD,* Tracey P. Bastrom, MA,† John Schlechter, DO,‡
Burt Yaszay, MD,†§ Peter O. Newton, MD,†§ and Harms Study Group

Study Design. A multicenter, prospective evaluation of pulmonary function testing (PFT) and radiographical measures in patients surgically treated for adolescent idiopathic scoliosis (AIS).

Objective. The objective of this study was to evaluate pulmonary function to determine whether a more proximal upper instrumented vertebra (UIV) negatively impacts pulmonary function in patients surgically treated for AIS.

Summary of Background Data. There seems to be increasing concern that a more proximal extent of posterior thoracic spinal instrumentation and fusion reduces postoperative pulmonary function. However, there are few reports that analyze the relation between the selection of UIV and pulmonary function in AIS.

Methods. PFT and radiographical examination of 154 patients with major thoracic AIS (Lenke type 1–4) undergoing posterior thoracic spinal instrumentation and fusion without thoracoplasty were completed prospectively. Patients were divided into groups based on UIV (T1–T3 *vs*. T4–T5) and Lenke curve type (2 and 4 *vs*. 1 and 3) and analyzed respectively. Demographic, radiographical measurements, and PFT data from preoperative and 2-year time points were analyzed.

Results. Patients with a structural upper thoracic curve (Lenke 2 and 4) had significantly lower preoperative PFT values than those without a structural upper thoracic curve (Lenke 1 and 3). Lenke 2 and 4 patients were also more likely to be fused proximally (82%, T1–T3) than those in the Lenke 1 and 3 groups (42%, T1–T3, $P < 0.05$). Preoperatively, those with UIV from T1 to T3 tended to have lower PFT values than those with UIV from T4–T5; however, only percent total lung capacity was statistically different ($P < 0.05$). Both UIV groups showed significant increases in all absolute values (forced vital capacity, forced expiratory volume in 1s, total lung capacity) at 2-year follow-up ($P < 0.05$) as expected with growth, and the percent predicted values (% forced vital capacity, % forced expiratory volume in 1s, % total lung capacity) remained stable.

Conclusion. Although patients with UIV: T1–T3 showed slightly lower PFT values than UIV: T4–T5, the presence of a double thoracic curve was the primary cause of PFT reduction in these patients. Including the upper thoracic spine in the fusion had no significant effect on pulmonary function 2 years after surgical correction of AIS.

Key words: pulmonary function, adolescent idiopathic scoliosis, selection of upper instrumented vertebra.

Level of Evidence: 3

Spine 2013;38:1920–1926

The primary goal for surgical correction of adolescent idiopathic scoliosis (AIS) is to prevent future curve progression with a stable arthrodesis while maintaining or improving pulmonary function. There is a well-known association between progression of thoracic curve magnitude and impairment of pulmonary function. In addition to curve magnitude, several factors such as greater number of vertebrae involved in the thoracic deformity, more cephalad location of the curve, hypokyphosis, and curve rigidity have been reported as predictive factors of pulmonary function.[1–6]

Pulmonary function after surgical correction of AIS has also been investigated.[7–19] The surgical approach chosen may directly impact the postoperative pulmonary function. A posterior-only approach has been shown to stabilize or modestly improve pulmonary function, whereas an open anterior

From the *Department of Orthopedic Surgery, Kanazawa University, Kanazawa, Japan; †Department of Orthopedic Surgery, Rady Children's Hospital and Health Center, San Diego, CA; ‡Department of Orthopedic Surgery, Children's Hospital of Orange County, Orange, CA; §Department of Orthopedic Surgery, University of California San Diego, San Diego, CA.

Acknowledgment date: August 10, 2012. First revision date: February 4, 2013. Second revision date: June 21, 2013. Acceptance date: July 22, 2013.

The device(s)/drug(s) is/are FDA-approved or approved by corresponding national agency for this indication.

Setting Scoliosis Straight Foundation received grant funds from DePuy Spine Inc. and JJKK Medical Company, a Division of DePuy Spine, Japan, to support this work.

Relevant financial activities outside the submitted work: board membership, consultancy, grants/grants pending, payment for lectures, royalties, expert testimony, patents, payment for development of educational presentations, and stock/stock options.

Address correspondence and reprint requests to Peter O. Newton, MD, 3030 Children's Way, Ste 410, San Diego, CA 92123; E-mail: pnewton@rchsd.org

DOI: 10.1097/BRS.0b013e3182a637a8

approach *via* a thoracotomy is associated with a further modest decline in pulmonary function.[8–12,15,19] A recent report using a multivariate analysis showed that open anterior approach and performing thoracoplasty were the major predictors of a decrease in 2-year postoperative pulmonary function.[14]

Another goal in surgical correction of AIS is to obtain ideal deformity correction while restoring/maintaining good global balance. Modern instrumentation and techniques have enabled substantial deformity correction in AIS. Occasionally, fusion of the upper thoracic spine is necessary due to a structural upper thoracic curve or uneven shoulders. However, there is a concern that the extension of the fusion proximally may decrease postoperative pulmonary function.[16,20,21] The purpose of this study was to evaluate pulmonary function to determine whether a more proximal extent of fusion *versus* a curve indicating a more proximal fusion, negatively impacts pulmonary function in patients surgically treated for AIS.

MATERIALS AND METHODS

A review of a multicenter prospective database of patients with AIS who underwent surgical correction was performed. A query was performed to include all patients with a diagnosis of main thoracic scoliosis (Lenke type 1–4), who underwent posterior spinal fusion without thoracoplasty, had an upper instrumented vertebra (UIV) of T5 or above, and who had preoperative and postoperative radiographical and pulmonary function test (PFT) data available. The current 2-year follow-up rate within the database is approximately 70%.

Pulmonary function tests were performed prior to surgery and at 2-year postoperative visits. Measures of total lung capacity (TLC), forced vital capacity (FVC), and forced expiratory volume in 1 s (FEV_1) were obtained from the PFT examinations. PFT testing at each institution was repeated 3 times, and the single best effort was recorded. Percent predicted values for each parameter were normalized according to the American Thoracic Society guidelines,[22] using age, sex, and height, or arm span matched standards. Further standardization on pulmonary function testing (PFT) between centers has not been undertaken, and variability in protocols may exist. However, analysis of the PFT values between centers indicated no significant differences in the homogeneity of the variances ($P > 0.05$).

Preoperative radiographical evaluation included full length, standing posteroanterior and lateral radiographs of the spine. The following radiographical parameters were evaluated: upper thoracic curve magnitude, main thoracic curve magnitude, lumbar curve magnitude, upper thoracic kyphosis (T2–T5), main thoracic kyphosis (T5–T12), and lumbar lordosis (T12 to sacrum). At 2-year visits, patients were similarly assessed to determine the degree of correction of each curve.

Statistical data were analyzed using SPSS (SPSS Inc., Chicago, IL). Each variable was reported as the mean ± standard deviation. To evaluate overall preoperative and 2-year change for all of the PFT and radiographical measurements, paired *t* tests were used. Two-way analysis of variance was used to evaluate the impact of UIV (T1-T3 vs. T4-T5) and Lenke class (Lenke 1 and 3 *vs*. Lenke 2 and 4) on change in PFT as well as to evaluate for any interactions between the two. The Pearson correlation was used to determine the relationship between PFT and the thoracic radiographical measurements of spinal deformity. A P value less than 0.05 was considered significant.

RESULTS

Overall Description

There were 154 patients (females, 112; males, 42). Mean age at the time of initial evaluation was 14.6 ± 2.2 years (10–21 yr). The Lenke classification breakdown was as follows: 105 patients were type 1, 36 were type 2, 11 were type 3, and 4 were type 4. The mean operative time was 279 ± 92 minutes with a mean blood loss of 1177 ± 1020 mL. The distribution of the UIV included 3 patients at T1, 38 at T2, 39 at T3, 55 at T4, and 19 at T5 (Table 1).

All of the radiographical parameters are described in Table 2. The preoperative upper thoracic, main thoracic, and TL/lumbar Cobb angles averaged 29.5° ± 10.6°, 54.8° ± 11.5°, and 34.0° ± 11.2°, respectively. At 2-year follow-up, those angles decreased significantly to 16.2° ± 7.7°, 20.9° ± 7.7°, and 13.2° ± 8.3°, resulting in correction rates of 46%, 61%, and 60% ($P < 0.05$). The average thoracic kyphosis from T2 to T5 was 8.2° ± 6.3° preoperatively, and 9.9° ± 6.2° at 2 years ($P < 0.05$). The average thoracic kyphosis from T5

TABLE 1. Descriptive Data

Age (yr)	14.6 ± 2.2 (10–21)				
Sex	112 (female)	42 (male)			
Risser score	2.7 ± 1.7 (0–5)				
Lenke classification	105 (type 1)	36 (type 2)	11 (type 3)	2 (type 4)	
Lumbar modifier	73 (A)	40 (B)	41 (C)		
Thoracic sagittal profile	32 (hypo)	13 (hyper)	109 (normal)		
Upper instrumented vertebra	3 (T1)	38 (T2)	39 (T3)	55 (T4)	19 (T5)
Operation time (min)	279 ± 92 (120–590)				
Estimated blood loss (mL)	1177 ± 1020 (200–1600)				

TABLE 2. Overall Radiographical and Pulmonary Parameters

	Preoperative	2-Year	Significance
Upper thoracic curve	29.5 ± 10.6	16.2 ± 7.7	$P < 0.01$
Upper thoracic flex (%)	36.8 ± 22.3		
Upper thoracic correction (%)		45.6 ± 20.3	
Main thoracic curve	54.8 ± 11.5	20.9 ± 7.7	$P < 0.01$
Main thoracic flex (%)	46.1 ± 19.5		
Main thoracic correction (%)		60.8 ± 14.7	
TL/lumbar curve	34.0 ± 11.2	13.2 ± 8.3	$P < 0.01$
TL/lumbar flex (%)	69.9 ± 22.4		
TL/lumbar correction (%)		59.6 ± 21.9	
T2–T12	28.5 ± 13.8	27.6 ± 10.8	$P = 0.34$
T2–T5	8.2 ± 6.3	9.9 ± 6.2	$P < 0.01$
T5–T12	20.4 ± 13.3	17.6 ± 8.2	$P < 0.01$
T12–S1	−60.2 ± 10.8	−56.7 ± 10.3	$P < 0.01$
Coronal C7–center sacral vertical line (cm)	−0.1 ± 2.3	−0.6 ± 1.3	$P < 0.01$
Sagittal C7–S1 (cm)	−1.5 ± 3.9	−0.5 ± 3.2	$P < 0.01$
Forced vital capacity (L)	2.90 ± 0.76	3.17 ± 0.78	$P < 0.01$
Percentage of predicted value	80.9 ± 14.6	80.6 ± 17.2	$P = 0.81$
Forced expiratory volume in 1 s. (L)	2.45 ± 0.63	2.71 ± 0.68	$P < 0.01$
Percentage of predicted value	76.9 ± 14.8	78.5 ± 14.0	$P = 0.14$
Total lung capacity (L)	3.96 ± 0.94	4.49 ± 0.98	$P < 0.01$
Percentage of predicted value	86.7 ± 13.9	87.5 ± 11.9	$P = 0.90$

to T12 decreased significantly from 20.4° ± 13.3° to 17.6° ± 8.2° ($P < 0.05$).

The average preoperative and 2-year values of FVC (L), FVC (%), FEV_1 (L), FEV_1 (%), TLC (L), and TLC (%) are also shown in Table 2. Significant increases were seen in all absolute values in FVC, FEV_1, and TLC ($P < 0.05$). The percent predicted values were similar ($P > 0.05$).

Pulmonary Function and Thoracic Radiographical Measurements

Table 3 shows the association between preoperative PFT data and thoracic radiographical variables. There was a small to moderate negative correlation between upper thoracic curve magnitude and all 3 preoperative percent predicted PFT values (Table 3, $P < 0.05$). The relationship between main thoracic curve magnitude and all of the preoperative PFT data also showed moderate negative correlations (range, $r = -0.25$ to -0.40; $P < 0.05$). There was a weak, but significant correlation observed between T2–T5 sagittal kyphosis and FEV_1 (%), TLC (%); T5–T12 kyphosis and FEV_1 (L) also showed a weak correlation. There was a small positive correlation between upper and main thoracic curve flexibility and 2-year absolute PFT values (FEV_1, FVC, Table 4). The relationship between preoperative main thoracic curve magnitude and 2-year PFT data showed small negative correlations (range, $r = -0.21$ to -0.26; $P < 0.05$).

Pulmonary Function and UIV Selection

The PFT data according to the selection of UIV are shown in Figure 1. UIV was grouped into 2 categories: from T1 to T3 and T4 to T5. Preoperative PFTs in patients with UIV from T1–T3 trended toward lower values than PFTs in the T4–T5 group, but was statistically significant only for percent TLC. At 2-year follow-up, a statistically significant difference was not observed between the groups. Each of the groups showed significant increases in all absolute values (FVC, FEV_1, TLC) at 2-year follow-up (Figure 1A). The percent predicted values (%FVC, %FEV_1, %TLC) were not changed (Figure 1B).

Pulmonary Function and Lenke Classification

The relationship between PFT and Lenke curve type (main thoracic curve, type 1–4) was also analyzed. When divided according to the rigidity of the upper thoracic curve (Lenke 1

TABLE 3. Correlation Between Preoperative PFT Data and Thoracic Radiographical Variables

	FEV_1 (L) / FEV_1 (%)	FVC (L) / FVC (%)	TLC (L) / TLC (%)
Upper thoracic curve	−0.06 (P = 0.47)	−0.02 (P = 0.80)	−0.05 (P = 0.58)
	−0.18 (P = 0.03)	**−0.17 (P = 0.03)**	**−0.32 (P < 0.01)**
Upper thoracic flex (%)	0.14 (P = 0.08)	0.15 (P = 0.07)	**0.20 (P = 0.03)**
	0.01 (P = 0.87)	0.03 (P = 0.75)	0.09 (P = 0.31)
Main thoracic curve	**−0.34 (P < 0.01)**	**−0.29 (P < 0.01)**	**−0.25 (P < 0.01)**
	−0.40 (P < 0.01)	**−0.40 (P < 0.01)**	**−0.34 (P < 0.01)**
Main thoracic flex (%)	0.09 (P = 0.29)	0.11 (P = 0.20)	0.14 (P = 0.12)
	0.07 (P = 0.41)	0.09 (P = 0.23)	0.09 (P = 0.31)
T2–T5	−0.01 (P = 0.91)	−0.06 (P = 0.43)	−0.04 (P = 0.71)
	0.18 (P = 0.03)	0.13 (P = 0.11)	0.18 (P = 0.05)
T5–T12	**0.17 (P = 0.03)**	0.14 (P = 0.08)	0.16 (P = 0.08)
	0.12 (P = 0.13)	0.10 (P = 0.21)	0.07 (P = 0.46)

PFT indicates pulmonary function testing; TLC, total lung capacity; FVC, forced vital capacity; and FEV_1, forced expiratory volume in 1 s. Bold values indicate $P < 0.05$.

and 3 compared with Lenke 2 and 4), the preoperative pulmonary values in types 1 and 3 trended higher than those in types 2 and 4. There were significant differences between the average preoperative FEV_1 (L), TLC (L), and TLC (%) in types 1 and 3 and those in types 2 and 4 ($P < 0.05$) (Figure 2A). The pre- to postoperative changes in absolute values were similar between both groups. On the contrary, the changes of all percent predicted values in the Lenke 2 and 4 curves were significantly greater than in the Lenke 1 and 3 curves, indicating that postoperative correction of the Lenke 2 and 4's results in greater improvement in PFT than Lenke types 1 and 3 (Figure 2B).

Table 4 shows the relationship between UIV selection and Lenke curve type. In Lenke 2 and 4 curves, 31 of the 38 patients (81.6%) had an UIV from T1 to T3. In Lenke 1 and 3 curves, 67 of the 116 patients (57.8%) had an UIV from T4 to T5. The expected difference was statistically significant ($P < 0.01$, χ^2 test).

TABLE 4. Correlation Between 2-Year PFT Data and Preoperative Thoracic Radiographical Variables

	FEV_1 (L) / FEV_1 (%)	FVC (L) / FVC (%)	TLC (L) / TLC (%)
Upper thoracic curve	−0.02 (P = 0.73)	0.01 (P = 0.99)	0.01 (P = 0.98)
	−0.05 (P = 0.51)	−0.02 (P = 0.83)	−0.01 (P = 0.39)
Upper thoracic flex (%)	**0.20 (P = 0.01)**	**0.19 (P = 0.02)**	0.19 (P = 0.08)
	−0.03 (P = 0.71)	−0.01 (P = 0.40)	−0.14 (P = 0.18)
Main thoracic curve	**−0.21 (P = 0.01)**	**−0.20 (P = 0.01)**	−0.12 (P = 0.25)
	−0.26 (P < 0.01)	**−0.26 (P < 0.01)**	−0.18 (P = 0.09)
Main thoracic flex (%)	**0.16 (P = 0.04)**	**0.16 (P = 0.04)**	0.06 (P = 0.58)
	0.03 (P = 0.65)	0.01 (P = 0.84)	−0.10 (P = 0.34)
T2–T5	−0.08 (P = 0.31)	−0.11 (P = 0.17)	−0.13 (P = 0.24)
	0.05 (P = 0.52)	0.07 (P = 0.37)	0.07 (P = 0.49)
T5–T12	0.07 (P = 0.35)	0.07 (P = 0.33)	0.04 (P = 0.67)
	0.01 (P = 0.99)	−0.01 (P = 0.85)	0.01 (P = 0.94)

PFT indicates pulmonary function testing; TLC, total lung capacity; FVC, forced vital capacity; and FEV_1, forced expiratory volume in 1 s. Bold values indicate $P < 0.05$.

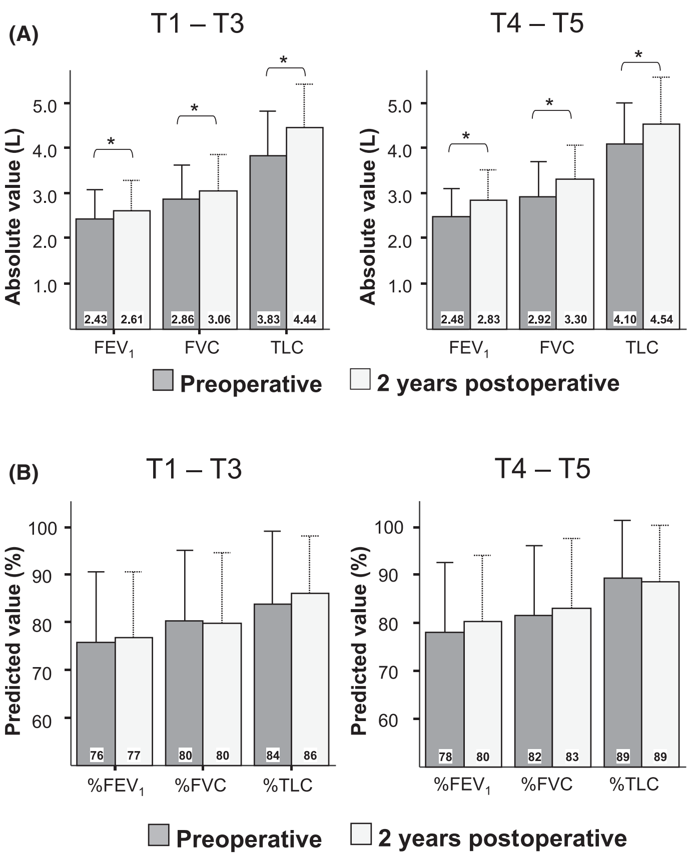

Figure 1. Preoperative and postoperative pulmonary function values for the 2 upper instrumented vertebra groups (T1–T3 and T4–T5). (**A**) Absolute PFT values. (**B**) Percent predicted values. PFT indicates pulmonary function testing; TLC, total lung capacity; FVC, forced vital capacity; and FEV_1, forced expiratory volume in 1 s.

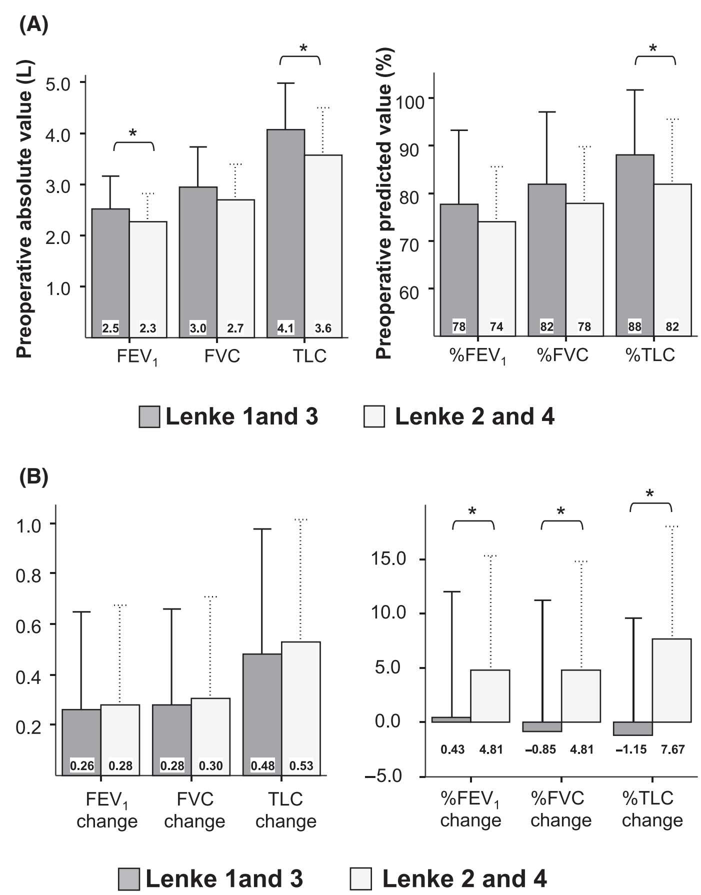

Figure 2. Preoperative and postoperative pulmonary function values based on rigidity of upper thoracic curve (Lenke 1 and 3 and Lenke 2 and 4). (**A**) Absolute PFT values. (**B**) Percent predicted values. PFT indicates pulmonary function testing; TLC, total lung capacity; FVC, forced vital capacity; and FEV_1, forced expiratory volume in 1 s.

Pulmonary Function, UIV, and Lenke Classification

Results of a 2-way analysis of variance with change in percent predicted values as the dependent variable demonstrate a significant main effect of Lenke class for FEV and FVC ($P < 0.05$, Figure 3). A trend for a main effect of Lenke class for TLC was observed ($P = 0.07$). There was no main effect of UIV ($P > 0.10$) for all 3 of the PFT assessments. Similarly, no significant interactions were observed between UIV and Lenke class ($P > 0.10$). However, only 7 patients comprised the subgroup of UIV at T4–T5 for the Lenke 2 and 4 groups and as such the interaction term may be underpowered.

DISCUSSION

This study evaluated 2-year postoperative pulmonary function after posterior thoracic spinal instrumentation and fusion (PSF) without thoracoplasty. Previous reports have commented on the superior effect of a posterior-only surgical approach on pulmonary function.[10–14] Vedantam *et al*[10] and Kim *et al*[12] reported that the patients without chest cage disruption resulted in greater improvement in pulmonary function than those with chest cage disruptions. Kim *et al*[13] also found that pulmonary function after posterior segmental spinal instrumentation improved absolute and predicted values, especially

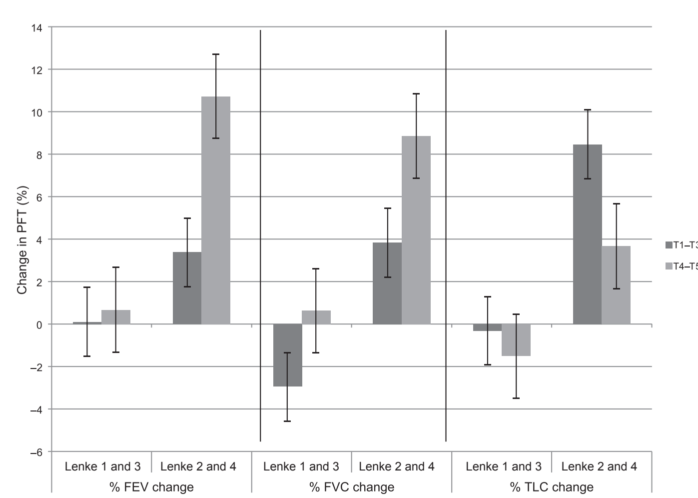

Figure 3. Change in percent predicted pulmonary function values based on rigidity of upper thoracic curve (Lenke class) and upper instrumented vertebra selection (T1–T3 and T4–T5). PFT indicates pulmonary function testing; TLC, total lung capacity; FVC, forced vital capacity; and FEV_1, forced expiratory volume in 1 s.

with the use of thoracic pedicle screw instrumentation. A prospective study of 254 patients surgically treated for AIS found that preoperative PFT values, use of an anterior approach, and having a thoracoplasty were predictors of 2-year pulmonary function values.[14] This study evaluated the impact of UIV selection in PSF on 2-year postoperative pulmonary function, thus removing the influence of surgical approach (open anterior approach) and chest cage disruption (thoracoplasty).

Several studies have reported the results of pulmonary function after PSF.[7–10,12–14] Lenke *et al*[23] evaluated PFTs of 48 adolescent and young patients with AIS after Cotrel Dobousset instrumentation and found that on average the FVC and FEV_1 improved to 16% and 15% at 17 months after the surgery. Vedantam *et al*[10] reported 47 cases after PSF without thoracoplasty and showed that the value of absolute FVC and FEV_1 improved significantly at final follow-up; however, the percent predicted values did not show significant differences between preoperative and final follow-up. More recently, Kim *et al*[13] examined 139 cases (thoracic pedicle screws in 53 cases, thoracic hook instrumentation in 86 patients) after posterior segmental spinal fusion and instrumentation and demonstrated significant improvement of absolute and percent predicted PFTs at 2-years postoperative, and that the improvement was related to thoracic pedicle screw instrumentation as compared with thoracic hook instrumentation. In this study of 154 cases after PSF without thoracoplasty (more than 80% had thoracic pedicle screw instrumentation; the remaining had thoracic hook or hybrid instrumentation), a significant increase in all absolute values in FVC, FEV_1, and TLC was observed, which is expected given the growth of these patients. However, change in percent predicted values was not significant, which is in contrast to the report of Kim *et al*.[13]

In terms of UIV selection, Lenke *et al*[23] reported that patients with an elevated left shoulder clinically or a positive T1 tilt radiographically usually require instrumentation and fusion of the proximal thoracic curve. Suk *et al*[24] recommended fusing both the proximal and distal curves when using segmental posterior instrumentation if the proximal thoracic curve is greater than 25°, and a level or elevated left shoulder is observed. However, there is concern that the proximal extent of a fusion might have a deleterious effect on postoperative pulmonary function. Previous studies have analyzed the relationship between UIV selection and pulmonary function. For example, Karol *et al*[20] analyzed pulmonary function in patients younger than 9 years with non-neuromuscular scoliosis who underwent thoracic spine fusions, and concluded that the proximal extent of fusion had a higher risk for the development of restrictive pulmonary disease. Luhmann *et al*[16] reported that postoperative predicted FEV_1 and FVC values progressively declined with more proximal upper instrumented vertebral levels in patients with idiopathic scoliosis. However, preoperative pulmonary function was not taken into account in either report. From this study, we now know that the presence of an upper thoracic curve (often the indication for a more proximal fusion) is associated with lower PFT values.

In this study, the selection of UIV from T1 to T3 showed significant increases in all absolute values and unchanged percent predicted values at 2-year follow-up. There were no significant differences in PFTs between the 2 UIV groups at 2-year follow-up. The preoperative FEV_1 (L), TLC (L), and TLC (%) in Lenke types 2 and 4, which consist of structural proximal and main thoracic curves, were significantly lower than those in types 1 and 3 (structural main thoracic curves without a structural proximal region). Furthermore, 31 of the 38 patients (81.6%) with Lenke 2 or 4 curves were instrumented proximally from T1 to T3. These findings indicate that the PFTs at 2-year follow-up were likely more affected by preoperative proximal thoracic deformity/rigidity than by fusion of the proximal thoracic spine.

One of the limitations of this study is that detailed factors such as smoking habit, level of physical activity, or history of asthma, which have previously been shown to affect pulmonary function,[14] were not available. However, the study includes a fairly homogenous population of patients in terms of diagnosis, age, and surgical approach for the correction of their curves.

CONCLUSION

There are many factors to consider when selecting the UIV for a given patient. Without a control group with similar curves who were not fused into the upper thoracic spine, it proves challenging to know the exact effect of the fusion of the upper thoracic spine on pulmonary function. However, based on the data collected in this study, including the upper thoracic spine in the fusion did not result in a measurable decline in pulmonary function 2 years after surgical correction of AIS.

➢ Key Points

- ❑ Patients with a structural upper thoracic curve had significantly lower preoperative PFT values than those without a structural upper thoracic curve.
- ❑ PFT at 2 years postoperatively did not seem to be affected by proximal fusion level (T1–T3 *vs.* T4–T5).
- ❑ The presence of an upper thoracic curve was associated with decreased PFT results at 2 years postoperatively.

Acknowledgments

This study was conducted at Rady Children's Hospital and Health Center-San Diego, CA with the membership of the Harms Study Group.

References

1. Weinstein SL, Zavala DC, Ponseti IV. Idiopathic scoliosis: long-term follow-up and prognosis in untreated patients. *J Bone Joint Surg Am* 1981;63:702–12.
2. Aaro S, Ohlund C. Scoliosis and pulmonary function. *Spine* 1984;9:220–2.
3. Upadhyay SS, Mullaji AB, Luk KD, et al. Relation of spinal and thoracic cage deformities and their flexibilities with altered

pulmonary functions in adolescent idiopathic scoliosis. *Spine* 1995;20(22):2415–20.
4. Leong JC, Lu WW, Luk KD, et al. Kinematics of the chest cage and spine during breathing in healthy individuals and in patients with adolescent idiopathic scoliosis. *Spine* 1999;24:1310–5.
5. Newton PO, Faro FD, Gollogly S, et al. 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* 2005;87:1937–46.
6. Kearon C, Viviani GR, Kirkley A, et al. Factors determining pulmonary function in adolescent idiopathic thoracic scoliosis. *Am Rev Respir Dis* 1993;148:288–94.
7. Kumano K, Tsuyama N. Pulmonary function before and after surgical correction of scoliosis. *J Bone Joint Surg Am* 1982;64: 242–8.
8. Gagnon S, Jodoin A, Martin R. Pulmonary function test study and after spinal fusion in young idiopathic scoliosis. *Spine* 1989;14: 486–90.
9. Kinnear WJ, Kinnear GC, Watson L, et al. Pulmonary function after spinal surgery for idiopathic scoliosis. *Spine* 1992;17:708–13.
10. Vedantam R, Lenke LG, Bridwell KH, et al. A prospective evaluation of pulmonary function in patients with adolescent idiopathic scoliosis relative to the surgical approach used for spinal arthrodesis. *Spine* 2000;25:82–90.
11. Graham EJ, Lenke LG, Lowe TG, et al. Prospective pulmonary function evaluation following open thoracotomy for anterior spinal fusion in adolescent idiopathic scoliosis. *Spine* 2000;25: 2319–25.
12. Kim YJ, Lenke LG, Bridwell KH, et al. Pulmonary function in adolescent idiopathic scoliosis relative to the surgical procedure. *J Bone Joint Surg Am* 2005;87:1534–41.
13. Kim YJ, Lenke LG, Bridwell KH, et al. Prospective pulmonary function comparison following posterior segmental spinal instrumentation and fusion of adolescent idiopathic scoliosis: is there a relationship between major thoracic curve correction and pulmonary function test improvement? *Spine* 2007;32:2685–93.
14. Newton PO, Perry A, Bastrom TP, et al. Predictors of change in postoperative pulmonary function in adolescent idiopathic scoliosis: a prospective study of 254 patients. *Spine* 2007;32: 1875–82.
15. Kishan S, Bastrom T, Betz RR, et al. Thoracoscopic scoliosis surgery affects pulmonary function less than thoracotomy at 2 years postsurgery. *Spine* 2007;32:453–8.
16. Luhmann SJ, Kim YJ, Lenke LG, et al. The impact of curve characteristics and spine fusion on pulmonary function in adolescent idiopathic scoliosis. Paper presented at: Annual Meeting of the Pediatric Orthopaedic Society of North America; 2006; Hollywood, FL.
17. Lenke LG, Bridwell KH, Baldus C, et al. Analysis of pulmonary function and axis rotation in adolescent and young adult idiopathic scoliosis patients treated with Cotrel-Dubousset instrumentation. *J Spinal Disord* 1992;5:16–25.
18. Lenke LG, Bridwell KH, Blanke K, et al. Analysis of pulmonary function and chest cage dimension changes after thoracoplasty in idiopathic scoliosis. *Spine* 1995;20:1343–50.
19. Lenke LG, Newton PO, Marks MC, et al. Prospective pulmonary function comparison of open versus endoscopic anterior fusion combined with posterior fusion in adolescent idiopathic scoliosis. *Spine* 2004;29:2055–60.
20. Karol LA, Johnston C, Mladenov K, et al. Pulmonary function following early thoracic fusion in non-neuromuscular scoliosis. *J Bone Joint Surg Am* 2008;90:1272–81.
21. Do PK, Taylor LA, Feng J, et al. 3D Kinematic Analysis of Regional Chest Wall Motion and Volume Changes During Respiration in Healthy Children. Paper presented at: 19th International Meeting on Advanced Spine Techniques; 2012; Istanbul, Turkey.
22. Murray J, Nadel J, eds. *Textbook of Respiratory Medicine*. 3rd ed. Philadelphia: Saunders; 2000.
23. Lenke LG, Bridwell KH, O'Brien MF, et al. Recognition and treatment of the proximal thoracic curve in adolescent idiopathic scoliosis treated with Cotrel-Dubousset instrumentation. *Spine* 1994;19:1589–97.
24. Suk SI, Kim WJ, Lee CS, et al. Indications of proximal thoracic curve fusion in thoracic adolescent idiopathic scoliosis: recognition and treatment of double thoracic curve pattern in adolescent idiopathic scoliosis treated with segmental instrumentation. *Spine* 2000;25:2342–9.