COVER SHEET

CT-based Volumetric Reconstruction of the Pulmonary System in Scoliosis: Trends in Lung Volume and Lung Volume Asymmetry with Spinal Curve Severity

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Scoliosis has been associated with reduced pulmonary capacity, however the source of the reduction in capacity (left, right or both lungs) is not clear. The objective of this study was to investigate trends in left, right and total lung volume and left/right lung volume asymmetry with spinal curve severity in scoliosis. Three-dimensional volumetric reconstruction of the pulmonary system was performed on existing pre-operative CT scans for 28 idiopathic scoliosis patients. Left, right and total lung volumes, and left/right lung volume ratios were calculated and correlated with the following spinal curve parameters; major Cobb angle, rib hump, number of vertebrae in the major curve, most cephalad vertebra in the major curve, and thoracic kyphosis. Left/right lung volume ratio increases significantly with increasing rib hump. Left, right and total lung volumes were significantly correlated with rib hump and number of vertebrae in the major curve ($P<0.05$), and near-significantly correlated with most cephalad vertebra in the major curve ($P<0.10$). Shorter, higher, more rotated thoracic curves therefore restrict lung volume more than longer, lower, less rotated curves. The mean lung volume ratio for scoliosis patients was lower than for age-matched controls ($P<0.10$). CT-based volumetric reconstruction of the pulmonary system in scoliosis patients shows differences in both lung volumes and lung volume ratios compared to normal controls.

Introduction

Previous studies using standardized pulmonary function testing (PFT) have shown that scoliosis patients with thoracic curves suffer from reduced respiratory capacity compared to age and height matched controls[1,2]. The reduction in pulmonary capacity has been linked to the severity of abnormal curvature, with reported correlations between pulmonary capacity and Cobb angle, vertebral rotation, number of vertebrae in the thoracic curve, cephalad location of the major curve, and thoracic hypokyphosis[3-6].

PFT can be used to estimate total lung capacity, but cannot distinguish where the reduction in capacity has occurred (left, right or both lungs). This information is of significant interest in studying the respiratory mechanics of scoliosis, since large asymmetrical thoracic deformities often accompany the spinal curvature, suggesting that the intrathoracic space may be reduced more on one side of the chest cavity than the other[1].

A method for computed tomography (CT) based volumetric reconstruction of the pulmonary system was presented by Gollogly et al in 2004[7], allowing individual determination of the left and right lung parenchyma volumes from thoracic CT scans. Gollogly et al used this method to establish baseline left, right and total lung volumes versus age and sex from CT scans of 1050 thoracically normal children aged 5-18. The children in the study had received CT scans to screen for either metastases or trauma.

The aims of the present study were; (i) to apply the CT-based lung reconstruction technique to a series of preoperative CT scans of idiopathic scoliosis patients with right thoracic curves, (ii) to compare the left and right lung volumes for these patients with age-matched normal data, and (iii) to investigate the dependence of left and right lung volumes and lung volume asymmetry on spinal curvature.

Materials and Methods

Twenty eight pre-operative CT scans which were performed on consecutive idiopathic scoliosis patients at the Mater Children's Hospital Brisbane, Australia, between November 2002 and November 2005 were retrieved from archives. A single low-dose CT scan is part of the pre-operative clinical assessment process for patients scheduled to undergo endoscopic anterior instrumented scoliosis correction, as pre-operative CT has been shown to allow safer screw sizing and positioning in endoscopic procedures[8]. Patients were selected for endoscopic anterior scoliosis correction on the basis of; (i) thoracic major curve, (ii) at least 50% curve correction on a bending film, (iii) 35° minimum Cobb angle with clear indications of continued curve progression. The scanner used was a 4-slice Toshiba Aquilion Multi (Toshiba Medical Systems Corporation, Japan) with 100kV 50mA source, 3mm raw image thickness, 6mm pitch, and 1.0sec rotation time. The resulting voxel size was $0.6\times0.6\times1.0$mm. The estimated radiation dose for paediatric patients using this protocol is 3.7mSv, with uncertainties due to the dose model in the order of ±20% (Schick D, Computed tomography radiation doses for paediatric scoliosis scans. Internal report commissioned by Paediatric Spine Research Group from Queensland Health Biomedical Technology Services, 2004).

The *Analyze* image processing software (version 5.0, Mayo Clinic, USA) was used to generate three dimensional volumetric reconstructions of the lung parenchyma with threshold limits of -992 to -198 Hounsfield Units. This density range allows segmentation of the pulmonary system (lung parenchyma, airways and airspace) from the rest of the CT dataset[7]. Figure 1 shows a typical volumetric reconstruction of the lungs and trachea. Having extracted the regions of interest, left (V_l), right (V_r) and total ($V_t=V_l+V_r$) lung volumes were calculated by counting the number of voxels within each lung.

Figure 1. Three-dimensional volumetric CT reconstruction showing lung parenchyma and trachea.

Resulting total lung volumes for the scoliosis patients in this study were graphed against the 5th, 50th and 95th percentile curves given by Gollogly et al[7] for CT-based total lung volume versus age in thoracically normal females aged 9-18. Gollogly et al's 50th percentile normal data was also used as a reference to calculate percent predicted left ($V_l^{\%}$), right ($V_r^{\%}$), and total ($V_t^{\%}$) CT-based lung volumes for each patient in the study.

The Lung Volume Ratio (LVR) is defined as V_l/V_r, so that LVR=1.0 if left and right lung volumes are equal (no asymmetry), and in the usual case where the left lung volume is less than the right lung volume, 0<LVR<1.0. For example, if V_l=1.0 litres and V_r=1.2 litres, then LVR=0.83, indicating that the left lung is 17% smaller than the right lung.

Multi-linear regression analysis was performed for LVR, V_l, V_r, V_t $V_l^{\%}$, $V_r^{\%}$, and $V_t^{\%}$ against major Cobb angle (from coronal radiographs), rib hump (scoliometer measurement), number of vertebrae in the major curve, most cephalad vertebra in the major curve, and thoracic kyphosis (T5-T12) in an attempt to identify any correlation between thoracic curve parameters and lung volumes. All of the aforementioned parameters had previously been measured for each patient as part of their usual preoperative clinical assessment. Twelve of the patients in the group also received standardised PFT as part of a separate study[9], allowing comparison between CT and PFT-based total lung volumes.

Results

The cohort comprised 27 females and one male with idiopathic scoliosis. Mean age was 15.0 (±3.6) years. Of the total group, 26 were classified as Lenke class 1, one as Lenke class 2, and one as Lenke class 3. All curves were right thoracic.

Table 1 gives the age, gender, curve type and severity, CT reconstructed lung volumes and percent predicted lung volumes for each patient in the study. Percent predicted values were not calculated for the male, or the three females older than 18 due to the age and gender limits of the control data. Figure 2 shows CT-based total lung volume versus age (over the range 9-18 years) for each case, compared with the 5th, 50th, and 95th percentile data of Gollogly et al[7] for normal females. Sixteen of the 24 female patients (67%) in the 9-18 year age range had total lung volumes below the 50th percentile of the controls.

Figure 3 shows a comparison of CT-based total lung volume versus PFT-based total lung volume for the subset of twelve patients who also underwent pulmonary function testing. The two assessment methods were significantly correlated (R=0.74, P=0.015).

Several of the factors investigated in the multi-linear regression analysis were statistically significant: Rib hump was correlated with V_l (P=0.040), V_r (P=0.007), V_t (P=0.014), LVR (P=0.038), and V_r% (P=0.045). The number of vertebrae in the major curve was significantly correlated with V_l (P=0.005), V_r (P=0.005), V_t (P=0.005), V_l% (P=0.040), V_r% (P=0.032), and V_t% (P=0.034). The most cephalad vertebrae of the major curve was near-significantly correlated with V_l (P=0.058), V_r (P=0.054) and V_t (P=0.053). Table 2 gives the regression equations for each of these statistically significant and near-significant correlations.

The difference between lung volume ratio for scoliosis patients (mean LVR=0.832) and age-matched controls (LVR=0.853) was near-significant at the 10% level (*P*=0.097, paired t-test, the male scoliosis patient was not included since the 50th percentile control data was for females). The coefficient of variation (COV) for LVR in the group was 9.7%, compared to COV=29.5%, 29.9% and 29.4% for V_l, V_r, and V_t respectively.

Table 1. Demographics, curve type & severity, and lung volumes determined by 3D volumetric CT reconstruction for 28 scoliosis patients

Patient	Age	Gender	Curve type	Major Cobb	Rib hump	No of levels	Most cephalad	T5-T12 kyphosis	V_l (l)	V_r (l)	V_t (l)	LVR	V_l%	V_r%	V_t%
1	13.3	F	idio	58°	15°	7	T6	10°	1.64	1.98	3.62	0.83	146	149	147
2	27.8	F	idio	45°	10°	7	T6	26°	1.23	1.67	2.90	0.73	-	-	-
3	13.1	F	idio	60°	20°	8	T5	10°	0.99	1.22	2.21	0.81	89	92	91
4	14.7	F	idio	52°	15°	8	T5	23°	1.45	1.71	3.16	0.85	120	119	119
5	12.7	F	idio	47°	20°	9	T4	15°	1.34	1.51	2.85	0.88	123	118	120
6	16.5	F	idio	51°	18°	8	T5	46°	1.20	1.52	2.72	0.79	91	99	95
7	13.6	F	idio	50°	12°	9	T4	10°	1.22	1.55	2.77	0.79	107	114	111
8	13.3	F	idio	52°	18°	7	T5	19°	1.23	1.53	2.76	0.80	109	114	112
9	15.4	F	idio	44°	15°	8	T5	22°	1.02	1.29	2.31	0.79	81	87	84
10	14.2	F	idio	42°	12°	8	T5	19°	1.88	2.14	4.02	0.88	159	153	156
11	15.5	F	idio	48°	17°	7	T5	16°	0.82	1.05	1.87	0.78	65	71	68
12	11.2	F	idio	35°	15°	6	T6	26°	0.94	1.14	2.08	0.83	95	99	97
13	13.2	F	idio	48°	15°	7	T6	18°	1.63	2.06	3.69	0.79	146	155	151
14	14.6	F	idio	42°	15°	6	T5	23°	0.75	0.92	1.67	0.82	62	64	63
15	14.4	F	idio	58°	15°	7	T5	19°	0.67	1.12	1.79	0.60	56	79	69
16	13.6	F	idio	52°	18°	7	T6	25°	0.93	0.92	1.85	1.01	82	68	74
17	18.2	F	idio	56°	13°	8	T5	18°	1.30	1.64	2.94	0.79	95	104	100
18	22.4	F	idio	52°	14°	7	T6	27°	0.96	1.15	2.11	0.84	-	-	-
19	16.2	F	idio	42°	14°	6	T5	9°	0.92	0.98	1.90	0.93	70	65	67
20	13.3	F	idio	58°	17°	7	T5	23°	0.78	0.86	1.64	0.91	69	64	66
21	14.1	M	idio	56°	15°	7	T5	1°	1.06	1.31	2.37	0.81	-	-	-
22	13.6	F	idio	40°	10°	6	T4	14°	0.94	1.06	2.00	0.88	82	78	80
23	21.2	F	idio	51°	24°	9	T6	46°	1.07	1.06	2.13	1.01	-	-	-
24	14.5	F	idio	60°	16°	8	T5	11°	0.82	1.04	1.86	0.78	68	73	71
25	16.5	F	idio	52°	12°	7	T6	21°	1.14	1.42	2.56	0.81	86	93	90
26	9.9	F	idio	58°	16°	7	T5	48°	0.72	0.84	1.56	0.86	81	83	82
27	12.1	F	idio	59°	18°	8	T5	16°	0.64	0.84	1.48	0.76	61	68	65
28	12.2	F	idio	64°	23°	9	T5	7°	0.67	0.75	1.42	0.88	63	61	62
Mean	**15.0**	-	-	**51.2**	**15.8**	**7.4**	**5.2**	**20.3**	**1.07**	**1.30**	**2.37**	**0.83**	**0.92**	**0.95**	**0.93**
SD	**3.6**	-	-	**7.2**	**3.4**	**0.9**	**0.6**	**11.3**	**0.32**	**0.39**	**0.70**	**0.08**	**0.29**	**0.29**	**0.29**

Table 2. Linear regression equations for each of the statistically significant and near-significant regressions (*P<0.05, **P<0.10)

Regression	Equation
Left lung volume (V_l) versus rib hump (RH)	V_l=-0.0268(RH)+1.4934*
Left lung volume (V_l) versus number of levels (NL)	V_l=0.0658(NL)+0.5815*
Left lung volume (V_l) versus most cephalad vertebra (MCV)	V_l=0.0699(MCV)+0.7086**
Percent predicted left lung volume (Vl%) versus number of levels (NL)	V_l%=0.0482(NL)+0.5476*
Right lung volume (V_r) versus rib hump (RH)	V_r=-0.0443(RH)+1.9954*
Right lung volume (V_r) versus number of levels (NL)	V_r=0.0665(NL)+0.8023*
Right lung volume (V_r) versus most cephalad vertebra (MCV)	V_r=0.0785(MCV)+0.8898**
Percent predicted right lung volume (V_r%) versus rib hump (RH)	V_r%=-0.0255(RH)+1.3348*
Percent predicted right lung volume (V_r%) versus number of levels (NL)	V_r%=0.0401(NL)+0.635*
Total lung volume (V_t) versus rib hump (RH)	V_t=-0.0711(RH)+3.4888*
Total lung volume (V_t) versus number of levels (NL)	V_t=0.1323(NL)+1.3838*
Total lung volume (V_t) versus most cephalad vertebra (MCV)	V_t=0.1484(MCV)+1.5984**
Percent predicted total lung volume (V_t%) versus number of levels (NL)	V_t%=0.0439(NL)+0.5943*
Lung volume ratio (LVR) versus rib hump (RH)	LVR=0.0086(RH)+0.6944*

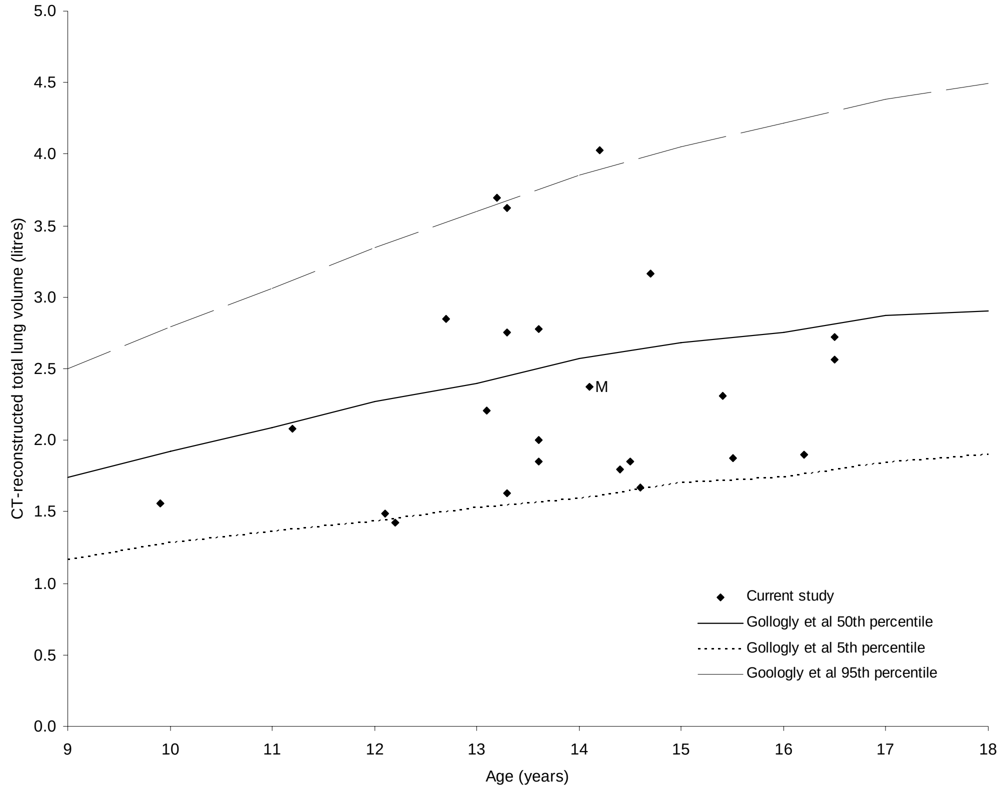

Figure 2. Total lung volume versus age for each case, compared with the 5th, 50th, and 95th percentile data of Gollogly et al (2004) for thoracically normal females. The male in the study is marked with an 'M'.

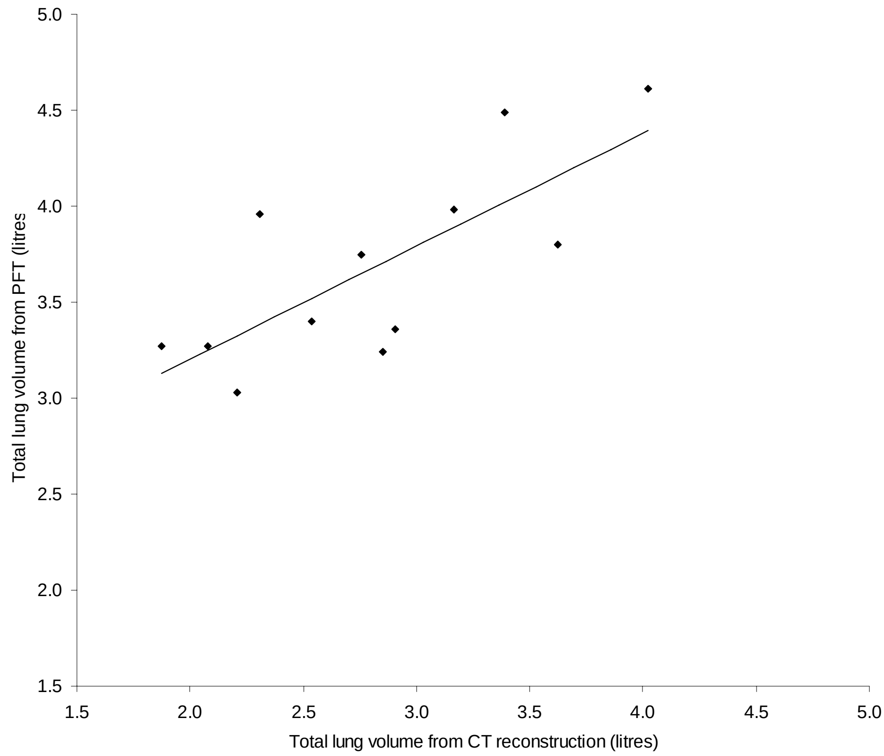

Figure 3. Comparison of total lung volumes determined from pulmonary function testing (PFT) versus CT-reconstruction

Discussion

CT examinations are not routinely performed for scoliosis assessment, and therefore the numbers of patients in this study were limited. Despite the constraints on group size however, the results demonstrate some interesting effects of spinal deformity on pulmonary capacity. CT-based total lung volumes were significantly correlated with PFT lung volumes, and showed the same reduction in pulmonary capacity for scoliosis patients compared to age-matched controls as is commonly reported using PFTs. When comparing individual lung volumes to the control data however, percent predicted values for left lung volume in scoliosis patients (mean 90.5%) were lower than percent predicted values for right lung volume (93.3%), implying that both lung volumes have decreased in the presence of the spinal deformity, but the left lung volume has decreased more. Since the left lung is normally smaller than the right lung, the additional reduction in left lung volume leads to greater lung volume asymmetry in scoliosis patients compared to normal subjects. Furthermore, while the left, right and total lung volumes determined using CT reconstruction exhibited quite wide variation from patient to patient, (COV~30% for the group), the left/right lung volume ratio was much less variable, with a coefficient of variation of less than 10% across the entire group of scoliosis patients.

On the basis of the study data in Table 1, we speculate that while increasing Cobb angle leads to similar decreases in both left and right lung volume due to the collapse in height of the spine, axial rotation impinges primarily on the right lung (for a right thoracic curve), with the result that increasing rib hump decreases lung capacity but increases left/right volume ratio. The protrusion of a rotated vertebral column into the right thoracic cavity is clearly shown in Figure 4.

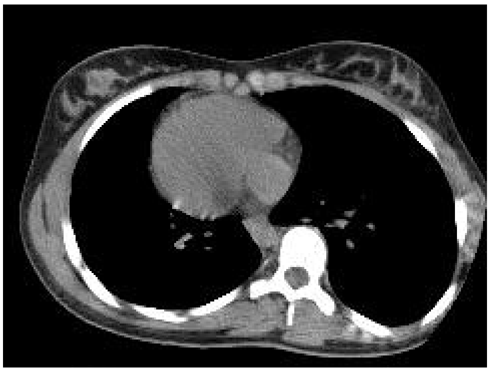

Figure 4. Axial CT slice showing protrusion of a rotated vertebral column into the right thoracic cavity

Regression analysis was performed to look for spinal deformity parameters which were predictive of lung volume or lung volume asymmetry. Rib hump was significantly correlated with actual lung volumes and lung volume asymmetry, while the number of vertebrae in the major curve was significantly correlated with all actual and percent predicted lung volumes, but not with lung volume asymmetry. The most cephalad vertebrae of the major curve was near-significantly correlated with lung volumes, and we suggest that the statistical significance of this result was limited by the size of the patient group. This finding implies that short, high, rotated curves restrict lung volume more than longer, lower, less rotated curves. From the regression equations in Table 2, a decrease in the number of vertebral levels from 9 to 6 reduces lung volume by 15%, while a high (T4) most cephalad vertebra corresponds to 12% less lung volume than a T6 most cephalad vertebra. The biggest effect however is due to rotation, with an increase in rib hump from 10° to 20° reducing total lung volume by 26%. No statistically significant correlation was found between T5-T12 kyphosis and lung volumes, although the use of T5-T12 rather than T1-T12 kyphosis (for reasons of radiograph clarity in the upper thoracic region) may have decreased the sensitivity of this measure.

The CT scans used in the study were not performed under breath-hold conditions, and the volumes obtained therefore represent a temporal averaging of the pulmonary system during several minutes of shallow breathing at rest in a supine position. The CT scans used by Gollogly et al. were performed under the same conditions, so we believe that a comparison between Gollogly's data for thoracically normal patients and our group is valid. Indeed the comparison of Figure 3 showed good correlation between CT-reconstructed total lung volumes and PFT total lung volumes considering the differences between techniques.

Previous studies using PFT have found that spinal curve parameters only account for a relatively small proportion of the inter-patient variations in pulmonary function in scoliosis[3,6], and the same appears to apply in this study. However, while pulmonary capacity varies widely between individuals, the presence of a spinal deformity has a noticeable detrimental effect on both lung volumes and left/right lung volume asymmetry.

There were several notable cases in the current patient group: patients 16 and 23 both had lung volume ratios greater than 1.0 (left lung larger than right lung). Patient 16 was a 14 year old female with 'typical' curve parameters (Lenke 1, 52° major Cobb, 18° rib hump, 25° T5-T12 kyphosis), however her percent predicted right lung volume of 68% was much smaller than expected, given that the percent predicted left lung volume was 82%. Patient 23 was a 21 year old female with a large (46°) T5-T12 thoracic kyphosis who had been braced for three years prior to the CT examination. Due to her age, percent predicted values were not calculated for this patient as Gollogly et al's control data only spanned the age range 9-18 years. The greatest lung volume asymmetry occurred in patient 15, with a LVR of only 0.60. This patient was a 14 year old intellectually disabled female with a 58 degree Lenke 3 thoracic major curve, and a 44 degree lumbar curve. This was the only Lenke 3 curve in the group, and serves to demonstrate that the findings of this study pertain primarily to Lenke 1 curves, since these curves comprised 26 of the 28 cases.

We do not propose routine use of CT scans for lung volume measurements due to the increased radiation dose associated with these scans. However in this study, the pulmonary reconstructions used an existing series of scans to provide additional insights into how the reduction in pulmonary capacity occurs in scoliosis. For infantile, juvenile, or intellectually impaired spinal deformity patients who cannot comply with PFT protocols, CT-based lung volume measurements may be an attractive alternative[10], particularly in severe spinal deformity cases where respiratory function compromise is a potential cause of mortality. In many such cases a CT scan is already performed for surgical planning purposes[11].

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