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REVIEW ARTICLE

Is impaired lung function related to spinal deformities in patients with adolescent idiopathic scoliosis? A systematic review and meta-analysis—SOSORT 2019 award paper

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Abstract

Purpose Some teenagers with adolescent idiopathic scoliosis (AIS) display compromised lung function. However, the evidence regarding the relations between pulmonary impairments and various spinal deformity parameters in these patients remains unclear, which affects clinical management. This systematic review and meta-analysis aimed to summarize the associations between various lung function parameters and radiographic features in teenagers with AIS.

Methods A search of PubMed, Embase, PEDro, SPORTDiscus, CINAHL, Cochrane Library, and PsycINFO (from inception to March 14, 2022) without language restriction. Original studies reporting the associations between lung function and spinal deformity in patients with AIS were selected. Independent reviewers extracted data and evaluated the methodological quality of the included studies according to Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines. Pearson correlation and 95% confidence intervals were calculated using random-effects meta-analysis.

Results Twenty-seven studies involving 3162 participants were included. Limited-quality evidence supported that several spinal parameters were significantly related to lung function parameters (e.g., absolute value and percent of the predicted forced vital capacity (FVC; %FVC), forced expiratory volume in one second (FEV_1; $\%FEV_1$), and total lung capacity (TLC; %TLC)) in AIS patients. Specifically, meta-analyses showed that main thoracic Cobb angles in the coronal plane were significantly and negatively related to FVC ($r = -0.245$), %FVC ($r = -0.302$), FEV_1 ($r = -0.232$), $\%FEV_1$ ($r = -0.348$), FEV_1/FVC ratio ($r = -0.166$), TLC ($r = -0.302$), %TLC ($r = -0.183$), and percent predicted vital capacity ($r = -0.272$) ($p < 0.001$). Similarly, thoracic apical vertebral rotation was negatively associated with %FVC ($r = -0.215$) and %TLC ($r = -0.126$) ($p < 0.05$). Conversely, thoracic kyphosis angles were positively related to %FVC ($r = 0.180$) and $\%FEV_1$ ($r = 0.193$) ($p < 0.05$).

Conclusion Larger thoracic Cobb angles, greater apical vertebral rotation angle, or hypokyphosis were significantly associated with greater pulmonary impairments in patients with AIS, although the evidence was limited. From a clinical perspective, the results highlight the importance of minimizing the three-dimensional spinal deformity in preserving lung function in these patients. More research is warranted to confirm these results.

Keywords Pulmonary function · Spinal deformity · Thoracic deformity · Adolescent idiopathic scoliosis · Systematic review · Meta-analysis

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Introduction

Adolescent idiopathic scoliosis (AIS) is a common three-dimensional spinal deformity affecting teenagers [1]. Females are 1.4–7.2 times more likely to have AIS than males [2]. While the etiology and risk factors for the development or progression of scoliosis remain inconclusive [3], AIS and/or related treatment may cause back pain, insomnia [4], psychological distress, poor body image [5], and suboptimal quality of life [4].

Patients with AIS are not uncommon to demonstrate compromised pulmonary function [6]. Multiple studies have substantiated the presence of suboptimal pulmonary function (e.g., decreased vital capacity) in these patients [7–9]. While up to two-thirds of AIS patients with large scoliotic curves demonstrate restrictive respiratory abnormalities [10], recent research suggests that suboptimal ventilatory function may occur in patients with mild or moderate AIS [7, 11]. Despite the controversy [12, 13], the suboptimal pulmonary function in these patients may be related to the distortion/restriction of the spine and/or thoracic cage [14], locations of the deformity, reduced chest wall mobility [15], and/or obstructive lung disorders secondary to intrathoracic airway compression [16]. Further, patients' pulmonary function can be compromised by the curve progression [9], and/or bracing [8, 9, 16, 17]. Conversely, these changes may be reversed by aerobic exercises.

Although a recent systematic review with meta-regression analysis revealed that the pulmonary function in patients with idiopathic scoliosis was inversely related to the curve severity [18], this review was limited by the summary of associations between coronal Cobb angles and various pulmonary parameters among patients of different types of idiopathic scoliosis. Because AIS is a three-dimensional spinal deformity, examining these associations based on coronal Cobb angles alone is incomprehensive [19]. Additionally, findings from a mixed cohort of patients with various idiopathic scoliosis cannot be generalized to patients with AIS. The current systematic review and meta-analysis addressed these limitations and summarized the evidence regarding the associations between various pulmonary functions and spinal parameters in patients with AIS, which may help clinicians identify patients at risk of having pulmonary impairment. Therefore, this review aimed to summarize the evidence regarding the: (1) associations between various pulmonary parameters and the severity of scoliosis in AIS patients; and (2) temporal relations between changes in the spinal curve due to progression/conservative treatments and the corresponding changes in pulmonary function.

Methods

This review protocol was registered with PROSPERO (CRD42016043599) and followed the Preferred Reporting Items of Systematic Reviews and Meta-analysis guidelines [20].

Search strategy

Seven databases: PubMed, Embase, PEDro, SPORTDiscus, CINAHL, Cochrane Library, and PsycINFO were searched for potential articles from inception to March 14, 2022. There were no restrictions on languages, but only English, Chinese, and Italian publications were screened. Search terms included keywords related to pulmonary function, spinal deformity, and AIS. Specifically, the Boolean search strings included ("cardiac*" OR "pulmonary" OR "lung" OR "thoracic" OR "cardiopulmonary") AND ("test*" OR "exam*") AND ("adolescent*" OR "teen*" OR "puberty" OR "youth") AND ("AIS" OR "adolescent idiopathic scoliosis"). The detailed search strategy is included in Supplementary Material eTable 1.

Eligibility criteria

Articles were included had they reported an association between pulmonary function and the severity of spinal curve in patients with AIS aged between 10 and 18 years [21]. Longitudinal, cross-sectional, and case–control studies were eligible. Randomized controlled trials were included if they reported the targeted associations in AIS patients preoperatively, or before and/or after conservative treatments. Studies were excluded had they examined patients with scoliosis other than AIS, cognitive impairment, Marfan syndrome, or pectus deformity.

Screening

Three independent reviewers (MK, JY, and RC) paired up to screen titles and abstracts of all identified citations for eligibility. Studies deemed to be eligible by either reviewer were included for full-text screening. Reviewers repeated the same procedure for full-text screening. If disagreements in inclusion could not be resolved by discussion, a senior reviewer (AW) arbitrated the disagreement. The reference lists of all included articles were screened and forward citation tracing was conducted on Scopus to identify additional articles. The corresponding authors of all included studies were contacted by emails to identify omitted studies, or to seek raw data for our meta-analyses.

Data extraction

Two reviewers (MK and RC) independently extracted data from each included paper. Any disagreements were resolved with the third reviewer (AW). The collected data included: (1) study characteristics (e.g., year of publication, study design); (2) participants' characteristics (e.g., age and gender); (3) absolute values and/or percentage predicted values of pulmonary parameters; (4) spinal/thoracic deformity parameters; and (5) statistical analyses of the associations between (3) and (4). If the included studies conducted subgroup analyses, relevant data were extracted. Missing data was marked as "not reported." A list of definitions of pulmonary and spinal parameters is shown in eTable 2. This includes common terminology such as Lenke and King's classifications of scoliotic curve [23], angle of trunk rotation [22], surface spinal penetration index [24] and endothoracic hump ratio [25].

Risk of bias assessments

Two independent reviewers (RC and AW) assessed the methodological quality of prospective studies using the Quality in Prognostic Studies (QUIPS) [26], cross-sectional studies using Appraisal tool for Cross-Sectional Studies (AXIS) [27], and case–control studies using Newcastle–Ottawa Scale (NOS) [28]. Studies that retrospectively analyzed data or collected data at a single time point were assessed using AXIS. Any disagreements in the assessment results were resolved by consensus.

Data syntheses

Meta-analyses

The primary measure was the associations (e.g., Spearman's/Pearson coefficients) between various spinal parameters and pulmonary functions in patients with AIS. The correlation coefficients were interpreted as weak, moderate, and strong if their values were 0.3, 0.5, and 0.7, respectively [29]. If three or more clinically homogenous studies investigated the same association, data were pooled for meta-analysis using random-effects model using the Comprehensive Meta-analysis version 3.0 software (Biostat, NJ, USA). Separate meta-analyses were conducted for studies involving multiple regression models. The significance level was set at 0.05. Statistical heterogeneity of the included studies in meta-analyses was graded as low, moderate, and high if the I^2 statistics were ≤ 25%, between 26 and 74%, and ≥ 75%, respectively [30]. If meta-analyses were not conducted, the correlations were summarized narratively.

Subgroup analyses

Subgroup analyses were planned to examine the cross-sectional/longitudinal associations between spinal parameters and pulmonary functions based on: (1) genders; (2) severity of the pulmonary impairment; (3) severity of scoliosis; (3) thoracic or lumbar scoliosis; and (4) before and after conservative treatments or curve progression.

Levels of evidence

Levels of evidence were rated as strong, moderate, limited, and very limited based on established criteria (eTable 3) [31, 32].

Results

Database searches yielded 3723 non-duplicated titles and abstracts for screening. Twenty-one out of 278 full-text articles were included. Further, manual searches of reference lists and forward citation of the included articles yielded six additional included articles (Fig. 1).

Study characteristics

Table 1 summarizes characteristics of the 22 included cross-sectional studies [8, 9, 11, 16, 17, 33–49] and five case–control studies [7, 50–53] that involved 3,162 participants. All included studies used spirometry and some also used plethysmography [9, 16, 33, 41, 49, 53] to evaluate lung function. The reported pulmonary function parameters included the absolute values of forced vital capacity (FVC), forced expiratory volume in the first second (FEV_1), FEV_1/FVC ratio, forced expiratory flow at 25% and 75% of FVC ($FEF_{25–75\%}$), $FEF_{25\%}$, $FEF_{50\%}$, peak expiratory flow (PEF), vital capacity (VC), residual volume (RV), total lung capacity (TLC), RV/TLC ratio, functional residual capacity, etc. Some studies reported these parameters as the percentage of predicted values (e.g., %FVC, %FEV_1, and %TLC). The predicted values were determined according to age-, gender-, and height-matched normative data [54]. Some included studies used equations to estimate patients' "actual height" from the arm span [7, 8, 16, 17, 35–37, 39, 47, 48, 53] or Cobb angles [11, 42, 45] to predict participants' pulmonary functions. Pulmonary functions were considered normal if their measured values exceeded 80% of the predicted values [9, 49].

Spinal parameters were measured by X-rays or computed tomography scans. Five studies used biplanar X-rays with three-dimensional reconstruction of the spine and/or rib cage

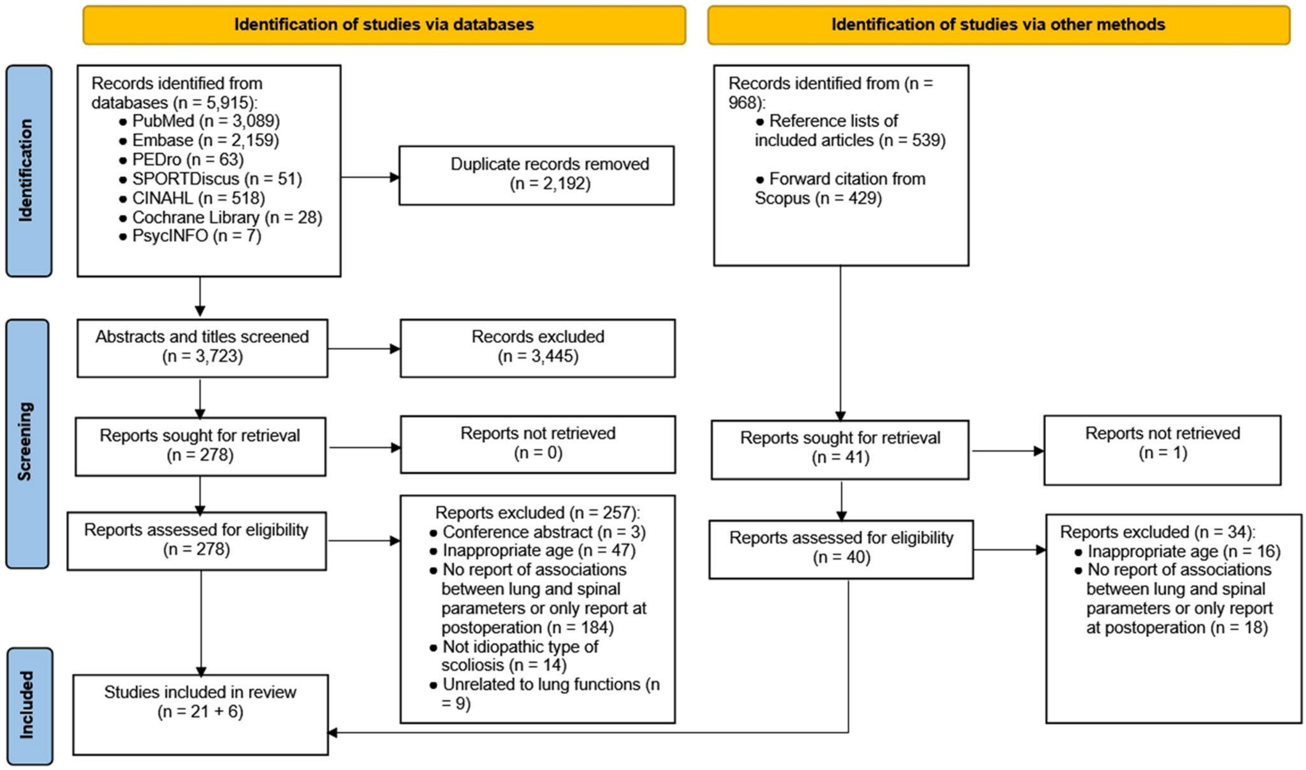


Fig. 1 PRISMA flow diagram

[17, 33, 43, 49, 55]. The reported spinal parameters included proximal thoracic Cobb angles [9, 35, 43, 55] main thoracic Cobb angles on anteroposterior radiographs in a standing [7, 8, 16, 17, 29–35, 34–43, 41–49, 53, 55] or supine bending position [39], thoracic kyphosis angles [9, 35, 41, 43, 45], and apical vertebral rotation angles [17, 39, 43, 49, 50, 55] (Table 1). Most included studies used univariate analyses to determine the associations of interest. Nine studies used multiple regression to evaluate such associations [9, 16, 38, 39, 37–44, 51] (Table 1).

Risk of bias assessments

All 22 included cross-sectional studies did not justify their sample sizes, nor report the response rate or non-responders' characteristics [8, 9, 11, 16, 17, 29–35, 33–49, 55] (eTable 4). Five cross-sectional studies [17, 37, 38, 40, 55] did not describe participants' demographics (e.g., gender distribution) [17, 38, 40], while seven studies [11, 34, 37, 39, 46, 48, 49] did not discuss their limitations. Nine included studies did not mention the ethical approval or the informed consent process [9, 11, 34, 33–39, 43, 44, 46]. Similarly, all included case–control studies [7, 46–53] did not describe the non-response rate, while four of them [7, 47–53] did not describe the recruitment process of controls (eTable 5).

Associations between spinal parameters and lung function

Univariate correlations between 43 spinal parameters and 32 pulmonary function parameters were reported (Table 2 and eTable 6). Twenty-seven meta-analyses were conducted to reveal 22 significant correlations. Of them, 20 showed significant but weak correlations. Further, 11 included studies used multivariate analyses to identify independent spinal parameters that predicted pulmonary function [9, 11, 16, 38, 39, 41–44, 51, 53]. Given the numerous investigated correlations, only significant correlations with at least limited-quality evidence were reported and discussed in this review.

No included studies investigated the gender-related correlations between spinal parameters and lung function. No included studies reported the temporal relations between changes in spinal structure and the corresponding changes in pulmonary function in conservatively treated patients with AIS. Although Lin et al. [35] reported that lung function parameters did not significantly differ between AIS patients with and without a history of brace usage, some studies [44, 51] found that compared to "non-brace" patients, those with bracing had poorer lung function. Furthermore, some studies compared patients' lung function based on different Lenke classification types [47, 48], a Cobb angle cutoff [52],

Table 1 Characteristics of the included studies (in alphabetical order of the first author's surname)

Authors	Region/Country	Study design	No. of participants (% of female)	Age ± SD (years)	Measures	Coronal/Sagittal Tx Cobb angles ± SD	Type of curve	Outcome measured	Findings
Abdelaal et al. 2018 [7]	Saudi Arabia	Case–control	73 AIS (76.7%) with Cobb angle of 10° to 20° 34 Healthy controls (85.3%)	13.4 ± 1.3	X-ray Spirometry Used arm span to estimate height for predicting lung functions	16.4° ± 1.6° (range 12° to 19°)	Tx curve ($n=67$): Right ($n=54$) Left ($n=13$) Thoracolumbar curve ($n=6$): Right ($n=5$) Left ($n=1$)	Tx Cobb angle FEV_1 $\%FEV_1$ FVC %FVC FEV_1/FVC MVV %MVV	Tx Cobb angle and FVC ($r=0.03$, $p=0.78$) Tx Cobb angle and FEV_1 ($r=0.03$, $p=0.75$) Tx Cobb angle and MVV ($r=0.01$, $p=0.90$) AIS group had significantly lower FVC, FEV1, and MVV than healthy controls ($p<0.05$) AIS group had shown a restrictive pulmonary pattern: mean %FVC, $\%FEV_1$, and %MVV < 80% of predicted values, whereas FEV_1/FVC was > 70% predicted
Akazawa et al. 2021 [45]	Japan	Prospective cohort (cross-sectional analysis of pre-op data)	45 (91.1%)	14.4 (range 12 to 19) at surgery	X-ray CT Spirometry Used Cobb angle to estimate corrected height in predicting lung functions	53.6° ± 10.1°/15.7° ± 10.3°	Proximal and main Tx curve Lx curve Lenke: Type 1 ($n=24$) Type 2 ($n=12$) Type 3 ($n=1$) Type 6 ($n=8$)	Proximal Tx Cobb angle Main Tx Cobb angle Lx Cobb angle Tx kyphosis angle (T5 to T12) Lx lordosis angle (L1 to S1) RAsag Rib hump Rib hump index FVC %FVC FEV_1 $\%FEV_1$ FEV_1/FVC PEF $FEF_{50\%}$ $FEF_{25\%}$ $FEF_{50\%}/FEF_{25\%}$ ratio	Main Tx Cobb angle and FVC ($r=-0.311$, $p=0.037$) Main Tx Cobb angle and %FVC ($r=-0.353$, $p=0.017$) Main Tx Cobb angle and FEV_1 ($r=-0.352$, $p=0.018$) Main Tx Cobb angle and $\%FEV_1$ ($r=-0.382$, $p=0.010$) Main Tx Cobb angle and PEF ($r=-0.198$, $p=0.192$) Main Tx Cobb angle and $FEF_{50\%}$ ($r=-0.290$, $p=0.053$) Main Tx Cobb angle and $FEF_{25\%}$ ($r=-0.384$, $p=0.009$) Tx kyphosis and FVC ($r=0.253$, $p=0.093$) Tx kyphosis and %FVC ($r=0.318$, $p=0.033$) Tx kyphosis and FEV_1 ($r=0.285$, $p=0.058$) Tx kyphosis and $\%FEV_1$ ($r=0.307$, $p=0.040$) Tx kyphosis and PEF ($r=0.253$, $p=0.094$) Tx kyphosis and $FEF_{50\%}$ ($r=0.224$, $p=0.138$) Tx kyphosis and $FEF_{25\%}$ ($r=0.226$, $p=0.136$) No report of correlation between preoperative Tx cage deformity and lung functions
Barrios et al. 2005 [50]	Spain	Case–control	37 (100%) with Cobb angle 20° to 45° Healthy control: 10 (100%)	13.6 ± 1.5 (range 11 to 16) Healthy controls 13.0 ± 0.9	X-ray Raimondi ruler Spirometry	32.8° (range 20° to 45°)	Single Tx curve ($n=4$) Thoracolumbar curves ($n=4$) Double curves: King II ($n=23$); King III ($n=6$)	Tx Cobb angle AVR FEV_1 FVC FEV_1/FVC ratio	AVR and FEV_1/FVC ($r=-0.461$, $p<0.05$) No significant difference in FVC and FEV_1 between AIS patients and healthy controls FVC and FEV_1 in AIS patients aged < 13 years lower than those ≥ 13 years ($p=0.03$)

Table 1 (continued)

Authors	Region/ Country	Study design	No. of participants (% of female)	Age ± SD (years)	Measures	Coronal/ Sagittal Tx Cobb angles ± SD	Type of curve	Outcome measured	Findings
Bouloussa et al. 2019 [33]	France	Cross-sectional	54 (83.3%) Tx Cobb angle > 50°	13.8 ± 1.2	X-ray (biplanar) Spirometry Plethysmography	68.7° ± 16.7°/ 20.5° ± 13°	Lenke 1 (n = 44) Lenke 2 (n = 10)	Tx Cobb angle Tx Kyphosis (T4-T12) Rib cage volume SPI Max rib hump Max rib cage thickness Max rib cage width FVC FEV_1/FVC TLC SVC	There were significant relations between: Tx Cobb angle and FVC (rho = −0.37, p = 0.007), Tx Cobb angle and TLC (rho = −0.47, p = 0.0001), Tx Cobb angle and SVC (rho = −0.44, p = 0.001); RCV and FVC (rho = 0.77, p < 0.0001), RCV and FEV_1/FVC (rho = −0.34, p = 0.014), RCV and TLC (rho = 0.76, p < 0.0001), RCV and SVC (rho = 0.78, p < 0.0001); Max rib hump and FVC (rho = −0.28, p < 0.05), Max rib hump and SVC (rho = −0.36, p < 0.01); Rib cage thickness and FVC (rho = 0.30, p < 0.001), Rib cage thickness and TLC (rho = 0.26, p < 0.05), Rib cage thickness and SVC (rho = 0.23, p < 0.05); and Max rib cage width and FVC (rho = 0.62, p < 0.0001), Max rib cage width and FEV_1/FVC (rho = −0.32, p < 0.05), Max rib cage width and TLC (rho = 0.56, p < 0.0001), Max rib cage width and SVC (rho = 0.60, p < 0.0001) TK and SPI were not significantly related to any pulmonary parameters (p > 0.05)
Daruwalla and Tan, 1985 [46]	Singapore	Prospective (cross-sectional analysis of pre-op data)	30 (93.3%)	14.5 ± 1.9 (range 10 to 17)	X-ray Spirometer	56.3° ± 16.6° (range 40°to 100°)/ No report	Tx curves: 2 double curves 26 right Tx curve 6 left Tx curve	Tx Cobb angle %FEV_1 %FVC	Tx curve was negatively correlated with %FEV_1 (p < 0.001) & %FVC (p < 0.005)
Gitelman et al. 2011 [47]	USA	Longitudinal (retrospective analysis of pre-op data)	49 (93.9%)	14.3 ± 2.4 at surgery	X-ray Spirometry Used arm span to estimate height for predicting lung functions	56.8°/ 20.9°	Lenke: type 1: (n = 20) type 2: (n = 8) type 3: (n = 5) type 4: (n = 2) type 5:(n = 6) type 6: (n = 8)	Tx Cobb angle FEV_1 %FEV_1 FVC %FVC	Tx Cobb angle and FEV_1 (r = −0.42, p = 0.003) Tx Cobb angle and %FEV_1 (r = −0.35, p = 0.014) Tx Cobb angle and FVC (r = −0.39, p = 0.007) Tx Cobb angle and %FVC (r = −0.41, p = 0.004) Patients with major thoracolumbar/Lx curve (Lenke 5) had a better %FEV_1 (p = 0.02) and %FVC (p = 0.013) than patients with a double Tx curve (Lenke 2) Patients with major thoracolumbar/Lx curve (Lenke 5) had a better %FVC (p = 0.029) than patients with a double major curve (Lenke 3)
Huh et al. 2015 [34]	South Korea	Cross-sectional (retrospective review of medical records)	81 (83.3%)	14.8 ± 2.2	X-ray Spirometry	53.8° ± 15.1°/ No report Lx curve: 53.4° ± 15.1°	Tx curve and Lx curve Tx-dominant (n = 72) Lx-dominant (n = 9)	Tx Cobb angle Lx Cobb angle %FVC %FEV_1 %FEV_1/FVC	Tx Cobb angle and %FVC (r = −0.331, p = 0.004) Tx Cobb angle and %FEV_1 (r = −0.391, p = 0.001) Tx Cobb angle and %FEV_1/FVC (r = −0.186, p > 0.05) Lx Cobb angle and %FVC (r = −0.162 p > 0.05) Lx Cobb angle and %FEV_1 (r = −0.140, p > 0.05) Lx Cobb angle and %FEV_1/FVC (r = −0.015, p > 0.05)
Ilharre-borde et al. 2013 [17]	France	Cross-sectional	54 (not reported) Group 1: Cobb angle > 65° (n = 22) Group 2: Cobb angle 40° to 65° (n = 32)	Group 1: 15.1 ± 1.5 Group 2: 14.6 ± 1.2	X-ray (biplanar) Spirometry Used arm span to estimate height for predicting lung functions	Group 1: 73.8° ± 9°/ 17.8° ± 11° Group 2: 49.2° ± 8°/ 16.3° ± 12°	Tx curve	Tx Cobb angle, TK (T4 to T12), AVR Tx volume, Volume SPI, Apical surface SPI %FVC %FEV_1 %TLC	Tx volume and %FVC (r = 0.82, p < 0.0001) Tx volume and %FEV_1 (r = 0.76, p < 0.0001) Tx volume and %TLC (r = 0.8, p < 0.0001) TK and %FVC (r = 0.4, p < 0.0001) TK and % FEV_1 (r = 0.37, p < 0.0001) No correlation was found between pulmonary function tests and Cobb angle or AVR or SPI (p > 0.05) %FVC and % FEV_1 were significantly lower in the hypokyphotic patients (< 20°) than in the other patients (p = 0.04 and p = 0.03, respectively) Volume SPI was significantly greater in the 26 patients with obstructive syndrome (i.e., < 80% of %FEV_1) than in the other 28 patients (p = 0.01)

Table 1 (continued)

Authors	Region/ Country	Study design	No. of participants (% of female)	Age ± SD (years)	Measures	Coronal/ Sagittal Tx Cobb angles ± SD	Type of curve	Outcome measured	Findings
Kim et al. 2005 [48]	USA	Prospective (cross-sectional analysis of pre-op data)	118 (93.2%)	14.4 ± 1.9 (range 10.9 to 18)	X-ray Spirometry Used arm span to estimate height for predicting lung functions	56°/ 16°	Tx curve Lenke: type 1: (n = 63) type 2: (n = 18) type 3: (n = 7) type 4: (n = 4) type 5: (n = 15) type 6: (n = 11)	Tx Cobb angle Number of vertebrae involved in major curve %FVC %FEV_1	Tx Cobb angle and %FVC (r = –0.18, p = 0.04) Tx Cobb angle and the %FEV_1 (r = –0.26, p = 0.005) Number of involved vertebrae in the major curve and %FVC (r = –0.27, p = 0.003) Number of involved vertebrae in the major curve and %FEV1 (r = –0.23, p = 0.02) Patients with a thoracolumbar/Lx curve (Lenke 5) had a significantly larger FEV_1 (p = 0.045) than those with a main Tx curve (Lenke 1)
Kim et al. 2007 [8]	USA	Prospective (cross-sectional analysis of pre-op data)	139 (82.0%) Lenke type 1–4	14.6 ± 2.2	X-ray Spirometry Used arm span to estimate height for predicting lung functions	60° ± 11.7° (range 40° to 91°)/ 21° ± 13.5° (range 10° to 61°)	Tx curve Lenke: type 1: (n = 84) type 2: (n = 25) type 3: (n = 26) type 4:(n = 4)	Tx Cobb angle FVC %FVC FEV_1 %FEV_1	Tx Cobb angle and FVC (r = 0.096, p = 0.25) Tx Cobb angle and %FVC (r = 0.045, p = 0.60) Tx Cobb angle and FEV_1 (r = 0.038, p = 0.66) Tx Cobb angle and %FEV_1 (r = 0.004, p = 0.96)
Lin et al. 2022 [35]	China	Cross-sectional	168 (85.1%)	Female: 14.2 ± 1.7 Male: 15.4 ± 1.6	X-ray (standing and side-bending) Spirometer Gas analyzer Used arm span to estimate height for predicting lung functions	Proximal: 28.5° (range 5° to 74°) Main Tx curve: 46.5° (range 14° to 97°) Thoracolumbar/ Lx curve: 41.7° (range 13° to 90°)	Proximal Tx curve Main Tx curve Thoracolumbar/Lx curve (apex located in and below T12)	Proximal Tx curve (T2 to T5) Main Tx curve (T6 to T11) Tx kyphosis (T5 to T12) %FEV_1 %FVC FEV_1/FVC %PEF	There were significant relationships between: Proximal Tx curve and %FEV_1 (r = − 0.324, p < 0.001) Main Tx curve and %FEV_1 (r = − 0.374, p < 0.001); Main Tx curve and %FVC (r = − 0.283, p < 0.001) Tx kyphosis and %FVC (r = 0.257, p < 0.001); Tx kyphosis and %TV (r = 0.266, p < 0.001) There were no significant differences (ps = 0.34 − 0.92) in any lung function parameters between patient with (n = 51) and without (n = 117) history of brace usage

Table 1 (continued)

Authors	Region/ Country	Study design	No. of participants (% of female)	Age ± SD (years)	Measures	Coronal/ Sagittal Tx Cobb angles ± SD	Type of curve	Outcome measured	Findings
Machino et al. 2021 [36]	Japan	Cross-sectional	67 (88.1%) with Lenke type 1 or 2	14.4 (range 11 to 17)	Biplanar X-ray Spirometry Used arm span to estimate height for predicting lung functions	50.8° ± 10.5°/ 22.2° ± 10.4°	Tx curve Lx curve	Cephalic Tx Cobb angle; Main Tx Cobb angle Cephalic Tx AVR; Main Tx AVR Tx kyphosis (T1 to T12) Lx lordosis (L1 to S1) Max. rib cage thickness; Max. rib cage width; Tx index; Rib hump; Rib cage volume; Volume SPI; Surface SPI at apex; Endothoracic hump ratio at apex; Vertebra–sternum angle at apex; Rib-vertebral angle difference; Vertebral lateral decentering at apex VC FVC, %FVC FEV_1, %FEV_1 FEV_1/FVC	The main Tx Cobb angle was significantly correlated with VC ($r = -0.277$, $p < 0.05$), FVC ($r = -0.263$, $p < 0.05$), %FVC ($r = -0.307$, $p < 0.05$), and FEV_1 ($r = -0.277$, $p < 0.05$) The cephalic Tx apical vertebra rotation was significantly correlated with VC ($r = -0.331$, $p < 0.05$), FVC ($r = -0.323$, $p < 0.05$), and FEV_1 ($r = -0.308$, $p < 0.05$) The main Tx apical vertebra rotation was significantly correlated with VC ($r = -0.254$, $p < 0.05$), FVC ($r = -0.236$, $p < 0.05$), %FVC ($r = -0.219$, $p < 0.05$), and FEV_1 ($r = -0.252$, $p < 0.05$) Max rib cage thickness was significantly correlated with VC ($r = 0.249$, $p < 0.05$), and FVC ($r = 0.248$, $p < 0.05$) Max rib cage width was significantly correlated with VC ($r = 0.724$, $p < 0.0001$), FVC ($r = 0.732$, $p < 0.0001$), %FVC ($r = 0.328$, $p < 0.01$), and FEV_1 ($r = 0.674$, $p < 0.0001$) Rib hump was significantly correlated with VC ($r = -0.296$, $p < 0.01$), FVC ($r = -0.279$, $p < 0.05$), %FVC ($r = -0.366$, $p < 0.01$), and FEV_1 ($r = -0.281$, $p < 0.05$) Rib cage volume was significantly correlated with VC ($r = 0.782$, $p < 0.0001$), FVC ($r = 0.798$, $p < 0.0001$), %FVC ($r = 0.368$, $p < 0.01$), and FEV_1 ($r = 0.759$, $p < 0.0001$) Endothoracic hump ratio was significantly correlated with VC ($r = -0.399$, $p < 0.01$), FVC ($r = -0.392$, $p < 0.01$), %FVC ($r = -0.452$, $p < 0.01$), and FEV_1 ($r = -0.375$, $p < 0.01$) Vertebra–sternum angle was significantly correlated with VC ($r = -0.311$, $p < 0.01$), FVC ($r = -0.313$, $p < 0.01$), %FVC ($r = -0.324$, $p < 0.01$), and FEV_1 ($r = -0.323$, $p < 0.01$) Vertebral lateral decentering was significantly correlated with %FVC ($r = 0.250$, $p < 0.05$) Cephalic Tx Cobb angle, Tx kyphosis, Lx lordosis, Tx index, SPI, and rib vertebra angle difference were not correlated with any pulmonary parameters ($p > 0.05$) When compared to "normal" AIS patients ($n = 50$), patients who had restriction lung disorder ($n = 17$) revealed a significantly smaller VC, FVC, %FVC, FEV_1, max rib cage width, rib cage volume but larger main Tx Cobb angle, rib hump, endothoracic hump ratio, and vertebra–sternum angle ($p < 0.05$)

Table 1 (continued)

Authors	Region/ Country	Study design	No. of participants (% of female)	Age ± SD (years)	Measures	Coronal/ Sagittal Tx Cobb angles ± SD	Type of curve	Outcome measured	Findings
McPhail et al. 2015 [16]	USA	Cross-sectional (retrospective analysis of preoperative records)	176 (86%) with Cobb angle ≥ 40°	13.2 ± 2.1	X-ray Spirometry Plethysmography Used arm span to estimate height for predicting lung functions	55.2° ± 11.7°/ 27.6° ± 14.4°	Tx curve	Tx Cobb angle Tx kyphosis angle No. of vertebrae within spinal curve %FVC %FEV_1 FEV_1/FVC %$FEF_{25\text{-}75\%}$ %TLC %FRC	34% patients (= 68/176) had obstructive lung disease, i.e., FEV_1/FVC < 95% CI of the predicted value 18% patients (= 31/175) had restrictive lung disease, i.e., TLC < 95% CI of predicted value Tx Cobb angle & %FVC ($r = -0.096$, $p = 0.206$) Tx Cobb angle & %FEV_1 ($r = -0.131$, $p = 0.082$) Tx Cobb angle & FEV_1/FVC ($r = -0.128$, $p = 0.090$) Tx Cobb angle & %$FEF_{25\text{-}75\%}$ ($r = -0.175$, $p < 0.05$) Tx Cobb angle & %TLC ($r = -0.172$, $p < 0.05$) Tx kyphosis angle & %FVC ($r = 0.248$, $p < 0.001$) Tx kyphosis angle & %FEV_1 ($r = 0.182$, $p < 0.05$) Tx kyphosis angle & FEV_1/FVC ($r = -0.070$, $p = 0.368$) Tx kyphosis angle & %$FEF_{25\text{-}75\%}$ ($r = 0.074$, $p = 0.336$) Tx kyphosis angle & %TLC ($r = -0.175$, $p < 0.05$) No. of Tx vertebrae in a curve & %FVC ($r = -0.037$, $p = 0.626$) No. of Tx vertebrae in a curve & %FEV_1 ($r = -0.119$, $p = 0.117$) No. of Tx vertebrae in a curve & FEV_1/FVC ($r = -0.159$, $p < 0.05$) No. of Tx vertebrae in a curve & %$FEF_{25\text{-}75\%}$ ($r = -0.163$, $p < 0.05$) No. of Tx vertebrae in a curve & %TLC ($r = -0.043$, $p = 0.576$) **Multiple regression models:** (1) Increased Tx Cobb angle were independent predictors for lower FEV_1/FVC ($r^2 = 0.080$, $p < 0.05$), %TLC ($r^2 = 0.061$, $p < 0.05$), and %FRC ($r^2 = 0.098$, $p < 0.01$) (2) Decreased Tx kyphosis angle were independent predictors for lower %FVC ($r^2 = 0.062$, $p < 0.001$), %FEV_1 ($r^2 = 0.052$, $p < 0.05$), %TLC ($r^2 = 0.061$, $p < 0.05$), and %FRC ($r^2 = 0.098$, $p < 0.05$) Independent variables: Cobb angle, kyphosis angle, and number of thoracic vertebrae in the spine curve (T-level count) Models were adjusted for height, age, and sex. Only height was a significant predictor (−0.18 ± 0.08, .027)
Muirhead and Conner, 1985 [37]	United Kingdom	Cross-sectional (Retrospective medical reports)	51 (80.3%) Other were infantile ($n = 16$) and congenital ($n = 25$) scoliosis	14.3	X-ray Spirometry Used arm span to estimate height for predicting lung functions	52° (range 20° to 93°)/ No report	Main Tx curve	Tx Cobb angle Kyphosis %FEV_1 %TLC %VC %RV	No significant relation between main Tx Cobb angle and %VC ($r = -0.161$, $p > 0.1$) No report of correlation between main Tx Cobb angle and other pulmonary function 4 out of 51 patients (7.8%) with AIS had moderately or severely affected lung function (e.g., %TLC or %FEV1 < 60% of predicted value) No significant difference in %VC between patients with hypokyphosis (< 20°; $n = 15$) and normal Tx kyphosis (≥ 20°; $n = 21$) ($0.5 > p > 0.1$)

Table 1 (continued)

Authors	Region/ Country	Study design	No. of participants (% of female)	Age ± SD (years)	Measures	Coronal/ Sagittal Tx Cobb angles ± SD	Type of curve	Outcome measured	Findings
Newton et al. 2005 [9]	USA	Cross-sectional	631 (84.3%)	Female: 14.5 ± 2.1 Male: 15.7 ± 2.1	X-ray Spirometry Plethysmography	52° ± 14° (range 2° to 110°)/ 24° ± 13° (range -10° to 64°) Cephalad Tx curve: 26° ± 11° (range -0° to 83°) Lx curve: 37° ± 13° (range 8° to 93°)	Lenke type 1 ($n=394$) Lenke 2 ($n=92$) Lenke 3 ($n=30$) Lenke 4 ($n=16$) Lenke 5 ($n=79$) Lenke 6 ($n=20$)	Cephalad Tx Cobb angle Cephalad Tx curve flexibility Main Tx Cobb angle Main Tx curve flexibility Lx Cobb angle Lx curve flexibility Tx apex displacement from plumb line at C7 Tx apex level Number of vertebrae within the main Tx curve C7 displacement from central sacral vertical line Kyphosis (T2—T12) Kyphosis (T5—T12) Lx lordosis %FVC %FEV_1 %TLC	Cephalad Tx Cobb angle was significantly related to %FVC ($r = -0.202$; $p < 0.002$), %FEV_1 ($r = -0.221$, $p < 0.002$), and %TLC ($r = -0.152$, $p < 0.002$) Main Tx Cobb angle was significantly related to %FVC ($r = -0.300$; $p < 0.002$), %FEV_1 ($r = -0.293$, $p < 0.002$), and %TLC ($r = -0.193$, $p < 0.002$) Tx apex displacement from plumb line at C7 was significantly related to %FVC (r=-0117; $p < 0.01$), %FEV_1 ($r = -0.148$, $p < 0.002$), and %TLC ($r = -0.186$, $p < 0.002$) No. of vertebrae with the main Tx curve was significantly related to %FVC ($r = -0.342$; $p < 0.002$), %FEV_1 ($r = -0.305$, $p < 0.002$), and %TLC ($r = -0.192$, $p < 0.002$) C7 displacement from central sacral vertical line was significantly related to %FVC ($r = -0.182$; $p < 0.002$), %FEV_1 ($r = -0.149$, $p < 0.002$), and %TLC ($r = -0.139$, $p < 0.01$) T5 to T12 kyphosis was significantly related to %FVC ($r = 0.157$; $p < 0.002$), %FEV_1 ($r = 0.174$, $p < 0.002$), and %TLC ($r = 0.153$, $p < 0.002$) T2 to T12 kyphosis was significantly related to %FVC ($r = 0.230$; $p < 0.002$), %FEV_1 ($r = 0.242$, $p < 0.002$), and %TLC ($r = 0.211$, $p < 0.002$) Lumbar lordosis was significantly related to %FVC ($r = -0.100$; $p < 0.002$) and %FEV_1 ($r = -0.127$, $p < 0.002$) Cephalad Tx curve flexibility, Main Tx curve flexibility, Lx Cobb angle, Lx curve flexibility, and Tx apex level were not significantly related to %FVC, %FEV_1, and %TLC Mean %FVC fell below 80% when main Tx Cobb angle > 70°; mean %FEV_1 fell below 80% when main Tx Cobb angle > 60° **Independent predictors for %FVC in a multivariate regression:** (1) greater Tx Cobb angle, (2) more vertebrae in Tx curve, (3) smaller T2 to T12 kyphosis angle, and (4) more C7 displacement from central sacral line predicted 19.7% of decreased %FVC **Independent predictors for %FEV_1 in a multivariate regression:** (1) greater Tx Cobb angle, (2) more vertebrae in Tx curve, (3) smaller T2 to T12 kyphosis angle, and (4) more C7 displacement from central sacral line predicted 18.0% of decreased %FEV_1 **Independent predictors for %TLC in a multivariate regression:** (1) greater Tx Cobb angle, (2) smaller T2 to T12 kyphosis angle, and (3) more Tx apex displacement from plumb line at C7 predicted 8.8% of decreased %TLC **In a correlation and regression analyses:** Patients were stratified into (1) normal to mild pulmonary impairment; (2) moderate to severe impairment (≤ 65% of the predicted value): increased percentage of moderate to severe impairment patients with increased Tx Cobb angle and increased number of vertebrae in the Tx curve ($p < 0.001$) Percentage of patients had moderate or severe pulmonary impairment: 20% (of 273) patients for Tx Cobb angle 50° to 70°, 41% (of 34) patients for Cobb angle 71° to 80°, and 74% (of 19) patients for Cobb angle ≥ 80° Percentage of patients had moderate or severe pulmonary impairment: 13% (of 391) patients with a Tx curve involving ≤ 7 vertebral levels, 30% (of 240) patients with ≥ 8 levels **In another correlation and regression analyses:** 13% (of 631) patients had hypokyphosis (≤ 10°), and the prevalence of moderate or severe pulmonary impairment in these patients was significantly higher than the others ($p \leq 0.01$) Percentage of patients had moderate or severe pulmonary impairment: 29% (of 83) for hypokyphosis patients, 19% (of 479) for normal kyphosis patients (10° to 40°), and 10% (of 69) for hyperkyphosis patients **Chi-square analysis** revealed a significant difference in the prevalence of pulmonary impairment across all Lenke types ($p < 0.001$); primary Tx curves were associated with impaired pulmonary function, whereas patients in whom the primary curve was lumbar or thoracolumbar were less likely to have moderate or severe impairment Independent variables: magnitude of the cephalad thoracic curve, magnitude of the main thoracic curve, displacement of the thoracic apex, displacement of the seventh cervical vertebra from the central sacral vertical line, degree of lumbar lordosis, and number of vertebral levels in the main thoracic curve

Table 1 (continued)

Authors	Region/ Country	Study design	No. of participants (% of female)	Age ± SD (years)	Measures	Coronal/ Sagittal Tx Cobb angles ± SD	Type of curve	Outcome measured	Findings
Pietton et al. 2022 [49]	France	Prospective (cross-sectional analysis of pre-op data)	45 (84.4%)	14.7 (range 12 to 17) at surgery	X-ray (biplanar) Spirometer Plethysmography	68.2° ± 17 (range 47° to 128°)/ 20.8°	Tx curve Lx curve Lenke: Type 1 (n = 33) Type 2 (n = 12)	Main Tx Cobb angle Tx Kyphosis (T4 to T12) Lx lordosis (L1 to S1) AVR Max rib hump Rib cage volume Max rib cage medial–lateral diameter (width) Max rib cage anteroposterior diameter (depth) Hypokyphosis index TLC FVC SVC FEV_1/FVC	There were significant relationships between: Tx Cobb angle and TLC ($rho = -0.38$, $p = 0.017$) Tx Cobb angle and SVC ($rho = -0.39$, $p = 0.012$) AVR and FVC ($rho = 0.34$, $p = 0.022$) AVR and SVC ($rho = 0.44$, $p = 0.004$) Rib cage volume and TLC ($rho = 0.78$, $p < 0.001$) Rib cage volume and FVC ($rho = 0.78$, $p < 0.001$) Rib cage volume and SVC ($rho = 0.77$, $p < 0.001$) Rib cage volume and FEV_1/FVC ($rho = -0.32$, $p = 0.035$) Rib cage width and TLC ($rho = 0.46$, $p = 0.003$) Rib cage width and FVC ($rho = 0.50$, $p = 0.001$) Rib cage width and SVC ($rho = 0.44$, $p = 0.004$) Rib cage depth and TLC ($rho = 0.53$, $p = 0.001$) Rib cage depth and FVC ($rho = 0.58$, $p < 0.001$) Rib cage depth and SVC ($rho = 0.53$, $p < 0.001$) Rib cage depth and FEV_1/FVC ($rho = -0.36$, $p = 0.016$) Hypokyphosis index and TLC ($rho = 0.43$, $p = 0.006$) Hypokyphosis index and FVC ($rho = 0.36$, $p = 0.017$) Hypokyphosis index and SVC ($rho = 0.36$, $p = 0.020$) Tx kyphosis, Lx lordosis, and rib hump were not correlated to pulmonary parameters ($p > 0.05$) AIS patients with "no or mild lung impairment" ($n = 24$) (%FVC > 65%) had significantly higher rib cage volume ($p = 0.023$) and rib cage width ($p = 0.039$) than those classified as "moderate or severe impairment" ($n = 21$) (%FVC < 65%)
Ran et al. 2016 [51]	China	Case–control study	237 (81.9%) 60 AIS brace group; 177 AIS non-brace Apex at T5 to T11/12 (n = 142); apex at T12 to L5 (n = 95)	Brace: 13.7 ± 1.5 Non-brace: 13.4 ± 1.5	X-ray Spirometry	Brace: 53.7° ± 13°/ 22.2° ± 14.5° Non-brace: 53.4° ± 12.7°/ 23.4° ± 15°	Main Tx curve Thoracolumbar/lumbar curve	Tx Cobb angle Tx Kyphosis angle (T5 to T12) FVC %FVC FEV_1 %FEV_1	Unclear whether the pulmonary function test was performed while wearing a brace Brace group had significantly smaller %FVC, FEV1, and %FEV_1 ($p < 0.05$) than non-brace controls for those with main Tx curves (not for those with primary thoracolumbar/lumbar curve) **Multiple regression models:** A greater Tx kyphosis was related to better %FVC in brace patients A greater Tx kyphosis angle and shorter brace treatment duration were related to better %FEV_1 Independent variables: Age at operation, height, coronal Cobb angle of main curve, number of involved vertebrae, sagittal Cobb angle of thoracic curve, brace treatment time per day, and brace treatment duration
Saraiva et al. 2017 [52]	Brazil	Case–control	AIS: 46 (100%) Cobb angles > 45° (n = 17); < 45° (n = 29) Healthy control: 20 (100%)	14 ± 2 (range 10 to 18)	X-ray Spirometry Gas analyzer	Cobb angle > 45° group: Cephalic Cobb angle: 26.0° ± 8.0°; main Tx: 55° (50° to 59°); Lx: 31° (30° to 39°) Cobb angle < 45° group: Cephalic 18.0° ± 5.0°; Main Tx: 34° (28° to 38°); Lx: 30° (20° to 36°)	Tx and Lx curves	Cephalic Tx Cobb angle; Main Tx Cobb angle; Lx Cobb angle FEV_1 %FEV_1 FVC %FVC FEV_1/FVC FRC	Main Tx Cobb angle and FVC ($r = -0.506$; $p = 0.004$) Main Tx Cobb angle and FEV_1 ($r = -0.462$; $p = 0.010$) AIS Cobb angle > 45° group had significantly smaller %FVC ($p < 0.001$) and %FEV_1 ($p < 0.001$) than those with Cobb angle < 45°

Table 1 (continued)

Authors	Region/ Country	Study design	No. of participants (% of female)	Age ± SD (years)	Measures	Coronal/ Sagittal Tx Cobb angles ± SD	Type of curve	Outcome measured	Findings
Szeinberg et al. 1988 [53]	Canada	Case–control	12 moderate curve (35° – 60°) (100%) 12 mild curve (< 35°) (100%) 38 Normal controls (100%)	Moderate: 14.0 ± 1.7 Mild: 13.6 ± 1.7 Normal controls: 14.8 ± 1.6	X-ray Spirometry Body plethysmography Used arm span to estimate height for predicting lung functions	Moderate: 49° ± 8° (range 35° to 60°) Mild: 21° ± 8° (range 10° to 35°)	Tx curve	Main Tx Cobb angle %FEV_1 %FVC	Tx Cobbs angle and %FVC ($r = -0.466$, $p < 0.05$) The %FVC of patients with moderate curve were significantly lower than normal controls ($p < 0.001$) There were no differences in lung parameters between patients with mild curve and normal controls ($p > 0.05$) **A stepwise multiple regression** showed that 61% of variance in %FVC was explained by arm span, age, and Tx Cobb angle (no results were shown) Impairment of pulmonary function was noted in mild-to-moderate AIS patients. Decreased lung volumes were related to the degree of thoracic deformity rather than to the impaired respiratory muscle strength
Takahashi et al. 2007 [11]	Japan	Cross-sectional (retrospective review of medical records)	109 (91.7%)	14.2 ± 1.8	CT scan Moiré topography Spirometry with Helium dilution Used Kono's equation (Cobb angle) to estimate height for predicting lung functions	37.7° ± 15.6° (range 16° to 82°)/ 24.2° ± 11.6° (range 0° to 50°)	Right Tx curve King's classification: Type I ($n = 12$) Type II ($n = 41$) Type III ($n = 41$) Type IV ($n = 3$) Type V ($n = 12$) Apex at T3 to T10 ($n = 19$) Apex at T8 to T10 ($n = 90$)	Tx Cobb angle (T1—T12) Hump sum RAsag at T1 to T12 Sagittal diameter of the thoracic cage (at T3 to T12) Kyphosis–lordosis index (at T3 to T12) Rib hump index (at T3 to T12) FVC, FEV_1 FEV_1 /FVC VC, %VC RV, %RV TLC, %TLC RV/TLC, %RV/DLCO DLCO, %DLCO	%VC was significantly related to: Tx Cobb angle ($r = -0.271$, $p = 0.004$), Tx kyphosis ($r = 0.056$, $p = 0.610$), RAsag (at T6 to T9) (r = ranging from -0.291 to -0.339, $p < 0.002$), Sagittal diameter (at T5 to T12) (r = ranging from 0.279 to 0.455, $p < 0.001$), and Kyphosis–lordosis index (at T5 to T12) (r = ranging from 0.258 to 0.329, $p < 0.007$) No correlation between spinal parameters and other pulmonary function parameters ($p > 0.05$) Independent predictors for %VC in two **multivariate regression models:** 1) total lung area and RAsag at T8 ($r^2 = 0.390$, $p < 0.0001$); and 2) sagittal diameter and total lung area at T9 ($r^2 = 0.411$, $p < 0.0001$) %VC was used as the dependent variable while lateral spinal curvature and thoracic cage deformity (at each vertebral level from T3 to T12) variables were used as independent variables
Tung et al. 2018 [38]	USA	Cross-sectional (Retrospective analyses of preoperation data)	142 with Cobb angle > 50º (No information on gender)	14 (SD not reported)	X-ray Spirometry	59°/ 35°	Tx curve	Tx Cobb angle Tx kyphosis (T2 to T12) %FVC BMI	Tx Cobb angle and %FVC ($r = -0.23$, $p = 0.01$) Tx kyphosis angle and %FVC ($r = 0.26$, $p < 0.01$) BMI and %FVC ($r = 0.37$, $p < 0.01$) **Multiple linear regression:** Tx Cobb angle, Tx kyphosis, and BMI were significant predictors of %FVC ($R^2 = 0.26$) The coefficients of determination for: Tx Cobb angle = −0.53 (95% CI: −0.76 to −0.29); Tx kyphosis = 0.31 (95% CI: 0.16, 0.47); and BMI = 1.04 (95% CI 0.52, 1.55) More obese/overweight (BMI ≥ 25) had significantly greater kyphosis angle ($p < 0.05$) and FVC ($P < 0.01$) than those with BMI < 25 Linear regression analysis used FVC as the primary outcome and BMI, TK, and Cobb angle as the independent variables

Table 1 (continued)

Authors	Region/ Country	Study design	No. of participants (% of female)	Age ± SD (years)	Measures	Coronal/ Sagittal Tx Cobb angles ± SD	Type of curve	Outcome measured	Findings
Upadhyay et al. 1995 [39]	Hong Kong	Cross-sectional	− 70 (91.4%)	− 13.8 ± 2.1 (range 10 to 18)	X-ray (standing and supine bending to the right) Spirometry with Helium dilution Used arm span to estimate height for predicting lung functions	− 59.0° ± 14.1° (range 35° to 100°)/ − 24.7° ± 15.1° − (range -7° to 55°)	Right Tx curve: Apex at T8 to T10 ($n = 60$) Apex at T7 or T11 ($n = 10$)	Tx Cobb angle Curve flexibility AVR AVR flexibility Kyphosis (T3 – T12) Maximum sternovertebral distance Maximum sternovertebral distance/ anteroposterior width ratio Rib-vertebral angle asymmetry (standing) Rib-vertebral angle asymmetry (supine bending) Changes in rib-vertebral angle asymmetry from standing to supine bending FVC, %FVC FEV_1, %FEV_1 VC, %VC RV, %RV TLC, %TLC FRC, %FRC $FEF_{25\text{-}75\%}$, %$FEF_{25\text{-}75\%}$, DLCO, %DLCO, DLCO/VA, %DLCO/VA	There were significant relationships between the following measurements: Tx Cobb angle and %FVC ($r = -0.303$, $p = 0.007$), Tx Cobb angle and %VC ($r = -0.303$, $p = 0.011$), Tx Cobb angle and %FRC (− 0.262, $p = 0.032$); AVR and %FVC ($r = -0.273$, $p = 0.024$), AVR and %VC ($r = -0.268$, $p = 0.025$); AVR flexibility and %FVC ($r = 0.361$, $p = 0.004$), AVR flexibility and %VC ($r = 0.353$, $p = 0.005$); Kyphosis and RV ($r = 0.249$, $p = 0.046$), Kyphosis and TLC ($r = 0.281$, $p = 0.022$), Kyphosis and FRC ($r = 0.258$, $p = 0.036$), Kyphosis and $FEF_{25\text{-}75\%}$ ($r = 0.403$, $p = 0.007$), Kyphosis and %$FEF_{25\text{-}75\%}$ ($r = 0.343$, $p = 0.024$); Maximum sternovertebral distance and FVC ($r = 0.269$, $p = 0.036$), Maximum sternovertebral distance and VC ($r = 0.277$, $p = 0.031$), Maximum sternovertebral distance and TLC ($r = 0.285$, $p = 0.029$), Maximum sternovertebral distance and $FEF_{25\text{-}25\%}$ ($r = 0.340$, $p = 0.032$); Rib-vertebral angle asymmetry (standing) and %FRC ($r = -0.266$, $p = 0.041$); Rib-vertebral angle asymmetry (supine bending) and %FVC ($r = -0.323$, $p = 0.011$), Rib-vertebral angle asymmetry (supine bending) and %VC ($r = -0.269$, $p = 0.035$), Rib-vertebral angle asymmetry (supine bending) and %FRC ($r = -0.260$, $p = 0.047$), Rib-vertebral angle asymmetry (supine bending) and DLCO/VA ($r = 0.405$, $p = 0.019$) Curve flexibility, Maximum sternovertebral distance/anteroposterior width ratio, and change in rib-vertebral angle asymmetry from standing to supine bending were unrelated to any of the lung function parameters ($p > 0.05$) **A multiple stepwise regression model:** AVR flexibility, maximum sternovertebral distance, and rib-vertebral angle asymmetry (standing) predicted 28.4% of the %VC ($p = 0.0002$) Independent variables: Relation of Spinal deformities and pulmonary functions: Cobb angle, curve flexibility, vertebral rotation, rotational flexibility, kyphosis Relation of thoracic cage deformities and pulmonary functions: Sternovertebral distance, sternovertebral distance/vertical width, rib-vertebral angle asymmetry (standing), rib-vertebral angle asymmetry (supine bending), Change in rib-vertebral angle asymmetry

Table 1 (continued)

Authors	Region/Country	Study design	No. of participants (% of female)	Age ± SD (years)	Measures	Coronal/Sagittal Tx Cobb angles ± SD	Type of curve	Outcome measured	Findings
Villamor et al. 2019 [40]	USA	Cross-sectional	91 (unknown) Tx Cobb angle > 20° Non-brace ($n = 46$) Brace ($n = 14$) Planning surgery ($n = 31$)	14 (range 11 to 17)	X-ray Scoliometer Spirometry	39.5° (range 20° to 88°)	Tx curve	Tx Cobb angle ATR %FEV_1 FEV_1/FVC FVC, %FVC MVV, %MVV	Tx Cobb angle and %FEV_1 ($r = -0.35$, $p = 0.02$) Tx Cobb angle and FVC ($r = -0.37$, $p = 0.01$) Tx Cobb angle and %FVC ($r = -0.32$, $p = 0.04$) Tx Cobb angle and MVV ($r = -0.41$, $p < 0.01$) TA Cobb angle and %MVV ($r = -0.24$, $p = 0.03$) ATR and FVC ($r = -0.16$, $p = 0.33$) ATR and %FVC ($r = -0.24$, $p = 0.13$) ATR and MVV ($r = -0.21$, $p = 0.06$) ATR and %MVV ($r = -0.14$, $p = 0.22$)
Wang et al. 2019 [41]	China	Cross-sectional (Retrospective analyses of preoperative data)	72 (76.4%) AIS with right main Tx Cobb angles ≥ 45°	Male: 14.7 ± 0.6 Female: 14.9 ± 0.4	X-ray (standing and supine bending) Plethysmography	67.5° ± 17.6°/29.3° ± 18.9°	Tx curve Lenke: Type 1 ($n = 41$); Type 2 ($n = 14$); Type 3 ($n = 12$); Type 6 ($n = 5$) Apex at T7 ($n = 11$); Apex at T8 ($n = 17$); Apex at T9 ($n = 31$); Apex at T10 ($n = 6$); Apex at T11 ($n = 7$)	Tx Cobb angle TK (T5-T12) Apical vertebral body-to-rib ratio Main Tx AVT Main Tx curve flexibility index Main Tx rib hump Main Tx depth %FEV_1 %FVC	Tx Cobb angle and %FEV_1 ($r = -0.812$, $p < 0.001$) Tx Cobb angle and %FVC ($r = -0.805$, $p < 0.001$) TK angle and %FEV_1 ($r = -0.248$, $p = 0.036$) TK angle and %FVC ($r = -0.172$, $p = 0.147$) Apical vertebral body-to-rib ratio and %FEV_1 ($r = -0.748$, $p < 0.001$) Apical vertebral body-to-rib ratio and %FVC ($r = -0.732$, $p < 0.001$) AVT and %FEV_1 ($r = -0.670$, $p < 0.001$) AVT and %FVC ($r = -0.619$, $p < 0.001$) Curve flexibility index and %FEV_1 ($r = 0.233$, $p = 0.048$) Curve flexibility index and %FVC ($r = 0.207$, $p = 0.81$) Rib hump and %FEV_1 ($r = -0.756$, $p < 0.001$) Rib hump and %FVC ($r = -0.723$, $p < 0.001$) Tx depth and %FEV_1 ($r = 0.227$, $p = 0.055$) Tx depth and %FVC ($r = 0.269$, $p = 0.022$) **Multiple linear regression:** Tx Cobb angle ($R^2 = 0.648$), apical vertebral body-to-rib ratio ($R^2 = 0.536$), AVT ($R^2 = 0.383$), and rib hump ($R^2 = 0.522$) were significant predictors of %FVC ($p < 0.05$) Compared to patients with normal lung function (%FVC ≥ 80%; $n = 45$), patients with lung impairment (%FVC < 80%; $n = 27$) had significantly larger Tx Cobb angle, apical vertebral body-to-rib ratio, AVT, and rib hump ($p < 0.001$) Patients with severe lung impairment (%FVC < 80% and %FEV_1 < 60%; $n = 16$) had significantly larger Tx Cobb angle, AVB-R, AVT, and rib hump than those with mild-to-moderate impairment (%FVC < 80% and %FEV_1 ≥ 60%; $n = 22$) ($p < 0.001$) *Independent variables: MT-Cobb, MT-TD, MT-RH, and MT-AVB-R
Xu et al. 2015 [42]	China	Cross-sectional	120 (100%)	14.5 ± 1.8 (range 13 to 15)	X-ray Spirometry Used Bjure's equation (Cobb angle) to estimate height for predicting lung functions	49.2° ± 10.4° (range 40° to 91°)/No report	Right Tx curve; apical vertebrae ranged from T7 to T11 BMI > 17.5 kg/cm^2 ($n = 54$) BMI ≤ 17.5 kg/cm^2 ($n = 66$)	Tx Cobb angle Location of apical vertebra Number of vertebrae in thoracic curve Tx kyphosis (T5 to T12) %VC %FVC %FEV_1 BMI	Tx Cobb angle and %VC ($r = -0.30$, $p = 0.01$) Tx Cobb angle and %FVC ($r = -0.26$, $p = 0.03$) Tx Cobb angle and % FEV_1 ($r = -0.24$, $p = 0.04$) Location of apical vertebra and %VC ($r = 0.33$, $p = 0.006$) Location of apical vertebra and %FVC ($r = 0.33$, $p = 0.006$) Location of apical vertebra and %FEV_1 ($r = 0.24$, $p = 0.04$) No. of vertebrae and %VC ($r = -0.39$, $p = 0.001$) No. of vertebrae and %FVC ($r = -0.38$, $p = 0.003$) No. of vertebrae and %FEV_1 ($r = -0.34$, $p = 0.004$) Patient with a lower BMI (≤ 17.5) had significantly lower %VC ($p = 0.004$), %FVC ($p = 0.002$), and %FEV_1 ($p = 0.01$) than patients with a higher BMI (> 17.5) **Multiple regression analysis models:** Lower BMI and location of apical vertebrae, and greater Tx Cobb angle and no. of vertebrae involved were independent predictors for reduced %VC, %FVC, and %FEV_1, which could account for 38.6%, 39.1%, and 33.0% of variance (R^2), respectively *Independent variables: BMI, curve magnitude, location of apical vertebrae, number of involved vertebrae

Table 1 (continued)

Authors	Region/ Country	Study design	No. of participants (% of female)	Age ± SD (years)	Measures	Coronal/ Sagittal Tx Cobb angles ± SD	Type of curve	Outcome measured	Findings
Yaszay et al. 2017 [43]	USA	Cross-sectional	163 (86.5%)	15 ± 2	X-ray (biplanar) Scoliometer Spirometry	3D Tx Cobb angle range 11° to 115° 3D Tx kyphosis angle: -56° to 44° 3D Tx AVR: 0° to 29° 3D Lx Cobb angle: 11° to 98°	Tx and Lx curves: Tx curve ($n=124$) Lx curve ($n=39$)	Upper Tx Cobb angle Main Tx Cobb angle Kyphosis (T5 – T12) Tx AVR Lx Cobb angle Lx AVR %FEV_1 %FVC %TLC	There were significant relationships between: Upper Tx Cobb angle and %FEV_1 ($r=-0.224$, $p<0.05$), Upper Tx Cobb angle and %FVC ($r=-0.166$, $p<0.05$); Main Tx Cobb angle and %FEV_1 ($r=-0.401$, $p<0.05$), Main Tx Cobb angle and %FVC ($r=-0.298$, $p<0.05$), Main Tx Cobb angle and %TLC ($r=-0.212$, $p<0.05$); T5—T12 kyphosis and % FEV_1 ($r=0.444$, $p<0.05$), T5—T12 kyphosis and %FVC ($r=0.298$, $p<0.05$), T5—T12 kyphosis and %TLC ($r=0.327$, $p<0.05$); T10—L2 kyphosis and %FEV_1 ($r=0.173$, $p<0.05$); Tx AVR and %FEV_1 ($r=-0.408$, $p<0.05$), Tx AVR and %FVC ($r=-0.256$, $p<0.05$); and Lx AVR and %FEV_1 ($r=0.233$, $p<0.05$), Lx AVR and %TLC ($r=0.197$, $p<0.05$) T1 to T5 kyphosis, T12 to L5 lordosis, and Lx Cobb angle were not significantly related to %FEV_1, %FVC, and %TLC **Multiple regression models:** Tx kyphosis was the most consistent predictor for FEV($r^2=0.087$), FVC ($r^2=0.069$), and TLC ($r^2=0.098$) impairment Independent variables: pulmonary function of each radiographic measure and the thoracic Scoliometer measurement
Yu et al. 2013 [44]	China	Cross-sectional	270 (100% With brace treatment ($n=70$) Without brace ($n=200$)	14.4 (range 10 to 18)	X-ray Spirometry	51.4° (range 35° to 105°)	Tx curve Lx curve Major Tx curve (apex at between T5 to T11) ($n=166$) Thoracolumbar/Lx curve ($n=104$)	With or without brace treatment Cobb angle Tx Kyphosis (T5 to T12) FVC %FVC FEV_1 %FEV_1	The %FVC and %FEV_1 were significantly lower in patients with brace treatment when compared with those without brace treatment $p<0.05$) In patients with major Tx curve ($n=166$), those with brace treatment ($n=48$) had significantly lower %FVC and %FEV_1 when compared with those without brace treatment ($n=118$) (both $p<0.05$) A **multiple linear regression analysis** was performed in patients with a major Tx curve: Smaller Tx kyphosis angle was an independent predictor for reduced FVC ($R^2=0.016$), %FVC ($R^2=0.546$), FEV_1 ($R^2=0.015$) and %FEV_1 ($R^2=0.533$ (all $p<0.05$) Independent variables: the actual value of FVC and FEV_1, %FVC and %FEV_1, and the age at operation, height, coronal and sagittal Cobb angles of the thoracic curve, the vertebra that the major curve involved, the hours with brace wearing, and the length of brace treatment

ATr = angle of trunk rotation; AVr = apical vertebral rotation; BMI = body mass index; DLCO = diffusion capacity of the lung for carbon monoxide; %DLCO = percentage of predicted DLCO; DLCO/VA = carbon monoxide diffusion capacity per liter of alveolar volume; %DLCO/VA = percentage of predicted DLCO/VA; $FEF_{25\text{-}75\%}$ = forced expiratory flow from 25% to 75% of FVC; %$FEF_{25\text{-}75\%}$ = percentage of predicted $FEF_{25\text{-}75\%}$; $FEF_{25\%}$ = The maximum forced expiratory flow at 25% of FVC; $FEF_{50\%}$ = The maximum forced expiratory flow at 50% of FVC; FEV_1 = forced expiratory volume in 1 s; %FEV_1 = percentage of predicted FEV_1; FEV_1/FVC = ratio of FEV_1 to FVC; %FEV_1/FVC = percentage of predicted FEV_1/FVC; FRC = functional residual capacity; %FRC = percentage of predicted FRC; FVC = forced vital capacity; %FVC = percentage of predicted FVC; Lx = lumbar; AVT = apical vertebra translation; MVV = maximum voluntary ventilation; %MVV = percentage of predicted MVV; PEF = peak expiratory flow; SPI = spinal penetration index; SVC = slow vital capacity; TK = thoracic kyphosis; TLC = total lung capacity; %TLC = percentage of predicted TCL; Tx = thoracic; VC = vital capacity; %VC = percentage of predicted VC; RV = residual volume; RV/TLC = ration of RV to TLC; %RV = percentage of predicted RV; %RV/TLC = percentage of predicted RV/TL

Table 2 Summary of significant correlation between various spinal deformities and pulmonary function parameters

Spinal deformity	Pulmonary parameter	References	N	Correlation, r	Cl, 95% UL	Cl, 95% LL	P	Level of evidence
Significant negative correlations								
Proximal thoracic Cobb angle	%FVC	Please refer to Supplementary Material eFigure 1 for meta-analysis	1029	−0.194	−0.134	−0.253	$P<0.001$	Limited evidence
	$\%FEV_1$	Please refer to eFigure 1 for meta-analysis	1029	−0.234	−0.175	−0.291	$P<0.001$	Limited evidence
Main thoracic Cobb angle	%FVC	Please refer to Fig. 2	2238	−0.302	−0.210	−0.388	$P<0.001$	Limited evidence
		Please refer to Fig. 3 (For multiple regression model)	965	−0.309	−0.365	−0.250	$P<0.001$	Limited evidence
	FVC	Please refer to Fig. 2	679	−0.245	−0.108	−0.374	$P<0.001$	Limited evidence
	$\%FEV_1$	Please refer to Fig. 2	1865	−0.348	−0.243	−0.414	$P<0.001$	Limited evidence
	FEV_1	Please refer to Fig. 2	419	−0.232	−0.037	−0.410	$P<0.001$	Limited evidence
	FEV_1/FVC	Please refer to Fig. 2	389	−0.166	−0.262	−0.067	$P=0.001$	Limited evidence
	%TLC	Please refer to Fig. 2	1090	−0.183	−0.125	−0.241	$P<0.001$	Limited evidence
	TLC	Please refer to Fig. 2	167	−0.302	−0.021	−0.538	$P=0.036$	Limited evidence
	%VC	Please refer to Fig. 2	350	−0.272	−0.171	−0.368	$P<0.001$	Limited evidence
Number of vertebrae in thoracic curve	%FVC	Please refer to eFigure 2	1045	−0.262	−0.215	−0.524	$P<0.001$	Limited evidence
	$\%FEV_1$	Please refer to eFigure 2	1045	−0.255	−0.159	−0.346	$P<0.001$	Limited evidence
Main thoracic apical vertebral rotation	%FVC	Please refer to eFigure 3	352	−0.215	−0.112	−0.314	$P<0.001$	Limited evidence
	%TLC	Please refer to eFigure 3	285	−0.126	−0.009	−0.240	$P=0.035$	Limited evidence
Maximum rib hump (°)	FVC	Please refer to eFigure 4	166	−0.225	−0.072	−0.367	$P=0.004$	Limited evidence
Lumbar lordosis	%FVC	Please refer to eFigure 5	861	−0.099	−0.032	−0.165	$P=0.004$	Limited evidence
	$\%FEV_1$	Please refer to eFigure 5	861	−0.116	−0.049	−0.182	$P<0.001$	Limited evidence
Significant positive correlations								
Main thoracic kyphosis (T5 to T12)	%FVC	Please refer to eFigure 6	1079	0.180	0.432	0.151	$P<0.001$	Limited evidence
		Please refer to Fig. 3 (for multiple regression model)	1271	0.226	0.277	0.172	$P<0.001$	Limited evidence
	$\%FEV_1$	Please refer to eFigure 6	1079	0.193	0.365	0.007	$P=0.042$	Limited evidence
		Please refer to Fig. 3 (for multiple regression model)	966	0.318	0.260	0.374	$P<0.001$	Limited evidence
Maximum rib cage thickness	FVC	Please refer to eFigure 7	166	0.377	0.562	0.155	$P<0.001$	Limited evidence
Maximum rib cage width	FVC	Please refer to eFigure 8	166	0.635	0.748	0.486	$P<0.001$	Limited evidence
Rib cage volume	FVC	Please refer to eFigure 9	166	0.784	0.838	0.716	$P<0.01$	Limited evidence

FEV_1 = forced expiratory volume in 1 s; $\%FEV_1$ = percentage of predicted forced expiratory volume in the first second; FVC = forced vital capacity; %FVC = percentage of predicted forced vital capacity; TLC = total lung capacity; %TLC = percentage of predicted total lung capacity; %VC = percentage of predicted vital capacity a kyphosis angle cutoff [17, 37], and BMI [38, 42]. Two included studies compared spinal parameters based on the severity of lung impairment [41, 49].

Significant negative univariate correlations

Meta-analyses showed that proximal thoracic Cobb angles were negatively related to %FVC ($r = -0.194$; 95% confidence interval [95% Cl]: -0.253 to -0.134) and %FEV$_1$ ($r = -0.234$; 95% Cl: -0.291 to -0.175) (Supplementary Material eFigure 1), while main thoracic Cobb angles were negatively associated with %FVC ($r = -0.302$), FVC ($r = -0.245$), %FEV$_1$ ($r = -0.348$), FEV$_1$ ($r = -0.232$), FEV$_1$/FVC ratio ($r = -0.166$), %TLC ($r = -0.183$), TLC ($r = -0.302$), and %VC ($r = -0.272$) (Fig. 2). Similarly, significant negative correlations were noted between the number of involved thoracic vertebrae and %FVC ($r = -0.262$; 95% Cl: -0.524 to -0.215) and %FEV$_1$ ($r = -0.255$; 95% Cl: -0.346 to -0.159), between main thoracic apical vertebral rotation and %FVC ($r = -0.215$; 95% Cl: -0.314 to -0.112) and %TLC ($r = -0.126$; 95% Cl: -0.240 to -0.009), between maximum rib hump and FVC ($r = -0.225$; 95% Cl: -0.367 to -0.072), as well as between lumbar lordosis and %FVC ($r = -0.099$; 95% Cl: -0.165 to -0.032) and %FEV$_1$ ($r = -0.116$; 95% Cl: -0.182 to -0.049) (Table 2; eFigures 2–5).

Significant positive univariate correlations

Thoracic kyphosis angles were positively related to %FVC ($r = 0.180$; 95% Cl, 0.151 to 0.432) and %FEV$_1$($r = 0.193$; 95% Cl: 0.007 to 0.365) (Table 2; eFigure 6). Other meta-analyses revealed that higher rib cage thickness ($r = 0.377$; 95% Cl: 0.155 to 0.562), width ($r = 0.635$; 95% Cl: 0.486 to 0.748), and volume ($r = 0.784$; 95% Cl: 0.716 to 0.838) were significantly associated with higher FVC (Table 2; eFigures 7–9).

Reported multivariate analyses

Three meta-analyses showed significant correlations between main thoracic Cobb angles and %FVC ($r = -0.309$), as well as between main thoracic kyphosis angles and FEV$_1$ ($r = 0.318$) or %FVC ($r = 0.226$) after adjusting for confounders (Fig. 3). These results were similar to the corresponding meta-analyses of univariate analysis (Fig. 2; eFigure 6).

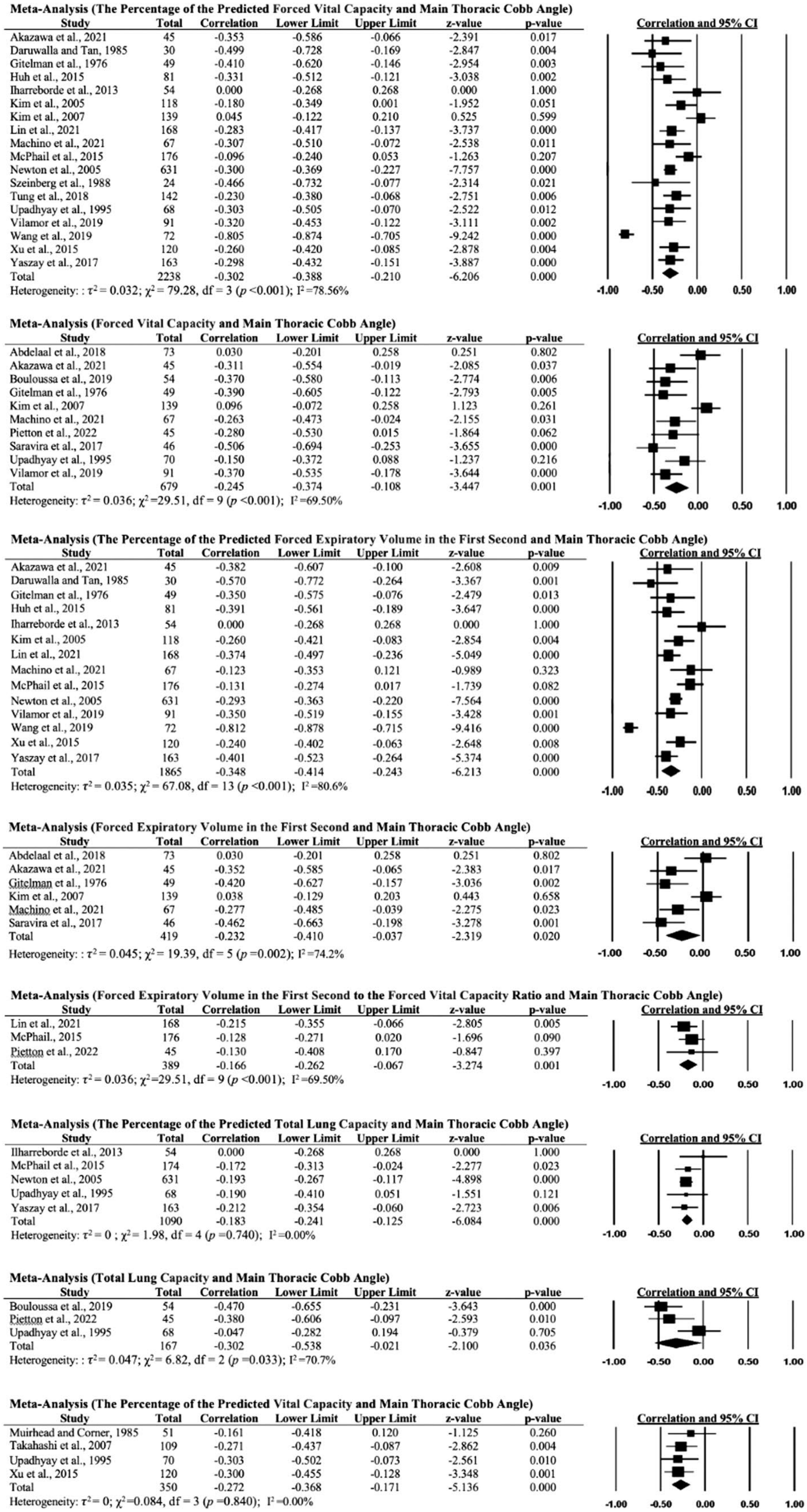
Discussion

This is the first systematic review and meta-analysis to summarize the associations between various spinal parameters and pulmonary function parameters in patients with AIS. Limited-quality evidence supports that increased thoracic Cobb angles, number of involved thoracic vertebrae, apical vertebral rotation, rib hump, and lumbar lordotic angles are related to decreased %FVC, whereas increased thoracic kyphosis angles are associated with larger %FVC and %FEV$_1$. Rib cage parameters are positively correlated with FVC.

Scoliosis involves three-dimensional spinal deformity and thoracic cage distortion that may affect each other and worsen lung function [56]. Notably, thoracic cage deformity may alter spinal curvature, and causes rotation and shortening of the thoracic spine, leading to compromised chest wall compliance [57], decreased lung volume under the rib hump, and lung impingement on the concave side. The compressed lung tissues may reduce lung compliance, causing restrictive lung diseases [58]. Similarly, the rotational vertebral deformity may cause thoracic asymmetry [11], which increases the chest wall stiffness [59], reduces the efficiency of respiratory muscles and the diaphragm [8]. The vertebral rotation and rib hump can also cause imbalance in bilateral paraspinal and respiratory muscles [60], limiting the elevation of ribs and reducing lateral and anteroposterior movements of the thoracic cage [11]. These altered chest wall and respiratory muscle mechanics may decrease TLC [61], and increase the risk of hypercapnia, hypoxemia, and alveolar hypoventilation, causing irreversible lung atrophy [57].

While it is well known that patients with thoracic Cobb angles > 50° display clinically significant pulmonary impairments [62], our findings suggest that pulmonary impairment exists even in patients with mild-to-moderate idiopathic scoliosis [53]. However, some patients with severe spinal curvature may not show pulmonary decline if they have good apical vertebral rotational flexibility [39]. Notably, AIS patients with a flexible spine (rotational flexibility > 55%) have normal lung function [56]. Therefore, thoracic curve flexibility should be considered in evaluating the associations.

The decreased %FVC and %VC but a normal FEV$_1$/FVC ratio among patients with AIS in the included studies indicate that they show restrictive lung characteristics [7, 55]. However, there are conflicting findings regarding the relation between spinal deformity and obstructive lung disease in patients with AIS. While one included study reported no significant relation between main thoracic Cobb angles and FEV$_1$/FVC ratio [34], another included study found that 68 out of 176 AIS patients with thoracic Cobb angle > 40° had obstructive lung diseases although no significant correlation between Cobb angles and FEV$_1$/FVC ratio was noted [16]. The latter study also showed that 73% of these 68 patients had irreversible obstructive lung disease that could not be improved by bronchodilator [16]. Although multiple factors (e.g., lower airway malacia, asthma) may lead to obstructive lung characteristics [16], rib cage deformity-related intrathoracic airway compression or respiratory muscle weakness



Meta-Analysis (The Percentage of the Predicted Forced Vital Capacity and Main Thoracic Cobb Angle)

Study	Total	Correlation	Lower Limit	Upper Limit	z-value	p-value
Akazawa et al., 2021	45	-0.353	-0.586	-0.066	-2.391	0.017
Daruwalla and Tan, 1985	30	-0.499	-0.728	-0.169	-2.847	0.004
Gitelman et al., 1976	49	-0.410	-0.620	-0.146	-2.954	0.003
Huh et al., 2015	81	-0.331	-0.512	-0.121	-3.038	0.002
Iharreborde et al., 2013	54	0.000	-0.268	0.268	0.000	1.000
Kim et al., 2005	118	-0.180	-0.349	0.001	-1.952	0.051
Kim et al., 2007	139	0.045	-0.122	0.210	0.525	0.599
Lin et al., 2021	168	-0.283	-0.417	-0.137	-3.737	0.000
Machino et al., 2021	67	-0.307	-0.510	-0.072	-2.538	0.011
McPhail et al., 2015	176	-0.096	-0.240	0.053	-1.263	0.207
Newton et al., 2005	631	-0.300	-0.369	-0.227	-7.757	0.000
Szeinberg et al., 1988	24	-0.466	-0.732	-0.077	-2.314	0.021
Tung et al., 2018	142	-0.230	-0.380	-0.068	-2.751	0.006
Upadhyay et al., 1995	68	-0.303	-0.505	-0.070	-2.522	0.012
Vilamor et al., 2019	91	-0.320	-0.453	-0.122	-3.111	0.002
Wang et al., 2019	72	-0.805	-0.874	-0.705	-9.242	0.000
Xu et al., 2015	120	-0.260	-0.420	-0.085	-2.878	0.004
Yaszay et al., 2017	163	-0.298	-0.432	-0.151	-3.887	0.000
Total	2238	-0.302	-0.388	-0.210	-6.206	0.000

Heterogeneity: : $\tau^2 = 0.032$; $\chi^2 = 79.28$, df = 3 ($p < 0.001$); $I^2 = 78.56\%$

Meta-Analysis (Forced Vital Capacity and Main Thoracic Cobb Angle)

Study	Total	Correlation	Lower Limit	Upper Limit	z-value	p-value
Abdelaal et al., 2018	73	0.030	-0.201	0.258	0.251	0.802
Akazawa et al., 2021	45	-0.311	-0.554	-0.019	-2.085	0.037
Bouloussa et al., 2019	54	-0.370	-0.580	-0.113	-2.774	0.006
Gitelman et al., 1976	49	-0.390	-0.605	-0.122	-2.793	0.005
Kim et al., 2007	139	0.096	-0.072	0.258	1.123	0.261
Machino et al., 2021	67	-0.263	-0.473	-0.024	-2.155	0.031
Pietton et al., 2022	45	-0.280	-0.530	0.015	-1.864	0.062
Saravira et al., 2017	46	-0.506	-0.694	-0.253	-3.655	0.000
Upadhyay et al., 1995	70	-0.150	-0.372	0.088	-1.237	0.216
Vilamor et al., 2019	91	-0.370	-0.535	-0.178	-3.644	0.000
Total	679	-0.245	-0.374	-0.108	-3.447	0.001

Heterogeneity: $\tau^2 = 0.036$; $\chi^2 = 29.51$, df = 9 ($p < 0.001$); $I^2 = 69.50\%$

Meta-Analysis (The Percentage of the Predicted Forced Expiratory Volume in the First Second and Main Thoracic Cobb Angle)

Study	Total	Correlation	Lower Limit	Upper Limit	z-value	p-value
Akazawa et al., 2021	45	-0.382	-0.607	-0.100	-2.608	0.009
Daruwalla and Tan, 1985	30	-0.570	-0.772	-0.264	-3.367	0.001
Gitelman et al., 1976	49	-0.350	-0.575	-0.076	-2.479	0.013
Huh et al., 2015	81	-0.391	-0.561	-0.189	-3.647	0.000
Iharreborde et al., 2013	54	0.000	-0.268	0.268	0.000	1.000
Kim et al., 2005	118	-0.260	-0.421	-0.083	-2.854	0.004
Lin et al., 2021	168	-0.374	-0.497	-0.236	-5.049	0.000
Machino et al., 2021	67	-0.123	-0.353	0.121	-0.989	0.323
McPhail et al., 2015	176	-0.131	-0.274	0.017	-1.739	0.082
Newton et al., 2005	631	-0.293	-0.363	-0.220	-7.564	0.000
Vilamor et al., 2019	91	-0.350	-0.519	-0.155	-3.428	0.001
Wang et al., 2019	72	-0.812	-0.878	-0.715	-9.416	0.000
Xu et al., 2015	120	-0.240	-0.402	-0.063	-2.648	0.008
Yaszay et al., 2017	163	-0.401	-0.523	-0.264	-5.374	0.000
Total	1865	-0.348	-0.414	-0.243	-6.213	0.000

Heterogeneity: $\tau^2 = 0.035$; $\chi^2 = 67.08$, df = 13 ($p < 0.001$); $I^2 = 80.6\%$

Meta-Analysis (Forced Expiratory Volume in the First Second and Main Thoracic Cobb Angle)

Study	Total	Correlation	Lower Limit	Upper Limit	z-value	p-value
Abdelaal et al., 2018	73	0.030	-0.201	0.258	0.251	0.802
Akazawa et al., 2021	45	-0.352	-0.585	-0.065	-2.383	0.017
Gitelman et al., 1976	49	-0.420	-0.627	-0.157	-3.036	0.002
Kim et al., 2007	139	0.038	-0.129	0.203	0.443	0.658
Machino et al., 2021	67	-0.277	-0.485	-0.039	-2.275	0.023
Saravira et al., 2017	46	-0.462	-0.663	-0.198	-3.278	0.001
Total	419	-0.232	-0.410	-0.037	-2.319	0.020

Heterogeneity: : $\tau^2 = 0.045$; $\chi^2 = 19.39$, df = 5 ($p = 0.002$); $I^2 = 74.2\%$

Meta-Analysis (Forced Expiratory Volume in the First Second to the Forced Vital Capacity Ratio and Main Thoracic Cobb Angle)

Study	Total	Correlation	Lower Limit	Upper Limit	z-value	p-value
Lin et al., 2021	168	-0.215	-0.355	-0.066	-2.805	0.005
McPhail., 2015	176	-0.128	-0.271	0.020	-1.696	0.090
Pietton et al., 2022	45	-0.130	-0.408	0.170	-0.847	0.397
Total	389	-0.166	-0.262	-0.067	-3.274	0.001

Heterogeneity: $\tau^2 = 0.036$; $\chi^2 = 29.51$, df = 9 ($p < 0.001$); $I^2 = 69.50\%$

Meta-Analysis (The Percentage of the Predicted Total Lung Capacity and Main Thoracic Cobb Angle)

Study	Total	Correlation	Lower Limit	Upper Limit	z-value	p-value
Ilharreborde et al., 2013	54	0.000	-0.268	0.268	0.000	1.000
McPhail et al., 2015	174	-0.172	-0.313	-0.024	-2.277	0.023
Newton et al., 2005	631	-0.193	-0.267	-0.117	-4.898	0.000
Upadhyay et al., 1995	68	-0.190	-0.410	0.051	-1.551	0.121
Yaszay et al., 2017	163	-0.212	-0.354	-0.060	-2.723	0.006
Total	1090	-0.183	-0.241	-0.125	-6.084	0.000

Heterogeneity: $\tau^2 = 0$; $\chi^2 = 1.98$, df = 4 ($p = 0.740$); $I^2 = 0.00\%$

Meta-Analysis (Total Lung Capacity and Main Thoracic Cobb Angle)

Study	Total	Correlation	Lower Limit	Upper Limit	z-value	p-value
Bouloussa et al., 2019	54	-0.470	-0.655	-0.231	-3.643	0.000
Pietton et al., 2022	45	-0.380	-0.606	-0.097	-2.593	0.010
Upadhyay et al., 1995	68	-0.047	-0.282	0.194	-0.379	0.705
Total	167	-0.302	-0.538	-0.021	-2.100	0.036

Heterogeneity: : $\tau^2 = 0.047$; $\chi^2 = 6.82$, df = 2 ($p = 0.033$); $I^2 = 70.7\%$

Meta-Analysis (The Percentage of the Predicted Vital Capacity and Main Thoracic Cobb Angle)

Study	Total	Correlation	Lower Limit	Upper Limit	z-value	p-value
Muirhead and Corner, 1985	51	-0.161	-0.418	0.120	-1.125	0.260
Takahashi et al., 2007	109	-0.271	-0.437	-0.087	-2.862	0.004
Upadhyay et al., 1995	70	-0.303	-0.502	-0.073	-2.561	0.010
Xu et al., 2015	120	-0.300	-0.455	-0.128	-3.348	0.001
Total	350	-0.272	-0.368	-0.171	-5.136	0.000

Heterogeneity: $\tau^2 = 0$; $\chi^2 = 0.084$, df = 3 ($p = 0.840$); $I^2 = 0.00\%$

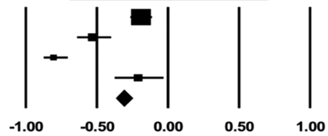
Fig. 2 Forest plots of univariate meta-analysis of main thoracic Cobb angles and pulmonary parameters

Meta-Analysis for Multiple Regression Model (The Percentage of the Predicted Forced Vital Capacity and Main Thoracic Cobb Angle)

Study	Total	Correlation	Lower Limit	Upper Limit	z-value	p-value
Newton et al., 2005	631	-0.190	-0.264	-0.113	-4.812	0.000
Tung et al., 2018	142	-0.530	-0.639	-0.400	-6.958	0.000
Wang et al., 2019	72	-0.805	-0.874	-0.705	-9.242	0.000
Xu et al., 2015	120	-0.210	-0.375	-0.032	-2.304	0.021
Total	965	-0.309	-0.365	-0.250	-9.858	0.000

Heterogeneity: : $\tau^2 = 0.124$; $\chi^2 = 65.12$, df = 3 ($p < 0.001$); $I^2 = 95.40\%$

Correlation and 95% CI

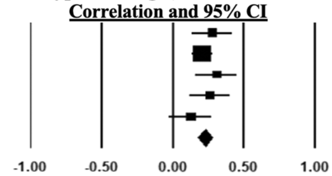


Meta-Analysis for Multiple Regression Model (The Percentage of Predicted Forced Vital Capacity and Thoracic kyphosis angle)

Study	Total	Correlation	Lower Limit	Upper Limit	z-value	p-value
McPhail et al., 2015	169	0.280	0.135	0.413	3.707	0.000
Newton et al., 2005	631	0.207	0.131	0.281	5.273	0.001
Tung et al., 2018	142	0.310	0.153	0.452	3.779	0.000
Yaszay et al., 2017	163	0.263	0.114	0.400	3.402	0.001
Yu et al., 2017	166	0.127	-0.026	0.274	1.624	0.104
Total	1271	0.226	0.172	0.277	8.133	0.000

Heterogeneity: $\tau^2 = 0$; $\chi^2 = 3.90$, df = 4 ($p = 0.420$); $I^2 = 0.00\%$

Correlation and 95% CI



Meta-Analysis for Multiple Regression Model (The Percentage of the Predicted Forced Expiratory Volume in the First One Second and Main Thoracic Kyphosis)

Study	Total	Correlation	Lower Limit	Upper Limit	z-value	p-value
McPhail et al., 2015	169	0.210	0.061	0.350	2.747	0.006
Newton et al., 2005	631	0.203	0.126	0.276	5.146	0.000
Yu et al., 2017	166	0.730	0.650	0.794	11.860	0.000
Total (95% CI)	966	0.318	0.260	0.374	10.207	0.000

Heterogeneity: $\tau^2 = 0.140$; $\chi^2 = 70.50$, df = 2 ($p < 0.001$); $I^2 = 97.16\%$

Correlation and 95% CI

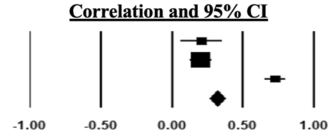


Fig. 3 Forest plots of multivariate meta-analysis

may contribute to such findings [8]. Given the high prevalence of irreversible obstructive lung diseases in patients with moderate to severe AIS, endoscopy or chest imaging may be indicated for this airway obstruction [16].

The consistent findings of significant but weak correlations between various structural characteristics and pulmonary function may be ascribed to no adjustment for confounders (e.g., BMI and duration of bracing). Abnormal mechanical loading of respiratory muscles and altered muscle length-tension relationship can affect respiratory muscle contraction and lung function [7, 63], especially in patients with mild AIS [60]. Higher BMI is associated with better %FVC in teenagers with Cobb angle > 40° [38, 42]. Research found that the association between BMI and %FVC was stronger than those between thoracic Cobb angles or kyphosis angles and %FVC [38]. Heavier teens tend to have greater thoracic kyphosis, which yields better %FVC than hypokyphotic peers [38]. Additionally, one study found that brace wearing temporarily compromised $\%FEV_1$ in AIS patients after accounting for thoracic kyphosis [51], although it was unclear whether participants took off the brace during spirometry. Compared to AIS patients without bracing, patients with a thoracic curve and bracing displayed significantly poorer %FVC and $\%FEV_1$ [44, 51]. However, the pulmonary function/compliance restores to previous conditions once the brace is removed [64]. Likewise, the negative association between lumbar lordosis and %FVC or $\%FEV_1$ might have disappeared if confounders were considered.

This review had some limitations. Because many included studies performed pulmonary function tests on AIS patients preoperatively, their findings may represent patients with more severe curves. Further, most included studies did not define the vertebral levels for classifying the proximal and main thoracic curves, which might introduce discrepancies in our pooled results.

Implications

Most included studies measured anteroposterior and lateral spinal features on radiographs. Future studies should adopt low-dose biplanar X-ray imaging for three-dimensional thoracic cage and spinal structure reconstruction [19], which could capture the three-dimensional impacts of spinal/thoracic deformities on patients with AIS. This allows comprehensive evaluation of the relations between spinal deformities and lung function, which may guide clinical management and research.

While patients with mild AIS may not show respiratory dysfunction at rest, they may display reduced functional capacity [65], or maximum oxygen uptake during exercise tolerance tests [50]. Spirometry may not detect subtle deterioration or dyspnea on exertion, which may indicate scoliosis-related respiratory decline. Clinicians should conduct progressive exercise tests on patients with suspected respiratory impairments to detect early respiratory dysfunction. If the curve progresses, regular progressive exercise tests are recommended [57].

Scoliosis can directly (spinal deformity) or indirectly (respiratory muscle weakness/ inefficiency) affect respiratory function. Although patients with mild-to-moderate scoliosis may not experience dramatic pulmonary impairments during daily activities, it is important to use bracing or physiotherapy scoliosis-specific exercises to prevent or delay curve progression in these patients [64]. However, bracing should be worn for at least 16 h per day to prevent curve progression [57, 66]. Therefore, aerobic training should be prescribed to patients with bracing to optimize their lung functions.

Since pulmonary deficits in AIS patients may worsen with curve progression, patients indicated for surgical correction may experience pulmonary impairment secondary to severe scoliosis [67]. While AIS patients with moderate lung volume are less likely to require postoperative ventilatory support [37], those with moderate or severe defects (< 60% of predicted VC) may indicate high-risk surgical fusion. The latter should undergo full spirometry before surgery. VC can be used as a screening indicator for all patients before spinal surgery [37] because such surgery may adversely affect pulmonary function/compliance [68].

Because there was no included prospective study, the causal relations between changes in spinal/thoracic deformity and changes in lung function remain unclear. Future prospective studies should investigate such relations after adjusting for confounders. Further, as prior research involving AIS patients aged > 18 years revealed that patients had worsening pulmonary function (e.g., FVC) as they aged [67, 69], future prospective research with long-term follow-ups should determine whether AIS patients with near-normal, mild, or moderate lung dysfunction would experience declined lung function and body's functionality in later life [70].

Conclusions

This systematic review highlights that larger proximal and main thoracic Cobb angles, smaller kyphosis angles, greater lumbar lordotic angles, a longer thoracic curve, a larger rib hump, increased apical vertebral rotation angles and smaller rib cages are associated with poorer pulmonary functions. Other factors can also affect the lung function in these patients. Nevertheless, the clinical impact of scoliosis on lung function is mainly subclinical except for those with severe structural deformity. We definitely need more research to strengthen the quality of evidence. Future prospective studies should evaluate the temporal relations between changes in spinal/thoracic parameters and changes in pulmonary function in order to inform the clinical management of AIS patients with potential respiratory decline.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interests There were no financial or competing conflicts of interest in relation to this work.

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