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Spinal penetration index: new three-dimensional quantified reference for lordoscoliosis and other spinal deformities

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Abstract We studied and conceptually analyzed a retrospective case series of patients with airway compression due to an anterior vertebral body protrusion. The goal was to describe the pathology, methods of management, and a new concept for quantifying deformity. Case reports have been published on this pathology, but there has been no case series to date. In this study 18 patients with ages ranging from 7.3 to 18.0 years had thoracic lordoscoliosis due to a variety of etiologies; most (n = 10) had a neuromuscular disorder. Following treatment, which most commonly was anterior subtotal subperiosteal vertebral body resection followed by posterior instrumentation and arthrodesis, atelectasia disappeared and any abnormal blood gases normalized; however, the effect on vital capacity was variable. Based on computed tomographic studies, the concept of the deformity as an endothoracic vertebral hump was developed and quantified. Study of this series of patients with compression of the airway due to vertebral body protrusion into the thorax provided the opportunity to describe treatment, define a new concept (the spinal penetration index), and make general recommendations about the management of both the endothoracic hump and the exothoracic rib hump.

Key words Thoracic cage · Three-dimensional · Airway compression

Introduction

During the past 15 years we have had the opportunity to observe 18 cases of compression of the airway by vertebral bodies resulting from thoracic spinal deformities. This is apparently the result of vertebral body protrusion inside the thorax and is associated mostly with lordoscoliosis. Although this condition has been reported sporadically in the past (usually as case reports),[3,8,11,12,15,16] it has not been subjected to systematic study.

The deformity, vertebral body protrusion, is a manifestation of the three-dimensional deformities of scoliosis and cannot be understood in terms of the most common used measure of the scoliosis deformity: the so-called gold standard Cobb angle, a one-planar two-dimensional measurement. This experience prompted us to conceive and develop a measurement which we have named *the spinal penetration index*, of vertebral body protrusion to compare the normal thorax with various scoliosis deformities and the results of their treatment.

The purposes of this paper are therefore to analyze the pathology of the 18 compressed airways and the results of surgically decompressing them. We also describe the conflict with measuring the spinal penetration index and explore the various possible causes of a hump in the scoliotic spine.

Material and methods

During the last 15 years we observed 18 patients (10 girls, 8 boys) (Table 1) between 7 and 20 years of age in whom anterior protrusion of the vertebral column at the level of the thoracic area resulted in airway compression leading to either intermittent or permanent atelectasis. The most common underlying disease was neuromuscular etiology (8 cases). The remainder represented a wide range of scoliosis etiologies, with idiopathic scoliosis being uncommon.

All patients presented with recurrent pneumonia and lung infection. Their vital capacity was poor, being less than 30% in seven patients, four of whom had a permanent tracheotomy and five had hypoxia and

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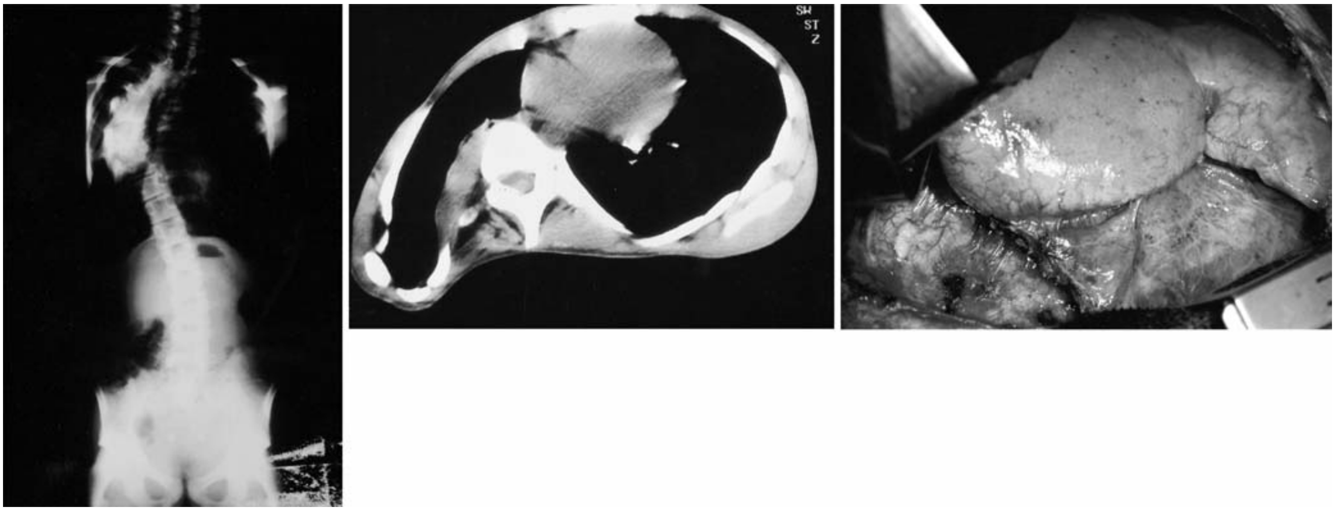
Table 1. Patients with documented compression of the operated airway

Case	Gender	Age at surgery (years)	Etiology	Preoperative data			Surgery		Last follow-up results			Follow-up (years)
				Coronal Cobb	Sagittal Cobb	VC (%)	Vertebral anterior and posterior	Lobectomy	Coronal Cobb	Sagittal Cobb	VC	
1	F	14.5	DMC	80°	−15°	22	Ant T5L3; post CD T2-sacrum	—	40°	5°	9	9.25
2	F	14.6	Escobar	68°	−20°	39	Ant T4T8; post CD T2L2	Inf R	60°	5°	38	4.80
3	M	14.5	Centcore	35°	−10°	19	Ant T4T8; post CD T2L1	M + inf R	30°	5°	21	15.20
4	M	20.0	Idiop.	30°	−25°	55	Ant T4T7; post CD T1L1	—	17°	13°	57	6.50
5	F	12.2	Cong	45°	−20°	46	Scheduled					
6	F	12.1	Escobar	16°	−25°	40	Early epiphysiodesis T5T12	—	25°	−18°	43	9.90
7	M	16.0	Cong	80°	−20°	24	Ant T4T9; post CD T1L12		60°	−5°	37	1.50
8	M	14.7	Radioth	29°	−23°	50	Ant T5T10; post T1L1	—	5°	−6°	61	4.33
9	M	7.3	DMC	35°	−25°	40	Early epiphysiodesis T4T8	—	35°	−30°	15	5.00
10	M	19.3	Muco	10°	−30°	30	Ant C5T5; post C3L10	—	10°	−30°	40	2.50
11	M	13.3	Arthrog	45°	−15°	45	Died in prone position before surgery					
12	F	12.9	DMC	60°	−5°	25	Ant T5T10; post CD T1L4	—	30°	20°	25	3.85
13	F	12.8	Neurobl	67°	−10°	44	Ant T6T11; post CD T2L4	—	52°	26°	46	4.47
14	F	14.3	Idiop.	57°	−10°	68	Ant T6T10; post CD T5L4	—	20°	17°	75	3.80
15	F	9.0	Escobar	90°	−30°	22	Ant T6T3; post SQR T1L2	—	30°	10°	20	11.30
16	F	10.4	Marfan	95°	−20°	30	Ant T4T12; post CD T2L4	—	30°	0°	26	4.20
17	F	12.9	SMA	60°	−10°	18	Ant T4T10; post CD T2-sacrum		50	10°	22,5	9.10
18	M	7.6	NF1	55°	−5°	45	Ant T6T11; post SQR T4L2	—	40	10°	50	2.00

DMC, congenital muscular dystrophy; Escobar, Escobar syndrome; Centcore, central core disease; Idiop., idiopathic scoliosis; Cong, congenital scoliosis; Radioth, postradiation therapy; Muco, mucopolysaccharidosis; Arthrog, arthrogryposis; Marfan, Marfan syndrome; SMA, spinal muscular atrophy; NF1, neurofibromatosis; Neurobl, neuroblastoma; SQR, subcutaneous rod; CD, CD instrumentation; VC, vital capacity; Ant, anterior; post, posterior



A B,C

Fig. 1. Case 7. **A** Standing posteroanterior (PA) radiograph of a 16 year 1 month male patient with congenital scoliosis treated at 6 years 2 months with posterior convex fusion. **B** Computed tomography (CT) scan shows penetration of the vertebral bodies inside the chest resulting in airway compression and subsequent atelectasis of the convex lung. **C** At surgery, atelectasis of the lower right lobe is evident

hypercapnia. Four patients experienced hemodynamic failure when placed in the prone position. Of the 18 patients, 1 had been operated on previously and had undergone placement of a subcutaneous rod during early infancy for arthrogryposis; only one had elongation of the rod prior to the development of airway compression.

All patients were evaluated by thoracic and lung computed tomography (CT) scans (Fig. 1), and three-dimensional reconstruction of the lung and spine was done in some. The angulation of the scoliosis varied from a 10° to 100° Cobb angle in the coronal plane and from a −5° to −45° Cobb angle in the sagittal plane. Thus, all patients were hypokyphotic. There was no correlation between the Cobb angle and the vital capacity in the coronal plane or the sagittal plane (Fig. 2). This probably is due to the large number of neuromuscular cases ($n = 10$) and congenital bone anomalies.

Atelectasis existed and was documented by CT scan in 15 cases (Fig. 1), always in the convex lung. The right inferior lobe was involved in 12 of these cases, and in 3 cases the inferior lobe was partially involved. The location of the compression was at the right main stem bronchi in 10 patients and was intermediate and posterior in 2. In two cases the compression was at the level of the trachea itself, and in one case a trapping phenomenon had occurred. For the last three cases, atelectasis was not documented by CT scan with a protrusion and it could not be determined if the atelectasis was intermittent (cases 5, 6, 9) or permanent. Extrinsic airway compression was confirmed in each case by fiberoptic bronchoscopy.

Of the 18 patients, 16 underwent surgery. In 14 of them, the first stage consisted of a subperiosteally anterior resection of one-half to two-thirds of the vertebral bodies (Fig. 3) at four or five apical levels, including adjacent disc space removal and subsequent anterior fusion. The continuous periosteal flap was then reattached with the cancellous bone, thereby creating a new shape with a decreased anterior profile of the vertebral bodies. The effect could be seen with repermeation of the airway and reventilation of the lung when it was repositioned. In 2 of the 16 patients a lobectomy for lung abscess was carried out during the same procedure. Posterior Cotrel Dubousset (Sofamor Danek, Memphis, TN, USA) kyphosing instrumentation and arthrodesis were performed in 12 of the patients. In two patients posterior instrumentation was realized with a subcutaneous rod.

Two patients (cases 6, 9) had a different scenario, as they presented with intermittent compression. They underwent only anterior hemiepiphysiodesis without resection of the vertebral body. One patient (case 11), the one previously operated on with a subcutaneous rod during infancy, died from hemodynamic failure as a result of prone positioning to remove the posterior spinal implants prior to surgery proposed for decompressing the airway. Postoperatively, all patients underwent CT thoracic and lung scanning.

Results

Coronal and sagittal plane Cobb measurements and vital capacity values at the most recent follow-up are

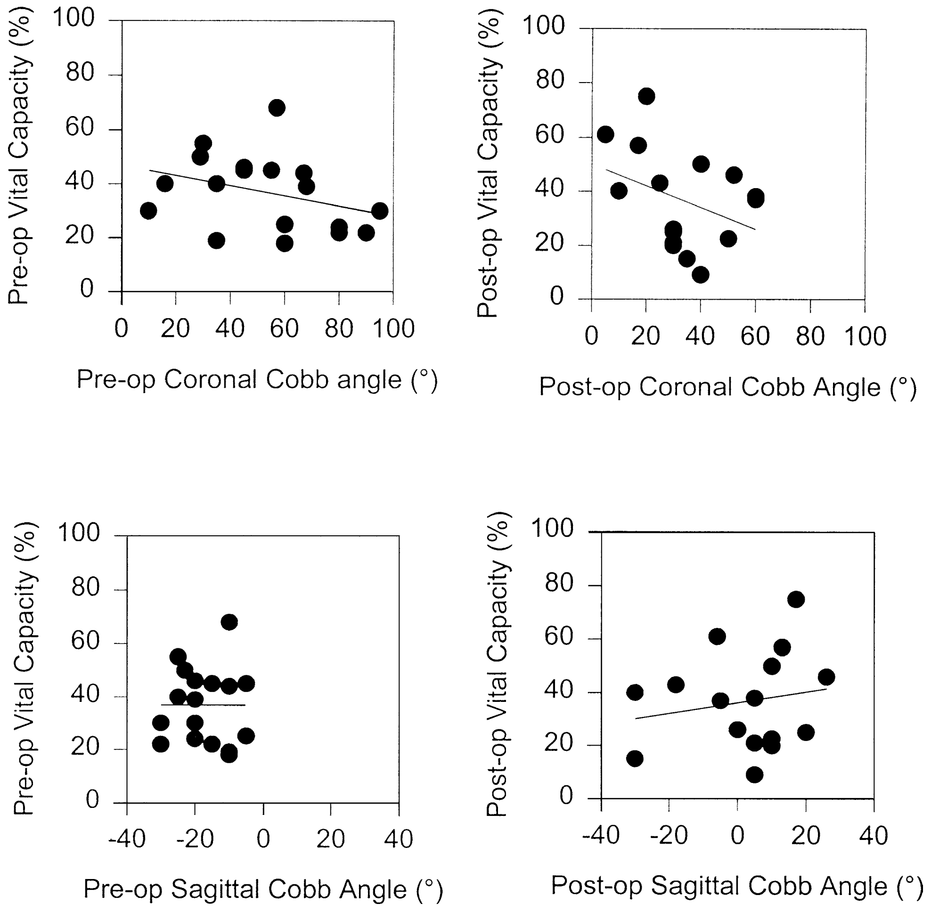


Fig. 2. Correlation between vital capacity and coronal and sagittal Cobb angles pre- and postoperatively

shown in Table 1. The follow-up varies from 1.5 to 15.2 years (mean 6.1 years).

An unobstructed airway with disappearance of atelectasis and normalization of the five abnormal patient's blood gases was achieved in all operated cases but could not be related to the decompression alone because intensive or chronic (sometimes concomitant) tracheostomies were done at the same time.

Episodes of pneumonia also disappeared in all of the 16 successfully operated patients. Postoperative CT scans demonstrated decompression of the airway in all patients. An increase in the anteroposterior (AP) diameter of the thorax was apparent for both the instrumented and noninstrumented spine. The mean coronal Cobb angle improved form 61° to 38° for the entire series, and the lordosis (hypokyphosis) improved from an average of −18° preoperatively to 0° postoperatively. It was better for those with instrumentation and a subcutaneous rod than for those with anterior epiphysiodesis alone.

It is remarkable that the vital capacity was improved in only six cases; it remained the same in seven and worsened slightly in two. Two patients still require a permanent tracheostomy. No pseudarthrosis was observed or suspected radiologically.

Two patients treated prophylactically, without anterior decompression but with anterior epiphysiodesis did not develop progressive lordosis (hypokyphosis) or airway compression, but her vital capacity did not improve, remaining at about 45%. The second had a decrease in vital capacity from 40 to 15%. This may be explained also by the etiology of her problem (congenital myopathy) for one and Escobar syndrome for the other.

Discussion

Although compression of the airway by vertebral body protrusion has been recognized, reported, and documented in case reports, our study is by far the largest series reported to date.[3,8,11,12,15,16] Anterior vertebral resection has been reported in the past, and others have also noted minimal if any improvement in the postoperative vital capacity.[16,17]

Although our patients experienced disappearance of atelectasis, normalization of blood gases, and disappearance of episodes of pneumonia in all cases, other reports have noted collapse of the bronchi.[11,15,16] This may be explained by bronchomalacia secondary to

A,B  C

Fig. 3. Case 14. **A** Principle of anterior resection of the vertebral bodies to free the airway. CT scans before (**B**) and after (**C**) anterior resection and posterior instrumentation

vascularization of the bronchial cartilage due to long-term compression.

It is clear that some patients have permanent, established atelectasis or even lung abscesses; in contrast, others have intermittent atelectasis, which may be more frequent than has been recognized. This could explain seasonally frequent respiratory problems of patients with lordoscoliosis in the thoracic area because of subsequent hypoventilation and hypovascularization of parts of the lungs.

That scoliosis is frequently associated with a lordotic phenomenon between two adjacent vertebrae within the apical area of torsion has been well documented in the past by Adams[1] and more recently by Roaf,[10] Somerville,[13] Dickson et al.,[4] Perdriolle,[9] and Graf et al.[7] Although the phenomenon of apical lordosis is constant, its expression is variable. In some cases torsion results in a large horizontal displacement with the global appearance of kyphosis (when horizontal rotation is more than 90°). However, this is a paradoxical kyphosis, as it has been well observed that the length of the spine measured at the level of the vertebral bodies is longer than the one measured at the level of the posterior arches, thus demonstrating lordosis.[4,7,9,10,13]

Such observations led Geyer, a French physiotherapist who stressed the importance of the AP diameter of the thorax, to the recognition of three types of thorax in the presence of scoliosis.[6] With the AP type the spine is pushed backward and the sternum foreward, regardless of the axial rotation, thus maintaining the volume and vital capacity, with little disturbance. With the transversal/lordotic-type, global lordosis is predominant, resulting in a substantial decrease in the thoracic AP diameter and impaired rib dynamics, resulting in greater disturbance of respiratory function. The intermediate type is a mixture of the first two with moderate consequences. Our experience with the case series presented and the observations of other[2] has caused us to develop and define a new concept: the spinal penetration index (SPI) (Fig. 4).

There are two SPIs: The spinal penetration index surface (SPIS) is a two-dimensional measurement; and the other, the spinal penetration index volume (SPIV) is a three-dimensional measurement. Both measure the penetration of the spine and accompanying elements inside the rib cage.

The spinal penetration indices are measured by CT at rest. First a tangent is drawn to the most posterior rib prominence on both the right and left sides at the inner side of the prominence, and then a direct tangential line is drawn from the inner surface of the thoracic area at the level of the cut going from one side to the other. We then measure the surface occupied from this tangential line by the vertebral and sometimes empty space, such as would occur with a large lordosis. The SPIS is calculated by dividing the area occupied by the vertebra and empty space by the thoracic area ×100; it is expressed as a percent (Fig. 4B). For the SPIV, each successive centimeter CT cut of the entire thorax is measured; the calculation is done by adding the volume calculated for each slice according to the thickness of the entire thoracic cage from top to bottom. Only the first slice at the top and last slice at the bottom are calculated with their half-thickness.

The computer program for these methods is available from one of the authors (V.P.). In the near future it is anticipated that the same reliable information can be obtained from a low-radiation (10 times less radiation than one exposure) stereo radiograph of the spine and thorax.

Application to various case presentations

Normal thorax

To determine the SPIS and SPIV in persons without a spinal deformity, we analyzed CT scans from a metastatic survey obtained from patients who had tumors on their limbs. The SPIV were consistently

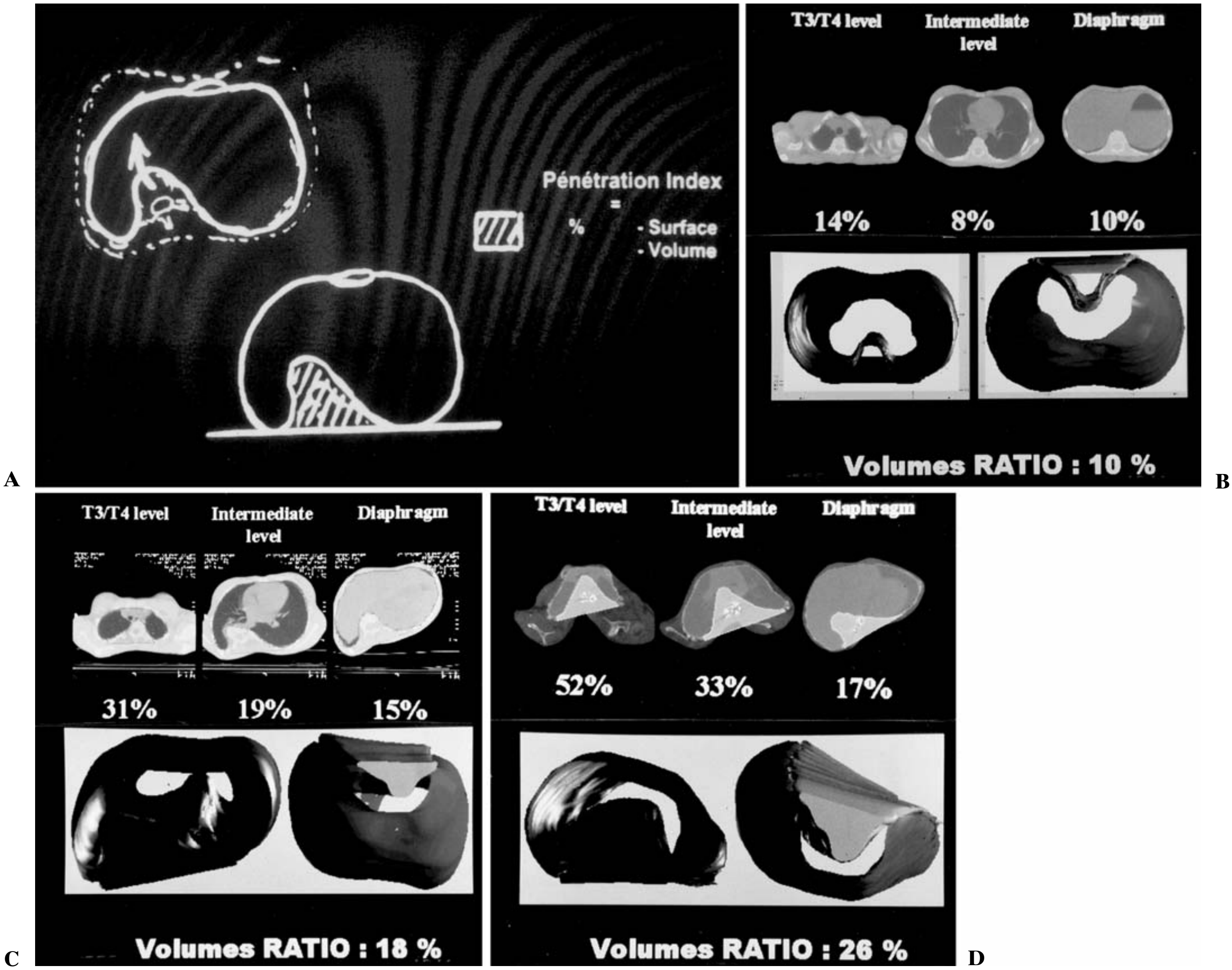


Fig. 4. A spinal penetration index (SPI) quantifies the penetration of the vertebral bodies and surrounding structures related to the theoretical thoracic room calculated from a tangent to the right and left posterior ribs. **B** Spinal penetration index surface (SPIS), a two-dimensional measurement, is shown for a nonscoliotic patient measured at the 14%, 8%, and 10% levels. Also shown is the spinal penetration index volume (SPIV), a three-dimensional measurement, for a nonscoliotic patient measured at 10%. **C** Girl of 13 years 6 months with idiopathic scoliosis. She had a right thoracic curve of a 110° Cobb angle and a thoracic kyphosis of 49° Cobb. The patient's SPIS face at several levels varied from 31% to 15%, and the SPIV was measured at 18%. No compression of the airway was documented. **D** Boy of 14 years 3 months with dystrophic and congenital myopathy and a right thoracolumbar scoliosis with a 70° Cobb angle and thoracolumbar kyphosis with a 28° Cobb angle. The SPIS shows penetration up to 52%. The SPIV is 26%. Surgery was discussed

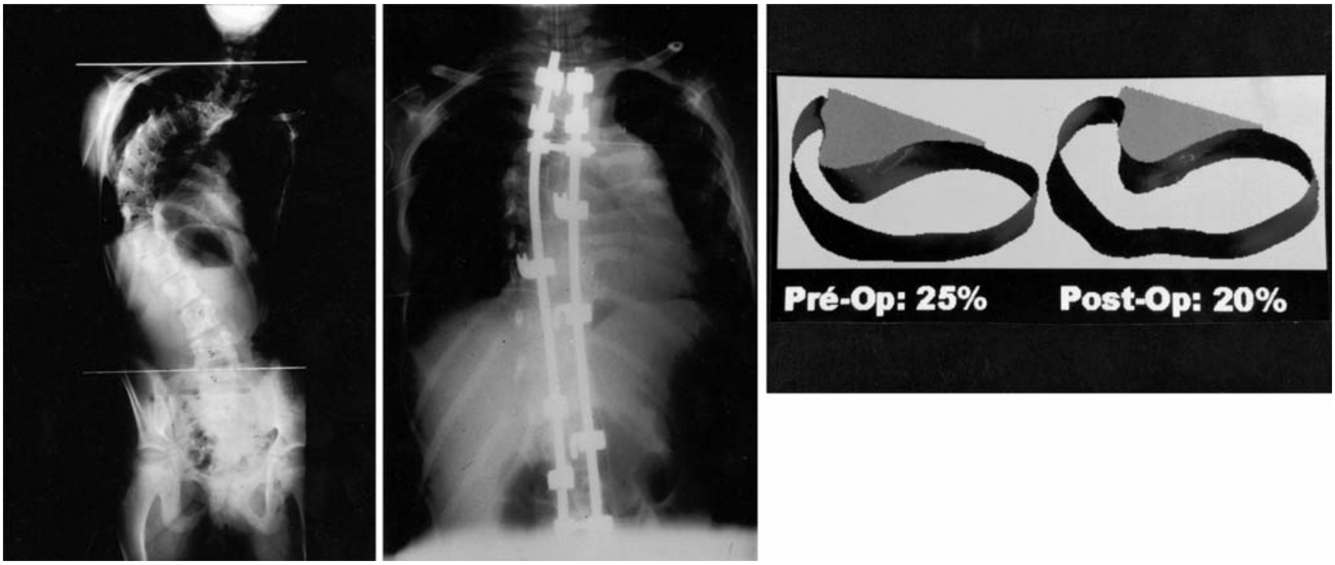
between 7% and 10% for the six patients studied, who were 13–15 years old.

Scoliotic deformities

For patients with thoracic scoliosis the SPIS may reach 15%–20% (Fig. 4C). In patients with severe lordoscoliosis the SPIS may reach 50% or more and the SPIV 25% or more (Fig. 4D).

Preoperative and postoperative changes

The SPIS and SPIV are also to measure the change between the preoperative and postoperative status. It is clear that despite an apparently good correction (68%) (Fig. 5) seen on radiographs, the reality of the three-dimensional situation seen with the SPIV is less evident. It seems more reliable than using the Cobb angle alone.



A,B C

Fig. 5. **A** Girl of 11 years with Marfan scoliosis. She had a right thoracic curve of 95° Cobb and airway obstruction. **B** After anterior decompression of the airway, thoracoplasty, and posterior CD instrumentation and arthrodesis the Cobb measurement was improved to 30°. **C** The spinal penetration index volume (SPIV) changed only from 25% preoperatively to 20% postoperatively

Thoracic volume

The exact useful thoracic volume, defined as the volume remaining after removal of the SPIV, can be measured at rest and at maximum inspiration. Because of x-ray dosage concerns, such repetitive measurements must await the availability of low-dose stereoradiography with a 1-s shot duration technique. Perhaps these techniques will provide a better, more reliable, and certainly complementary measurement than the Cobb angle.

The spinal penetration index and volume can be measured independently for one or the other side of the thoracic cavity. It is a morphological index measuring, at rest (and soon at maximum inspiration), the basic bony thoracic cage volume relative to the viscera (lungs and cardiovascular, thymic, and digestive structures). Only the position of the diaphragm and contraction or relaxation of intercostal muscles can change this volume. It must be distinguished clearly from the vital capacity, which measures not only this volume but also the related function of muscles of the thoracic structure (including the diaphragm) as well as the rigidity or stiffness of the ribs, joints, and so on.

We also believe it is necessary to check precisely the thoracic growth by three-dimensional reconstruction of the spine with the SPI in patients with a thorax "at risk" (transversal/lordotic) and to proceed to anterior early epiphysiodesis prior to airway elongation, hoping to prevent compression and future bronchomalacia.

Classification of humps

The SPI concept leads to the realization that there are two humps associated with thoracic scoliosis: the visible or cosmetic rib hump and the hidden or functional vertebral hump. These observations have important therapeutic implications. So far we have been describing the hidden or functional vertebral hump and its measurement using SPIS and SPIV techniques. This hidden or functional vertebral hump is an endothoracic vertebral hump (Figs. 1, 4).

The visible or cosmetic rib hump is the result of displacement of the rib space and the spine being influenced by a torsional phenomenon. It involves both the convexity and the concavity of the curve, the bony structures of the rib cage (ribs, spine, sternum) with a particular emphasis on the costal transverse and costovertebral joints (Fig. 6).

Analysis of the three-dimensional (3D) aspect of the rib hump relative to the spine can be done with radiographs (including tangential radiographs), and a surface topography 3D technique including a 3D computerized reconstruction model, with or without finite elements. In addition, this visible or cosmetic rib hump could be quantified with the same techniques used to quantify the hidden or functional vertebral hump, (i.e., SPIS and SPIV). The technique would involve determining the volume that is in excess of the convex side of the curve (exothoracic rib hump) and the volume deficit on the concave side of the curve (exothoracic "missing hump"). The values would be determined by comparing it to an ideal normal transverse plane contour (Fig. 6).

In unusual circumstances, in conjunction with extreme horizontal torsion and lateralization of the spine, occurring generally within a thorax mostly developed in the AP direction and little in the transverse plane, there is an exothoracic vertebral hump (Fig. 7). Here the extreme torsion of the vertebral body has placed it against the thoracic cage at the level of the apical rib laterally as far as it can go, in some cases creating scars on the rib because the parietal pleural is being squeezed between the vertebral body and rib. This is, in effect, expulsion of the vertebral body from the thoracic functional area — hence the term exothoracic vertebral hump.

These observations about the visible or cosmetic rib hump and the hidden or functional vertebral hump have practical consequences regarding their treatment. For a moderate exothoracic convex rib hump, as is usually seen in classical adolescent idiopathic scoliosis with a 10°–12° smooth slope on an inclinometer, we propose no specific treatment for the hump but treatment of the spine only, from either the back or the front. Correction of the spine torsion can improve the cosmetic aspect generally by 50% or more.

For larger exothoracic convex rib humps (Fig. 4C) and a substantial exothoracic missing concave valley (e.g., with an inclinometer slope of 15°–20°), we recommend classical thoracoplasty in addition to spinal instrumentation and arthrodesis via a posterior approach. This convex thoracoplasty can also be done with an anterior approach when anterior release is indicated to prevent the crankshaft phenomenon or to give more mobility for posterior correction by either thoracotomy or endoscopy.

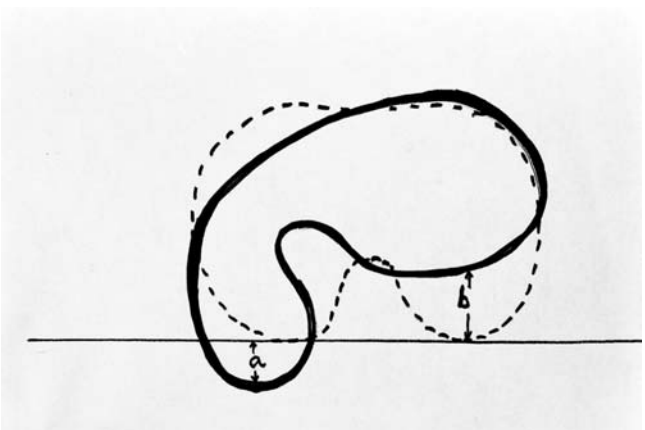


Fig. 6. Comparison of the normal thoracic contour (*dotted line*) with the scoliotic thoracic contour (*full line*) shows the exothoracic rib hump on the convex side (*a*) and the exothoracic "missing hump" on the concave side (*b*).

For severe exothoracic rib humps, thoracoplasty on the concave side may be used to lift up the ribs and a rod can be placed in front of the ribs, as advocated first by Stagnara.[14] It is important to be aware that in these severe cases postoperative respiratory care with positive-pressure ventilation may have to be continued for a long time. If it is not, the thoracoplasty may produce good cosmesis but a disastrous respiratory effect.

For an endothoracic vertebral hump and compression of the airway, it is necessary to perform decompression by anterior resection and arthrodesis followed by posterior instrumentation and arthrodesis. This measure avoids permanent atelectasia and usually corrects the intermittent atelectasia; it does not correct bronchomalacia if it exists. This is why it is important to detect hyperlordosis before airway compression is established so as to perform anterior release and posterior kyphosing instrumentation. In very young children we favor early isolated anterior epiphysiodesis with the hope of achieving better pulmonary function, rather than doing it only when the airway is already compressed. Prevention is better than correction.

Finally, for the exothoracic vertebral hump (Fig. 7), which is a hump from the vertebrae and spine, thoracoplasty is not useful because the ribs are in close contact with vertebral bodies. In such cases treatment for the spine only is required.

Conclusions

The 18 patients reported here represent the largest series with compression of the airway due to

Fig. 7. Typical exothoracic vertebral hump where the spine in "excluded" from the thorax and a vertebral body impinges on the rib

intrathoracic vertebral protrusion. On the basis of this experience, we developed the spinal penetration index concept to describe and quantify the hidden, functional, endothoracic vertebral hump associated with lordoscoliosis. This analysis and line of reasoning led to a rational treatment approach for the endothoracic vertebral hump, the exothoracic rib hump, and its counterpart the exothoracic "missing hump."

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