

Longitudinal Pulmonary Outcomes After Posterior Spinal Fusion in Duchenne Muscular Dystrophy: A Retrospective Cohort Study

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Abstract

Introduction

Whether posterior spinal fusion (PSF) alters pulmonary decline in patients with Duchenne muscular dystrophy (DMD) remains uncertain. This study evaluated longitudinal changes in pulmonary function and respiratory muscle strength after PSF and examined whether the magnitude of scoliosis correction was associated with postoperative pulmonary outcomes.

Methods

We retrospectively reviewed patients with DMD who underwent PSF and had pulmonary function testing before and after surgery. Pulmonary measures were assessed preoperatively, at approximately 5 to 6 months postoperatively, and at final follow-up of approximately 2 years.

Results

Sixteen nonambulatory male patients were included at a mean age of 17.9 ± 2.9 years. The mean Cobb angle improved from $63.6^\circ \pm 15.4^\circ$ preoperatively to $19.1^\circ \pm 13.3^\circ$ postoperatively. Mean FVC percent predicted remained stable from the preoperative to early postoperative assessment ($41.0\% \pm 15.5\%$ vs $41.1\% \pm 18.0\%$) but decreased to $34.4\% \pm 13.7\%$ at final follow-up. MEP decreased significantly during the early postoperative period ($P = 0.010$), whereas maximal inspiratory pressure remained unchanged. Greater absolute curve correction was associated with greater reductions in measured FVC at early postoperative assessment ($\rho = -0.62$, $P = 0.019$) and final follow-up ($\rho = -0.65$, $P = 0.012$).

Conclusions

In nonambulatory patients with DMD, FVC percent predicted did not change significantly during early follow-up but declined significantly by approximately 2 years. In our cohort, greater absolute curve correction was associated with greater measured FVC loss. These findings do not support pulmonary preservation as an expected benefit of greater deformity correction and reinforce the functional, postural, and quality-of-life goals of PSF.

Introduction

Duchenne muscular dystrophy (DMD) is an X-linked neuromuscular disorder characterized by progressive skeletal, respiratory, and cardiac muscle weakness.¹ Scoliosis develops in many affected individuals, with clinically significant spinal curvature occurring in up to 90% of patients not treated with corticosteroids.^{2,3} Progressive scoliosis may further compromise respiratory mechanics through

thoracic distortion and reduced chest-wall compliance.^{1,4} Forced vital capacity declines at an estimated rate of approximately 4% to 6% per year in the nonambulatory phase, and respiratory insufficiency remains a leading cause of morbidity and mortality in DMD.⁵

Posterior spinal fusions (PSF) are recommended for progressive curves exceeding approximately 20° to 30° in patients with DMD, with the goals of preventing further deformity, restoring sitting balance, and improving comfort and care.^{6,7} Whether PSF also preserves pulmonary function remains uncertain. Several studies have reported slower postoperative declines in FVC% predicted, and comparative observational studies have suggested improved function or survival among surgically treated patients.^{4,5,8,9} However, other studies have found that spinal fusion did not alter pulmonary decline, and a recent Cochrane review concluded that the current evidence is insufficient to support respiratory function alone as an indication for surgery.^{1,5}

The association between the magnitude of scoliosis correction and postoperative pulmonary outcomes remains poorly understood. This study aimed to characterize longitudinal changes in pulmonary function and respiratory muscle strength after PSF in patients with DMD and to determine whether the degree of curve correction was associated with postoperative pulmonary decline.

Methods

Study Design and Setting

We performed a retrospective cohort study of patients with DMD and scoliosis who underwent PSF and follow-ups at our institution from September 2011 to June 2025. The study was approved by our Institutional Review Board and the requirement for individual informed consent was waived given the retrospective design.

Participants

Patients were eligible for inclusion if they had a confirmed diagnosis of DMD and scoliosis, were treated with PSF, and had documented pulmonary function testing (PFT) both before and after surgery. Patients were excluded if their scoliosis was attributable to another neuromuscular etiology or if pre- or postoperative PFT data were incomplete.

Data Collection

Demographic and clinical variables were extracted from the electronic medical record, including age at surgery, sex, ambulatory status, and medication exposure, including corticosteroids, bisphosphonates, and exon-skipping or gene therapy. Radiographic variables included the coronal Cobb angle at initial presentation, the immediately preoperative Cobb angle, and the postoperative residual Cobb angle. The

magnitude of curve correction was calculated as the difference between the preoperative and postoperative Cobb angles. Operative variables included the uppermost and lowermost instrumented vertebrae, operative duration, estimated blood loss, length of hospital stay, and intraoperative and postoperative complications.

Pulmonary function was assessed at three time points: preoperatively, at an early postoperative visit approximately 5 to 6 months after surgery, and at final follow-up approximately 2 years after surgery. At each assessment, we recorded measured forced vital capacity (FVC; L), predicted FVC (L), FVC percent predicted, the FEV₁/FVC ratio expressed as a percentage of the predicted value, maximal inspiratory pressure (MIP; cm H₂O), and maximal expiratory pressure (MEP; cm H₂O). Predicted FVC was reported descriptively as the denominator used to calculate FVC percent predicted and was not treated as a separate longitudinal outcome. Absolute curve correction was calculated as the preoperative Cobb angle minus the first postoperative Cobb angle. Relative curve correction was calculated as the absolute correction divided by the preoperative Cobb angle and expressed as a percentage.

Outcome Measures

The primary outcomes were within-patient changes in measured FVC and FVC percent predicted across the preoperative-to-early postoperative, preoperative-to-final follow-up, and early postoperative-to-final follow-up intervals. Secondary outcomes were changes in the FEV₁/FVC ratio, MIP, and MEP. Exploratory analyses assessed associations between absolute and relative curve correction and changes in measured FVC and FVC percent predicted.

Statistical Analysis

Continuous variables are reported as mean $\pm$ standard deviation or median with interquartile range, as appropriate, and categorical variables as counts and percentages. Denominators are provided for variables with missing data. Within-patient changes over time were assessed using the Wilcoxon signed-rank test. Exact p values were also calculated and produced no changes in statistical significance. Associations between continuous variables were evaluated using Spearman rank correlation coefficients (ρ). Between-group differences in pulmonary function changes according to corticosteroid and bisphosphonate exposure were assessed using two-sided Mann–Whitney U tests. All tests were two-sided, with $p < 0.05$ considered statistically significant. Analyses were performed using Python version 3.11 with NumPy and SciPy.

Results

Study Population

Nineteen patients with DMD met the initial inclusion criteria, but three were excluded due to lack of operative data. Sixteen patients were included in the analysis (Table 1). All patients were male and

nonambulatory at baseline, with a mean age at surgery of 17.9 ± 2.9 years. The mean Cobb angle at presentation was $29.0^\circ \pm 21.5^\circ$, and curves progressed by a mean of $34.5^\circ \pm 25.3^\circ$ during the 2.95 ± 2.37 years between presentation and surgery. Corticosteroid therapy was documented in 14 patients (87.5%). Of the 15 patients with available medication data, 8 (53.3%) had received bisphosphonate therapy. No patient had received exon-skipping or gene-transfer therapy.

Table 1
Baseline demographic, radiographic, and pharmacologic characteristics of the study cohort (n = 16, unless specified). Values are mean $\pm$ standard deviation for continuous variables and n (%) for categorical variables. All patients carried a clinically confirmed diagnosis of Duchenne muscular dystrophy, and all were non-ambulatory at baseline and remained so postoperatively. Cobb angle at presentation refers to the major curve measured on the first available upright or seated radiograph; curve progression is the difference between the Cobb angle at presentation and the immediate preoperative Cobb angle.

Characteristic	Mean $\pm$ SD or n (%)
Age at surgery, years	17.9 $\pm$ 2.9
Male sex	16/16 (100.0)
Non-ambulatory at baseline	16/16 (100.0)
Cobb angle at presentation, $^\circ$	29.0 $\pm$ 21.5
Curve progression, presentation to surgery, $^\circ$	34.5 $\pm$ 25.3
Presentation to surgery, years	2.95 $\pm$ 2.37
Corticosteroid therapy	
Yes	14 (87.5)
No	2 (12.5)
Bisphosphonate therapy (n = 15)	
Yes	8 (53.3)
No	7 (46.7)
Disease-modifying therapy (exon skipping or gene transfer)	
No	16 (100.0)

Operative Characteristics

Operative characteristics are summarized in Table 2. The mean Cobb angle improved from $63.6^\circ \pm 15.4^\circ$ preoperatively to $19.1^\circ \pm 13.3^\circ$ postoperatively, corresponding to an absolute correction of $44.4^\circ \pm 17.1^\circ$ and a relative correction of $69.6\% \pm 22.6\%$. Mean operative time was 6.5 ± 1.4 hours, estimated blood loss was 1022 ± 410 mL, and hospital length of stay was 7.0 ± 3.5 days.

Table 2

Operative, radiographic, and perioperative outcomes following posterior spinal fusion (n = 16, unless specified).

Values are mean $\pm$ standard deviation or n (%). Pre- and postoperative Cobb angles refer to the major curve; absolute curve correction is the difference between preoperative and first postoperative Cobb angle, and relative correction is that difference expressed as a percentage of the preoperative Cobb angle.

Variable	Mean $\pm$ SD or n (%)
Cobb angle, pre-operative, °	63.6 $\pm$ 15.4
Cobb angle, post-operative, °	19.1 $\pm$ 13.3
Absolute curve correction, °	44.4 $\pm$ 17.1
Relative curve correction, %	69.6 $\pm$ 22.6
Operative time, hours	6.5 $\pm$ 1.4
Estimated blood loss, mL	1022 $\pm$ 410
Length of hospital stay, days	7.0 $\pm$ 3.5
Upper instrumented vertebra	
T2	12 (75.0)
T3	4 (25.0)
Lowest instrumented vertebra	
S1	7 (43.8)
S2 (including S2-alar-iliac)	3 (18.8)
Pelvis / ilium	6 (37.5)
Pelvic fixation	
Yes	13 (81.2)
No	3 (18.8)
Intra-operative complication (n = 13)	
No	13 (100.0)
Post-operative complication (n = 13)	
No	11 (84.6)
Yes	2 (15.4)

The upper instrumented vertebra was T2 in 12 patients (75.0%) and T3 in 4 (25.0%). The lowest instrumented level was S1 in 7 patients (43.8%), S2 or S2-alar-iliac in 3 (18.8%), and the pelvis or ilium in 6 (37.5%). Overall, pelvic fixation was used in 13 patients (81.2%). Among the 13 patients with available complication data, no intraoperative complications occurred and 2 (15.4%) experienced postoperative complications, including one patient who developed urinary retention, and another patient who sustained a periprosthetic femur fracture followed by pulmonary embolism and duodenal ulcer.

Pulmonary Function Across the Perioperative Course

Pulmonary function and respiratory muscle strength at each assessment are presented in Table 3 and Figs. 1 and 2. Mean FVC percent predicted was $41.0\% \pm 15.5\%$ preoperatively, $41.1\% \pm 18.0\%$ at early postoperative follow-up, and $34.4\% \pm 13.7\%$ at final follow-up (Fig. 1A). Corresponding measured FVC values were 1.47 ± 0.60 L, 1.44 ± 0.66 L, and 1.35 ± 0.71 L, respectively (Fig. 1B).

Table 3

Pulmonary function at the three prespecified study time points. Values are mean $\pm$ standard deviation. FVC is reported in absolute liters and as percent predicted; FEV₁/FVC is expressed as percent of predicted; maximal inspiratory and maximal expiratory pressures are reported in cm H₂O.

Variable	Pre-operative	Early Post-operative	Final Follow-up
FVC, L	1.47 ± 0.60	1.44 ± 0.66	1.35 ± 0.71
FVC, predicted	3.61 ± 0.68	3.57 ± 0.93	3.82 ± 0.83
FVC, % predicted	41.0 ± 15.5	41.1 ± 18.0	34.4 ± 13.7
FEV1/FVC ratio, % of predicted	101.4 ± 13.1	99.1 ± 19.2	99.5 ± 13.4
Maximal inspiratory pressure, cm H ₂ O	33.5 ± 20.1	37.9 ± 21.2	33.5 ± 18.3
Maximal expiratory pressure, cm H ₂ O	33.4 ± 16.9	27.6 ± 15.0	29.0 ± 14.3

The mean FEV1/FVC ratio, expressed as a percentage of the predicted value, was $101.4\% \pm 13.1\%$ preoperatively, $99.1\% \pm 19.2\%$ at early follow-up, and $99.5\% \pm 13.4\%$ at final follow-up. Mean maximal inspiratory pressure was 33.5 ± 20.1 cm H₂O preoperatively, 37.9 ± 21.2 cm H₂O at early follow-up, and 33.5 ± 18.3 cm H₂O at final follow-up (Fig. 2A). Mean maximal expiratory pressure was 33.4 ± 16.9 cm H₂O, 27.6 ± 15.0 cm H₂O, and 29.0 ± 14.3 cm H₂O at the respective assessments (Fig. 2B).

Within-Patient Changes in Pulmonary Function

Within-patient changes across each study interval are presented in Table 4. From the preoperative to early postoperative assessment, MEP decreased significantly by 8.9 ± 10.5 cm H₂O (effect size $r = -0.80$, $P = 0.010$). Changes in the remaining pulmonary measures were not significant.

Table 4

Within-patient change in pulmonary function after posterior spinal fusion. Values are represented as mean change $\pm$ standard deviation, with negative values indicating decline. Effect size r was calculated as the standardized Wilcoxon test statistic divided by the square root of the number of paired observations. p -values correspond to the paired within-patient comparison across the interval.

Variable	Mean change $\pm$ SD	r	p -value
<i>Pre-operative to Early post-operative</i>			
FVC, L	-0.10 ± 0.27	-0.39	0.175
FVC, % predicted	-1.8 ± 10.0	-0.20	0.511
FEV1/FVC ratio, % of predicted	-2.6 ± 17.3	-0.06	0.587
Maximal inspiratory pressure, cmH ₂ O	0.2 ± 7.7	-0.14	0.931
Maximal expiratory pressure, cmH ₂ O	-8.9 ± 10.5	-0.80	0.010
<i>Pre-operative to final follow-up</i>			
FVC, L	-0.20 ± 0.38	-0.59	0.070
FVC, % predicted	-8.9 ± 10.2	-0.81	0.006
FEV1/FVC ratio, % of predicted	-4.5 ± 16.2	-0.20	0.319
Maximal inspiratory pressure, cmH ₂ O	-3.1 ± 15.9	-0.12	0.481
Maximal expiratory pressure, cmH ₂ O	-7.2 ± 14.9	-0.55	0.095
<i>Early post-operative to Final follow-up</i>			
FVC, L	-0.12 ± 0.37	-0.34	0.249
FVC, % predicted	-7.7 ± 10.7	-0.74	0.023
FEV1/FVC ratio, % of predicted	-1.1 ± 21.0	-0.21	0.856
Maximal inspiratory pressure, cmH ₂ O	-4.6 ± 15.0	-0.38	0.317
Maximal expiratory pressure, cmH ₂ O	1.7 ± 8.7	0.27	0.502

From the preoperative assessment to final follow-up, FVC percent predicted decreased significantly by 8.9 ± 10.2 percentage points ($r = -0.81$, $P = 0.006$). Measured FVC decreased by 0.20 ± 0.38 L, although this difference did not reach significance ($r = -0.59$, $P = 0.070$). No significant changes were observed in the FEV1/FVC ratio, MIP, or MEP.

Between the early postoperative assessment and final follow-up, FVC percent predicted decreased significantly by 7.7 ± 10.7 percentage points ($r = -0.74$, $P = 0.023$). Changes in measured FVC, the FEV1/FVC ratio, MIP and MEP were not significant.

Associations Between Curve Correction and Pulmonary Function

Associations between clinical and operative variables and changes in pulmonary function from the preoperative assessment to final follow-up are presented in Table 5. The change in FVC percent predicted was not significantly associated with age at surgery, preoperative Cobb angle, absolute or relative curve correction, preoperative FVC percent predicted, estimated blood loss, or operative time (all $P \geq 0.122$).

Table 5
Spearman rank correlations between preoperative, radiographic, and operative covariates and the change in pulmonary function. Values are the Spearman correlation coefficient (ρ) with the corresponding p-value; negative coefficients indicate that higher values of the covariate were associated with greater pulmonary decline.

Covariate	Spearman ρ	p-value
<i>Change in FVC % predicted, Pre-operative to Final follow-up</i>		
Age at surgery, years	0.222	0.446
Pre-operative Cobb angle, °	-0.209	0.474
Absolute curve correction, °	-0.433	0.122
Relative curve correction, %	-0.341	0.233
Pre-operative FVC, % predicted	-0.411	0.144
Estimated blood loss, mL	0.131	0.656
Operative time, hours	-0.204	0.503
<i>Change in FVC (L), Pre-operative to Final follow-up</i>		
Age at surgery, years	0.059	0.840
Pre-operative Cobb angle, °	-0.503	0.067
Absolute curve correction, °	-0.648	0.012
Relative curve correction, %	-0.253	0.383
Pre-operative FVC, % predicted	-0.218	0.455
Estimated blood loss, mL	0.104	0.724
Operative time, hours	-0.192	0.529

In contrast, greater absolute curve correction was associated with a greater decrease in measured FVC from the preoperative assessment to final follow-up ($\rho = -0.648$, $P = 0.012$). Change in measured FVC

was not significantly associated with age at surgery, preoperative Cobb angle, relative curve correction, preoperative FVC percent predicted, estimated blood loss, or operative time.

Interval-specific associations are illustrated in Fig. 3. Greater absolute curve correction was associated with a greater decrease in measured FVC from both the preoperative to early postoperative assessment ($\rho = -0.62$, $P = 0.019$; Fig. 3A) and the preoperative assessment to final follow-up ($\rho = -0.65$, $P = 0.012$; Fig. 3B). Absolute curve correction was not significantly associated with change in FVC percent predicted during either interval (Fig. 3C and 3D).

Greater relative curve correction was also associated with a greater early postoperative decrease in measured FVC ($\rho = -0.68$, $P = 0.008$), but this association was not maintained at final follow-up. Neither absolute nor relative curve correction was associated with changes in measured FVC or FVC percent predicted between the early postoperative assessment and final follow-up ($|\rho| \leq 0.18$; all $P \geq 0.56$).

Subgroup Analyses by Corticosteroid and Bisphosphonate Exposure

Changes in pulmonary function stratified by corticosteroid and bisphosphonate exposure are presented in Table 6. No significant differences were observed between patients who had and had not received corticosteroid therapy in the change in FVC, FVC percent predicted, FEV1/FVC ratio, MIP, or MEP during any study interval (all $P \geq 0.132$).

Table 6

Change in pulmonary function by pre-operative corticosteroid and bisphosphonate exposure. Change in pulmonary function stratified by preoperative pharmacologic exposure: (A) corticosteroid use and (B) bisphosphonate use. Values are median change [interquartile range] within each exposure group for the three study intervals, with negative values indicating decline.

Time interval and variable	Median Change [IQR]		p-value
	Medication	No medication	
A. Steroid use			
Pre-operative to Early post-operative			
FVC, L	−0.04 [− 0.38 to 0.16]	−0.05 [− 0.16 to 0.07]	0.659
FVC, % predicted	−3.6 [− 9.9 to 2.3]	10.0 [6.3 to 13.8]	0.132
FEV ₁ /FVC ratio, % predicted	3.5 [− 10.2 to 8.2]	−0.5 [− 4.8 to 3.8]	1.000
Maximal inspiratory pressure, cm H ₂ O	−3.0 [− 4.5 to 1.0]	2.3 [− 0.8 to 5.4]	0.769
Maximal expiratory pressure, cm H ₂ O	−10.0 [− 13.5 to − 6.5]	−0.3 [− 0.4 to − 0.2]	0.231
Pre-operative to final follow-up			
FVC, L	−0.21 [− 0.41 to − 0.09]	0.04 [0.04 to 0.05]	0.198
FVC, % predicted	−9.9 [− 15.1 to − 2.2]	−7.5 [− 10.0 to − 4.9]	0.923
FEV ₁ /FVC ratio, % predicted	0.5 [− 10.8 to 5.5]	0.0 [− 1.5 to 1.5]	0.923
Maximal inspiratory pressure, cm H ₂ O	−2.0 [− 12.5 to 4.0]	10.9 [6.7 to 15.1]	0.264
Maximal expiratory pressure, cm H ₂ O	−8.0 [− 15.0 to − 3.8]	0.3 [− 0.2 to 0.9]	0.198
Early post-operative to Final follow-up			
FVC, L	−0.26 [− 0.38 to 0.05]	0.04 [0.04 to 0.05]	0.513
FVC, % predicted	−6.0 [− 10.4 to − 0.1]	−7.5 [− 10.0 to − 4.9]	0.410
FEV ₁ /FVC ratio, % predicted	0.0 [− 10.5 to 2.0]	0.0 [− 1.5 to 1.5]	0.769
Maximal inspiratory pressure, cm H ₂ O	−1.4 [− 14.8 to 0.0]	10.9 [6.7 to 15.1]	0.485
Maximal expiratory pressure, cm H ₂ O	5.0 [− 5.2 to 8.5]	0.3 [− 0.2 to 0.9]	0.606
B. Bisphosphonate use			
Pre-operative to Early post-operative			
FVC, L	−0.39 [− 0.41 to -0.15]	0.17 [− 0.13 to 0.18]	0.014
FVC, % predicted	−10.4 [− 13.0 to -7.6]	1.3 [0.5 to 4.5]	0.035
FEV ₁ /FVC ratio, % predicted	4.5 [− 7.2 to 8.8]	6.0 [− 6.0 to 7.5]	0.975

Time interval and variable	Median Change [IQR]		p-value
	Medication	No medication	
A. Steroid use			
Maximal inspiratory pressure, cm H ₂ O	-3.5 [- 4.8 to 2.2]	0.0 [- 3.5 to 10.8]	0.193
Maximal expiratory pressure, cm H ₂ O	-11.0 [- 14.2 to 10.0]	-0.6 [- 8.5 to 0.6]	0.072
Pre-operative to final follow-up			
FVC, L	-0.33 [- 0.42 to 0.18]	0.04 [- 0.23 to 0.10]	0.138
FVC, % predicted	-12.8 [- 15.3 to 7.5]	-9.6 [- 11.4 to 1.5]	0.295
FEV ₁ /FVC ratio, % predicted	0.5 [- 6.0 to 1.8]	3.0 [- 9.5 to 9.0]	0.628
Maximal inspiratory pressure, cm H ₂ O	-7.0 [- 10.8 to 1.0]	4.0 [- 7.2 to 13.0]	0.279
Maximal expiratory pressure, cm H ₂ O	-9.5 [- 16.0 to 6.0]	-0.8 [- 8.5 to 8.2]	0.138
Early post-operative to Final follow-up			
FVC, L	-0.06 [- 0.36 to 0.16]	-0.13 [- 0.41 to 0.12]	0.792
FVC, % predicted	-2.5 [- 6.0 to 1.4]	-10.0 [- 16.4 to - 1.9]	0.432
FEV ₁ /FVC ratio, % predicted	1.0 [- 8.0 to 1.0]	-4.0 [- 9.0 to 3.0]	0.721
Maximal inspiratory pressure, cm H ₂ O	0.0 [- 8.0 to 0.0]	-1.9 [- 11.5 to 3.0]	0.965
Maximal expiratory pressure, cm H ₂ O	3.0 [0.0 to 7.0]	2.0 [- 3.9 to 8.0]	0.909

During the preoperative to early postoperative interval, patients who had received bisphosphonate therapy experienced a greater decrease in measured FVC than those who had not received bisphosphonates (median, - 0.39 L [IQR, - 0.41 to - 0.15] vs 0.17 L [IQR, - 0.13 to 0.18]; P = 0.014). A similar difference was observed for FVC percent predicted (median, - 10.4 percentage points [IQR, - 13.0 to - 7.6] vs 1.3 percentage points [IQR, 0.5 to 4.5]; P = 0.035). The between-group difference in early MEP change did not reach significance.

Bisphosphonate exposure was not associated with differences in the change in FVC, FVC percent predicted, FEV1/FVC ratio, MIP, or MEP from the preoperative assessment to final follow-up or from the early postoperative assessment to final follow-up (all P ≥ 0.138).

Discussion

The effect of PSF on pulmonary function in DMD remains one of the most debated topics in neuromuscular scoliosis management. In this retrospective cohort of 16 nonambulatory males with DMD who underwent PSF, we found that FVC percent predicted was preserved in the early postoperative

period (41.0% to 41.1%) but declined significantly by final follow-up at approximately 2 years (34.4%, $P = 0.006$). Additionally, we found that greater absolute curve correction was associated with a greater reduction in measured FVC but not FVC percent predicted. Maximal expiratory pressure decreased early after surgery, and patients with documented bisphosphonate exposure experienced greater early declines in FVC and FVC percent predicted. These findings suggest that correction of spinal deformity does not prevent the progressive respiratory deterioration characteristic of DMD and identify several perioperative associations that warrant further investigation.

Pulmonary Function After Posterior Spinal Fusion

The early stability of FVC percent predicted followed by a subsequent decline is broadly consistent with previous studies suggesting that pulmonary function may stabilize temporarily after PSF before the underlying respiratory decline of DMD resumes. Velasco et al. reported that the annual decline in FVC percent predicted decreased from 4.0% before surgery to 1.75% after surgery.⁸ Yang et al. similarly observed an initial postoperative increase in FVC followed by subsequent decline, although deterioration was slower among surgically treated patients than among nonsurgical controls.⁷ Chua et al. and Suk et al. also reported slower postoperative pulmonary decline among surgically treated patients.^{10,11}

Conversely, other studies have not demonstrated a meaningful pulmonary benefit from PSF. Alexander et al. found no reduction in the rate of FVC decline after surgery and no association between scoliosis severity and respiratory dysfunction, supporting progressive respiratory muscle weakness as the primary determinant of pulmonary decline.¹² A Cochrane review likewise concluded that the available evidence was insufficient to establish whether scoliosis surgery preserves respiratory function in DMD.⁵ Differences across studies likely reflect variation in age at surgery, baseline respiratory function, corticosteroid exposure, follow-up duration, and the methods used to quantify pulmonary decline.

Our findings may be explained by the natural history of DMD. After loss of ambulation, FVC percent predicted commonly declines by approximately 4% to 6% annually.^{9,13} Patients in the present cohort underwent surgery at a mean age of 17.9 years with a mean preoperative FVC percent predicted of 41.0%, placing them at a stage when continued respiratory deterioration would be expected irrespective of surgical treatment. Therefore, the decline observed at final follow-up may primarily reflect disease progression rather than an adverse effect of PSF.^{9,14} Importantly, this study evaluated pulmonary function at discrete perioperative assessments and did not compare longitudinal rates of decline before and after surgery.

Curve Correction and Pulmonary Function

Greater absolute curve correction was associated with a greater reduction in measured FVC from the preoperative assessment to both early and final follow-up. However, absolute correction was not associated with change in FVC percent predicted, and relative curve correction was associated with measured FVC change only during the early postoperative interval. These findings do not establish that

greater correction directly impairs pulmonary function.^{6,12} Absolute correction is related to the magnitude and flexibility of the preoperative deformity and may therefore serve as a marker of deformity severity, surgical complexity, or overall disease burden.^{4,15,16} Measurement factors may also contribute to the discrepancy between measured and percent-predicted FVC. Predicted FVC depends partly on height, which is difficult to estimate accurately in nonambulatory patients with contractures and severe spinal deformity. Changes in spinal alignment after surgery may further alter height estimates and the predicted FVC denominator.

This finding contrasts with the general assumption in the scoliosis literature that greater correction should yield greater respiratory benefit.^{16–18} Kim et al. recently demonstrated that three-dimensional rotational asymmetry, rather than the Cobb angle alone, is the strongest predictor of pulmonary impairment in scoliosis, and that this association is attenuated in neuromuscular subtypes.¹⁶ This suggests that in DMD, the relationship between spinal deformity and pulmonary function is fundamentally different from that in idiopathic or congenital scoliosis, with respiratory muscle weakness dominating over mechanical chest wall restriction.^{19,20}

Respiratory Muscle Strength

Maximal expiratory pressure decreased significantly during the early postoperative period, whereas maximal inspiratory pressure remained unchanged. Expiratory pressure depends substantially on abdominal and truncal muscle function and may be particularly sensitive to postoperative pain, deconditioning, positioning, and altered trunk mechanics.^{6,21} The subsequent improvement in maximal expiratory pressure between early and final follow-up suggests that this decline may represent a transient perioperative effect. Nevertheless, neither inspiratory nor expiratory strength improved above preoperative values, consistent with the progressive respiratory muscle weakness underlying DMD.

Steroid and Bisphosphonate Exposure

No significant differences in pulmonary function change were observed between patients with and without documented corticosteroid exposure during any study interval. However, only 2 patients had not received corticosteroids, resulting in markedly imbalanced groups and limited power to identify clinically meaningful differences. Therefore, no definitive conclusions can be drawn regarding the effects of corticosteroid exposure on postoperative pulmonary function in patients with DMD.

Patients with documented bisphosphonate exposure experienced greater early declines in measured FVC and FVC percent predicted than patients without bisphosphonate exposure. These differences were not sustained at final follow-up. This finding should be interpreted cautiously. Bisphosphonates are generally prescribed to patients with osteoporosis, vertebral fractures, or other manifestations of impaired bone health and may therefore identify patients with greater cumulative corticosteroid exposure, longer disease duration, or more advanced disease.^{4,22} The absence of a significant difference at final follow-up further suggests that this early difference may reflect confounding by disease severity

rather than a direct pulmonary effect of bisphosphonates. No prior studies have specifically examined the interaction between bisphosphonate use and perioperative pulmonary outcomes in DMD.

Limitations

This study has several limitations. The small sample size limited statistical power and increased the risk of both type I and type II error. The retrospective design introduced the potential for selection bias, missing data, and variation in the timing and technique of pulmonary testing. The absence of a nonsurgical control group and serial preoperative pulmonary measurements prevented determination of whether surgery altered the natural rate of respiratory decline. FVC, maximal inspiratory pressure, and maximal expiratory pressure are effort-dependent and may be influenced by cooperation, fatigue, pain, positioning, and testing technique. Estimation of height in nonambulatory patients with contractures and spinal deformity may also introduce error into percent-predicted values. Medication data were limited, particularly regarding the indication, timing, duration, and cumulative exposure to corticosteroids and bisphosphonates. Finally, the approximately 2-year pulmonary follow-up may not capture the longer-term respiratory trajectory after PSF.

Conclusions

In this cohort of nonambulatory males with DMD, PSF for scoliosis was associated with early stabilization of FVC percent predicted followed by a significant decline by 2-year follow-up, consistent with the expected natural history of respiratory decline in DMD. Greater absolute curve correction was paradoxically associated with greater FVC loss, suggesting that the primary driver of pulmonary decline in DMD is progressive respiratory muscle weakness rather than scoliosis-related chest wall restriction. These findings add to the growing body of evidence that the primary driver of pulmonary decline in DMD is progressive respiratory muscle weakness rather than scoliosis-related chest wall restriction, and that the goals of PSF should be framed in terms of functional, postural, and quality-of-life benefits rather than respiratory preservation.

Declarations

Author Contribution

RR contributed to study conceptualization, methodology, data curation, formal analysis, and writing the original draft. JK and MAS contributed to methodology, data curation, and manuscript review and editing. RCG, AB, and ST contributed to conceptualization, supervision, and manuscript review and editing. RCC and DTD contributed to validation and manuscript review and editing. KTF contributed to methodology, formal analysis, and manuscript review and editing. AK contributed to conceptualization, methodology, supervision, and manuscript review and editing. All authors reviewed and approved the final version of the manuscript.

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Figures

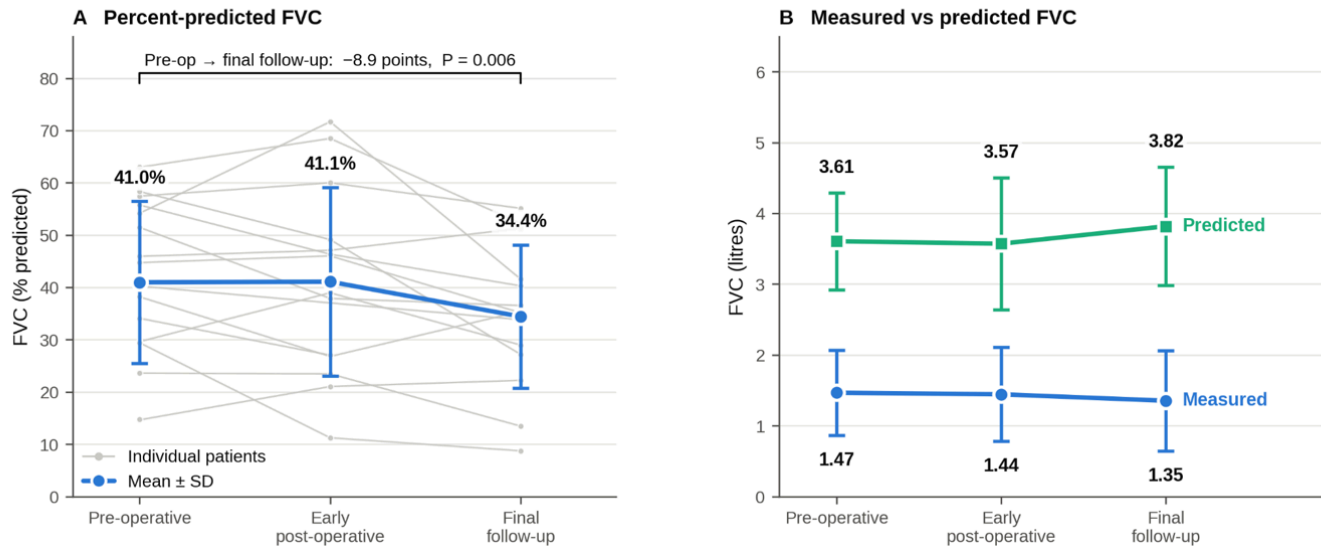


Figure 1

Percent-predicted and absolute forced vital capacity across the perioperative course. (A) Percent-predicted FVC in individual patients (grey lines) and cohort mean $\pm$ SD (blue) at the pre-operative, early post-operative, and final follow-up assessments. Mean percent-predicted FVC was unchanged between the pre-operative and early post-operative assessments. (B) Mean $\pm$ SD predicted (green) and measured (blue) FVC in liters at the same assessments. Predicted FVC increased over the study period while measured FVC remained comparatively stable.

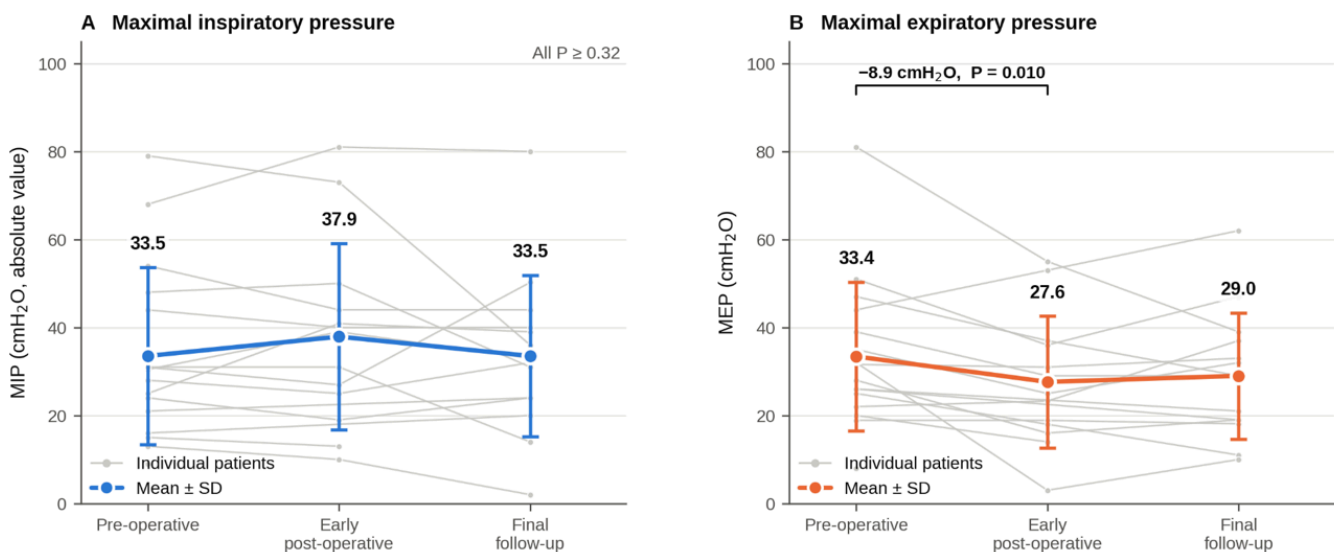


Figure 2

Respiratory muscle strength across the perioperative course. (A) Maximal inspiratory pressure (MIP, absolute value) at the pre-operative, early post-operative, and final follow-up assessments. MIP did not change significantly at either interval. (B) Maximal expiratory pressure (MEP) at the same assessments. MEP fell between the pre-operative and early post-operative assessments ($P = 0.010$) and was 29.0 cm H₂O at final follow-up, not significantly different from either earlier value.

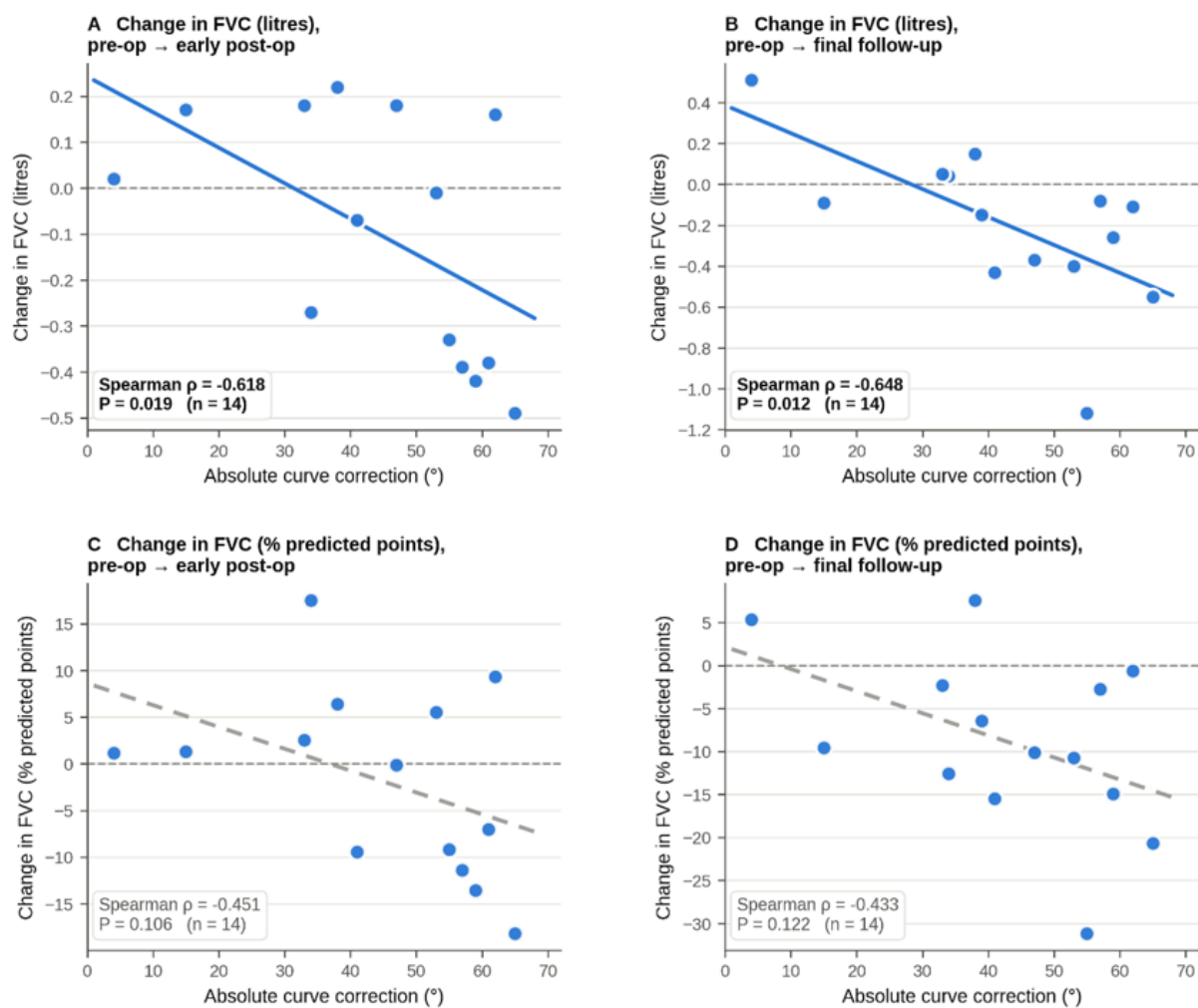


Figure 3

Association between curve correction and change in pulmonary function (n=14). (A–D) Absolute curve correction (pre-op minus post-op Cobb angle) against within-patient change in FVC volume (A, B) and FVC percent predicted (C, D), pre-op → early (A, C) and pre-op → final follow-up (B, D). Lines are least-squares fits, solid where the Spearman correlation reached significance. Greater correction was associated with greater loss of FVC volume both early ($\rho = -0.62$, $P = 0.019$) and at final follow-up ($\rho = -0.65$, $P = 0.012$)