Review

The multiplane initial skeletal remodeling during scoliogenesis

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Abstract

In this opinion paper a concise introduction, describes the variety of published 2D and 3D related studies enabling deeper insight on the initial skeletal patho-remodeling during scoliogenesis. The changes in the spinal column and thorax are quoted for adolescent, childhood and infantile idiopathic scoliosis (AIS, CIS and IIS). In spinal column the changes analyzed in frontal, transverse and sagittal plane, and is commented where is initially the spine deformed while developing the idiopathic scoliosis (IS) that is vertebra vs intervertebral discs (IVD). Next the initial changes at the rib cage (RC) and the impact of these changes on spine deformity are mentioned as well as the impact on RC of the spinal operations for correction

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of AIS. Finally, the concept of the progression of IS due to the diurnal variation "accordion"-like phenomenon of wedged IVDs is quoted and suggested as the 3D model of initial spinal changes of IS.

Keywords

Idiopathic scoliosis; rib index; double rib couture sign; segmental rib index; rib cage; thorax; diurnal variation; rib vertebra angle; thoracic ratios.

Introduction

Knowledge of normality is necessary for the study of abnormality. One way to study the normality, is the analysis of data which are collected not only from the Paediatric and Scoliosis Clinics of the outpatient departments of the hospitals but also from the implementation of school scoliosis screening programs (SSSP). The SSSP beyond its original aim, which is prevention in terms of selecting and referring the scoliotic and asymmetric children, provides the opportunity for collection of various cross-sectional data of normal children in the general population (height, weight, menarche, handedness etc.) except of the similar data of asymmetric/ scoliotic children and adolescents. Then comparison of normals to asymmetric/scoliotics can be done. SSSP serves also the epidemiology and natural history of idiopathic scoliosis (IS). Moreover and most interestingly, SSSP is a "human evidence- based" "clinical research" tool of IS scoliogeny based on the study of humans not animals and on the established concept that the "morphology" expresses-reflects and deciphers-decodes the physiology and pathology.

At the initial stages of IS development and progression, deformity is not easily diagnosed since the signs are subtle. The structural skeletal changes on the thorax and spine are initiated also gradually and the patho-remodeling happens more rapidly later during the rapid growth period of these children.

The aim of this opinion paper is to describe the sequential changes happening in the bones of thorax in spinal column and the truncal deformity in initiating and mild IS and not at developed and progressed deformity. These initial changes are described in the published radiological and clinical literature.

First it would be necessary to have a look at the definitions of the severity of scoliosis. Mild idiopathic scoliosis is characterized by a Cobb angle either of more than 10 and less than 30 degree[1] or of more than 10 but less than 25 degrees[2] or of more than 10 but less than 20 degrees.[3] Moderate IS is characterized by a Cobb angle of 25–40 degrees, which is indicated for non-operative treatment[4, 5] or a Cobb angle greater than 21 to 35 degrees.[3] We consider as mild curves those with a Cobb angle of greater than 10 but less than 20 degrees and as moderate those with a Cobb angle of greater than 21 to 35–40 degrees. The above published definitions are listed as we consider that "at initiating and mild scoliosis, the patho-biomechanics are dissimilar from the biomechanics when the curve is severe". Furthermore, it appears that at initiating and mild IS, genetics, epigenetics, and biology have the dominant / protagonistic aetiological role, having non or minimal structural skeletal changes; however, it should not have overlooked the non-protagonistic role of patho-biomechanics, which later become dominant for progressive IS, when the skeletal deformities are well established.

At present, more frequently three-dimensional analysis is used as a procedure to study the morphology of IS curvature and rib cage, as any study based exclusively on coronal, sagittal or transverse plane has its limitations. However, the most important and frequently used radiological parameters are designed and measured on postero-anterior (P-A) and lateral radiographs (i.e. Cobb, Mehta RVAs, Perdriolle angles). Lateral radiographs are not systematically made for children with IS in most hos-

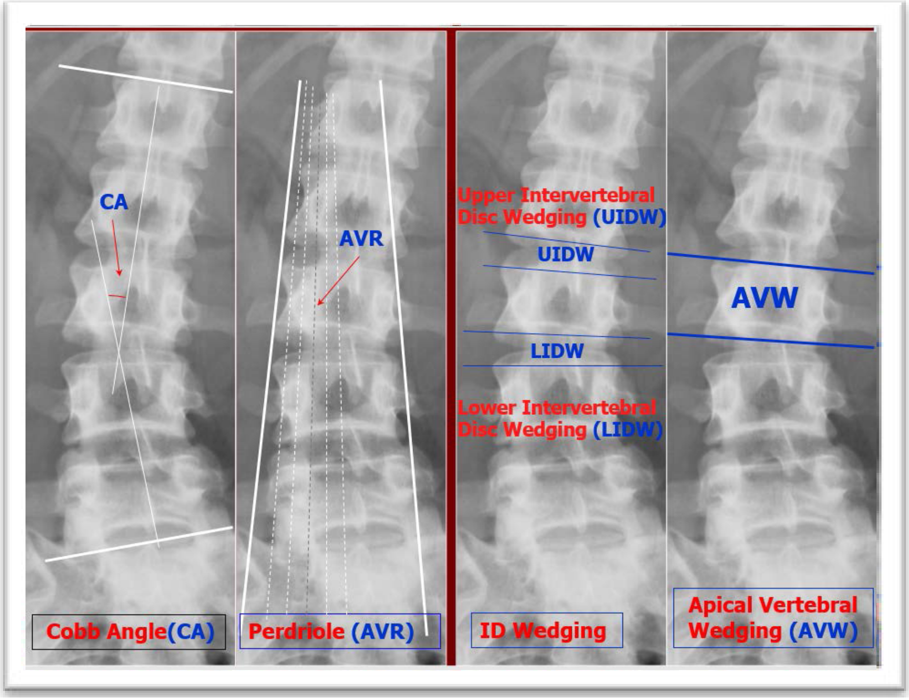


Figure 1: *The readings on the PA radiographs Cobb angle (CA), apical vertebral rotation (AVR), apical vertebral wedging (AVW) and the adjacent to the apical vertebra Upper (UIVDW) and Lower (LIVDW) Inter-Vertebral Discs Wedging.*[5]

pitals and the useful parameters for longitudinal or retrospective studies are taken almost exclusively from frontal plane radiographs. Currently the new technology of GAN-based deep learning framework can generate synthetic sagittal radiographs from coronal views to cure the limitation of missing lateral radiographs and to reduce radiation exposure in monitoring AIS. However, while these synthetic images appear visually consistent with real ones their quality remains insufficient for accurate clinical assessment, as the authors note.[6]

Imaging available for retrospective studies primarily consists of frontal plane radiographs. Plain chest and spinal films, which are readily accessible in medical archives, can effectively provide the necessary parameters for studying the onset, development, and progression of scoliotic thoracic and spinal deformities, without requiring additional special radiographs or extra radiation exposure. By utilizing the initial films of IS patients, the 2D parameters can support both cross-sectional and longitudinal studies on the development of these children or those with truncal asymmetry at risk of developing scoliosis.[6] Furthermore, these films can be used for both prospective and retrospective studies on non-operative and operative treatments of IS, as long as radiographic procedures are standardized. Such studies are also valuable for examining post-operative thoracic and spinal column morphology, allowing us to assess the impact of surgery on remaining growth potential and the progression of thoracic and spinal deformities.[7] It is important to note that the models currently used for predicting the progression of IS curves in cross-sectional and longitudinal studies also rely on parameters from 2D radiographs. This is because the foundational data for IS assessment, which forms the basis of these models, was primarily derived from 2D imaging methods in most centers, rather than 3D. While 3D analysis is increasingly used to study the morphology of scoliotic children, studies based solely on the coronal or sagittal planes have inherent limitations.[8-10]

Dansereau el al. 1987 proposed a 3D rib cage as-

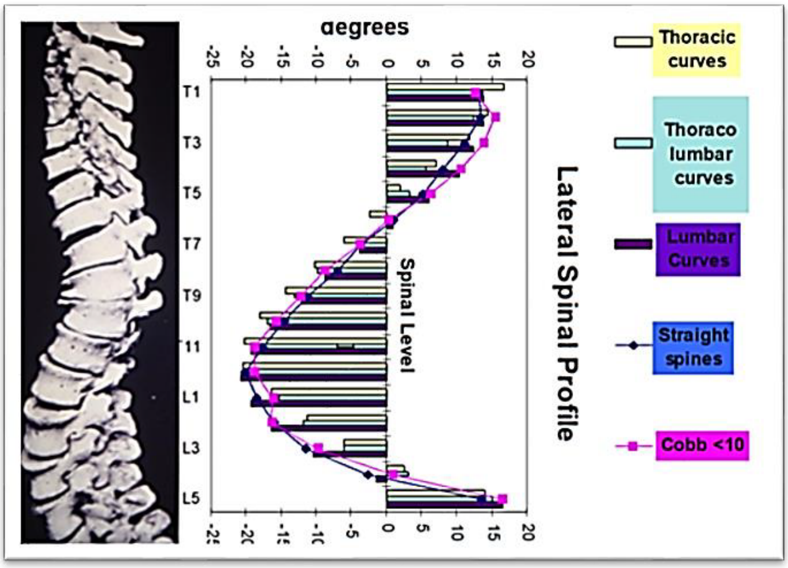


Figure 2. The Lateral Spinal Profile for the various groups of children, boys and girls. Yellow bars = thoracic curves, azure bars = Thoracolumbar curves, mauve bars = lumbar curves, line with blue diamonds = straight spines, line with red rectangles = curves with Cobb < 10 degrees.[35]

sessment, which certainly offers interesting possibilities but requires special equipment.[7-9] However, 3D reconstruction from CT scans is not routinely performed due to exposure to ionizing radiation.[10, 11]

In recent years, there has been a rise in transdisciplinary studies using machine learning on clinical data to develop in-house programs for predicting curve progression, which involves specialized terminology that may be not only challenging to digest yet difficult to assess. It is also interesting to note that these currently developed models of the prediction of progression of IS curves use as predicting parameters resulted from 2D radiography.[12-16]

Initial changes in the spinal column in IS

Initial changes in the spinal column: In frontal plane

The frontal plane morphology of the spine during the initial development of IS, has been reported.[5] In standing P-A radiographs of 92 children suffering mild scoliotic IS the following readings were obtained: Cobb angle (CA), apical vertebral rotation (AVR), apical vertebral wedging (AVW) and the adjacent to the apical vertebra Upper (UIVDW) and Lower (LIVDW) Inter-Vertebral Discs Wedging (Fig. 1). The mean thoracic CA was 13,4°, lumbar CA 13,8°, thoracic AVR 5,3°, lumbar AVR 4,7°, thoracic AVW 1,4°, lumbar AVW 1,5°, thoracic UIVDW 1.6°, thoracic LTVDW 1°, lumbar UIVDW 1,3° and lumbar LIVDW 2°. It was shown that in mild IS curves, when the deformity is initiating, the IVD is found wedged, but not the vertebral body. The spine is deformed first at the level of the IVD, due to the increased plasticity of the IVD, in the way of either torsion or wedging as an expression of other initiating factors that may start the deformity.[5]

In their 2009 study, Will et al. aimed to assess the relative contributions of vertebral and disc wedging to the increase in Cobb angle in IS by examining 18 girls across three phases of adolescent skeletal growth and maturation.[17] Their findings, consistent with Grivas et al.'s 2006 study, concluded that AIS first increases due to IVD wedging during the rapid growth spurt, followed by a gradual progression of vertebral wedging at a later stage.[5]

Initial changes in the spinal column: In sagittal plane

The lateral spinal profile (LSP) and its significance

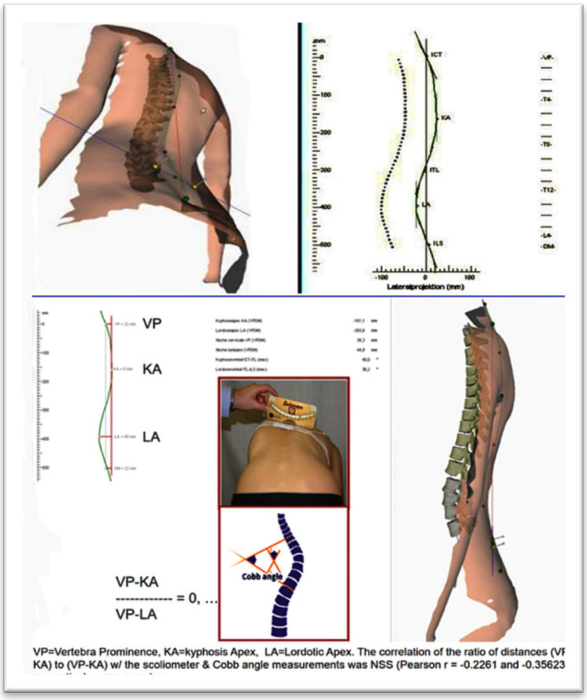


Figure 3*. Study of the sagittal profile of the spine in IS using radiography and surface topography.*[42]

in IS scoliogenesis is a topic that was discussed by research for many years.[18-38] The LSP was often regarded as a primary cause of IS because the kyphotic thoracic apex in IS is positioned higher in the thoracic vertebrae, causing more vertebrae to tilt posteriorly. This creates conditions of increased rotational instability, leading to a higher susceptibility for the development of IS.[28] The role of the configuration of the sagittal profile in the initial stages of development in IS was reported by Grivas et al.[35] This study assessed the lateral spinal profile (LSP) in school-screening referrals with and without late-onset idiopathic scoliosis (IS) of small curves (10°-20° Cobb angle) in 133 children—47 boys and 86 girls, with mean ages of 13.28 and 13.39 years, respectively. The Axial Trunk Rotation (ATR), Cobb angle, and segmental spinal profile from T1-L5 were evaluated. Intervertebral LSP (ILSP), which is the difference between two consecutive spinal levels of LSP, was also calculated. Five groups were established: 1) straight spines, 2) spinal curvatures with Cobb angles less than 10°, and 3) scoliotic children with a) thoracic, b) thoracolumbar, and c) lumbar curves of 10°-20° (Fig.2).

The results indicated that scoliotic children had slightly less kyphotic segmental angulation and almost normal lordotic angulation compared to normal children. LSP correlations with the Cobb angle showed: a) a positive correlation at T6, T7, T8, and T9 in thoracic curves of scoliotic boys, and b) a negative correlation at T3, T4, and T5 in lumbar curves of scoliotic girls. The observed LSP differences were primarily located in the lumbar spine, suggesting that factors affecting the lumbar spine in the sagittal plane contribute to the development of AIS in boys. The slight hypokyphosis of the thoracic spine and the minimal differences observed in the small curves when compared to non-scoliotic individuals support the idea that reduced kyphosis may facil-

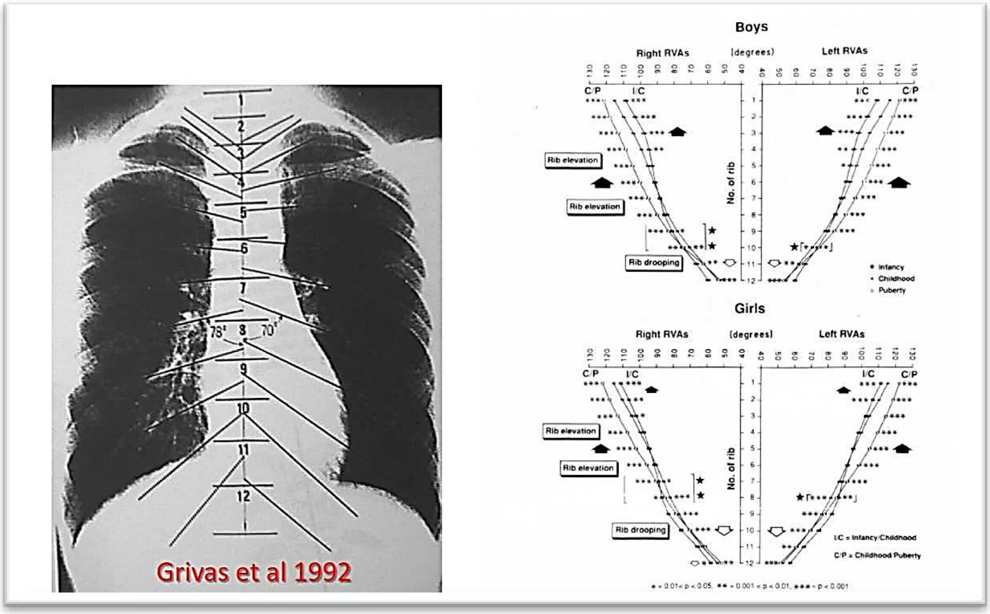


Figure 4: Segmental Rib-vertebra angles (RVAs),in infant childhood and adolescent boys and Girls.[45]

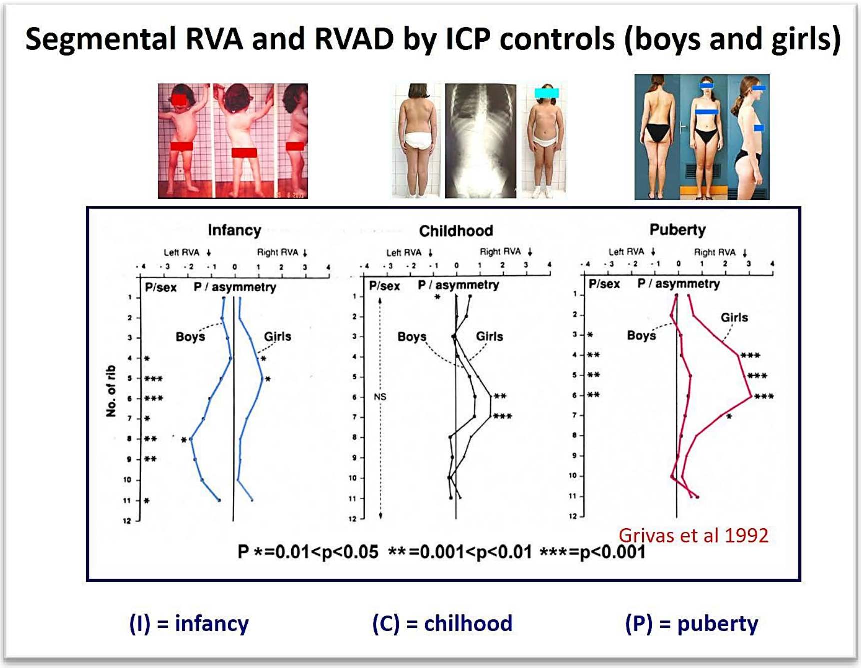


Figure 5: Segmental RVAD in Boys and girls by Infancy Childhood and Puberty (ICP) model.[45]

itate axial rotation, acting as a permissive factor rather than an etiological one in the development of IS. In other words, a straight (non-curved) beam is more easily rotated than a curved one.[35]

The view that the reduced kyphosis, by facilitating axial rotation, could be viewed as being permissive, rather than as aetiological, in the pathogenesis of IS was confirmed in other research studies.[39-41] The sagittal profile of the spine in IS was evaluated using surface topography and radiography. The study included 45 children, 4 boys and 41 girls, with an average age of 12.5 years (range 7.5–16.4 years),

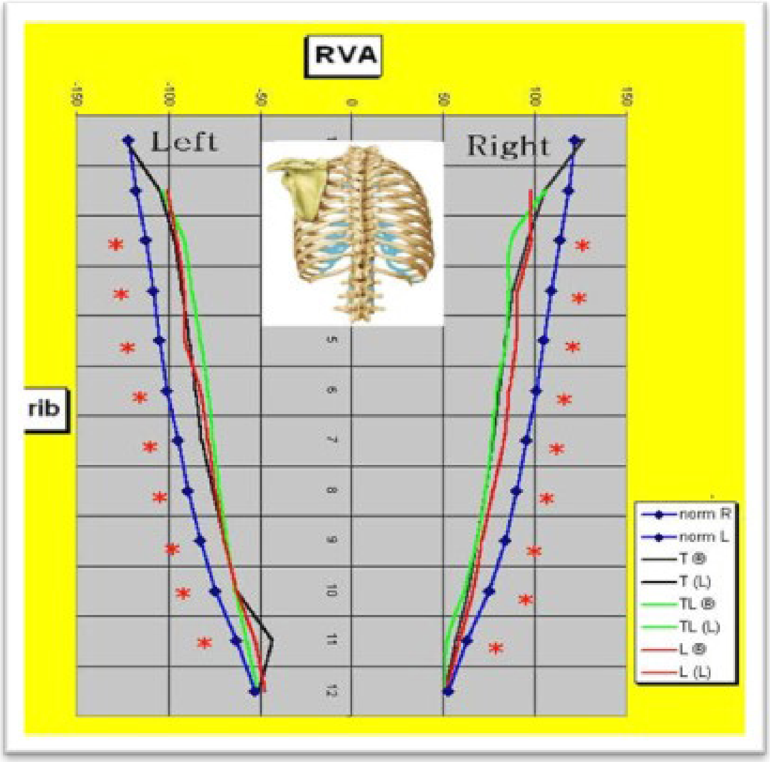


Figure 6: *Radiological evaluation of the deformation of the Thoracic Cage in AIS.*[49]

who were referred to the scoliosis clinic from the SSS. The children were divided into two groups: Group A consisted of 17 children with IS (15 girls and 2 boys), all of whom had a scoliometric trunk asymmetry of 5 degrees or greater. Group B, the control group, included 26 children (15 girls and 11 boys) with an Axial Trunk Rotation (ATR) of less than 2 degrees. The children's height and weight were measured, and the Prujis scoliometer was used during the standing Adam test in the thoracic (T), thoraco-lumbar (TL), and lumbar (L) regions. The Cobb angle was assessed using postero-anterior radiographs in Group A. A posterior truncal surface topogram was also taken using the "Formetric 4" apparatus, and the distance from the vertebral prominence (VP) to the apex of the kyphosis (KA), as well as from VP to the apex of the lumbar lordosis (LA), was calculated. The ratio of the distances (VP-KA) to (VP-LA) was also computed. The averages of these parameters were analyzed, and the correlation between the ratio of distances (VP-KA) to (VP-LA) and the scoliometer and Cobb angle measurements were assessed (Pearson correlation coefficient, r) within both groups and between them (Fig.3).

In Group A (IS), the average height was 1.55 m (range 1.37–1.71) and the average weight was 47.76 kg (range 33–65). The children with IS had right-sided (Rt) thoracic (T) or thoracolumbar (TL) curves. The mean Cobb angle for thoracic curves was 24 degrees, and for lumbar curves, it was 26 degrees. In the same group, the kyphotic apex (KA (VPDM)) distance was −125.82 mm (range −26 to −184), and the lordotic apex (LA (VPDM)) distance was −321.65 mm (range −237 to −417). The correlation between the ratio of distances (KA (VPDM) / (LA (VPDM)) and the Major Curve Cobb angle as well as the scoliometer findings were not statistically significant (Pearson r = 0.077, −0.211, p = 0.768, 0.416, respectively). Similarly, in the control group, the ratio of distances (KA (VPDM)) / (LA (VPDM)) was not significantly correlated with scoliometer results (Pearson r = −0.016, p = 0.939). The findings of this and the former mentioned study[35] do not con-

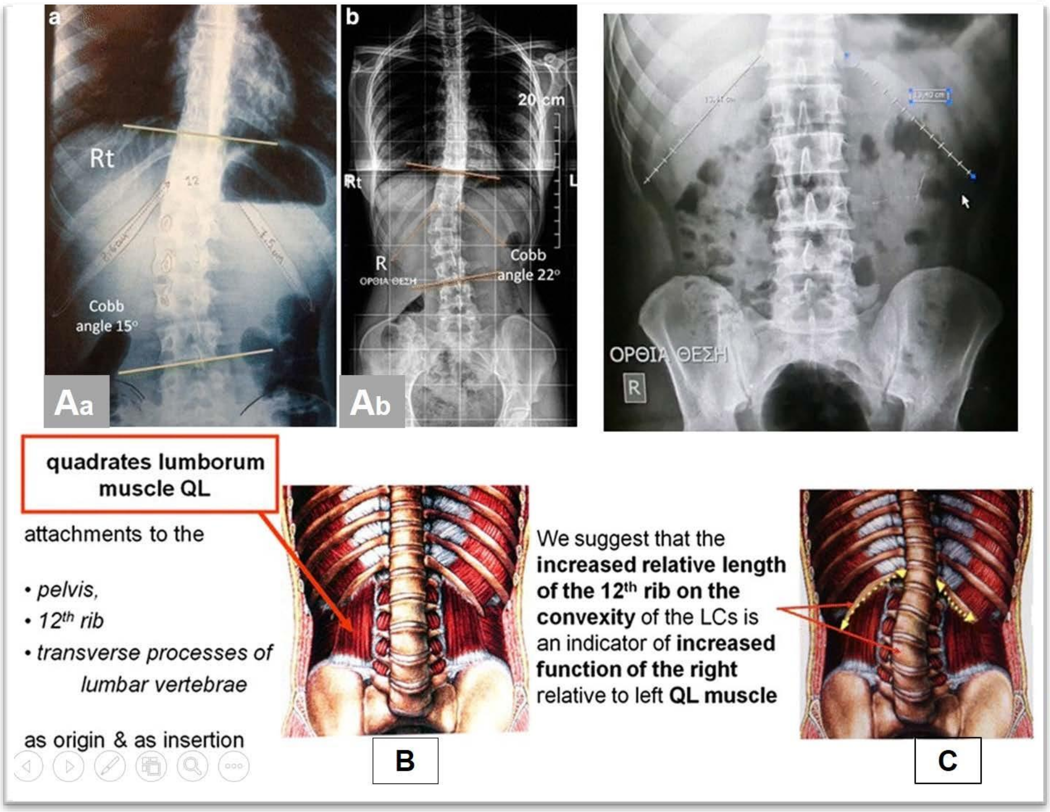


Figure 7: A)a, Cobb angle Rt lumbar IS curve with a longer Rt 12th rib, likewise in b, a 22 of Cobb angle Rt lumbar IS with a Rt 12th rib longer B) QL attachments, C) the suggested hypothesis for Rt lumbar IS curves.[54]

firm this hypothesis, that lateral profile of the spine is a primary aetiological factor for IS, since the correlation of the (VP-KA) to (VP-KA) ratio with the truncal asymmetry, assessed with the scoliometer and Cobb angle measurements, is not statistically significant, in both groups A and B. In addition, the aforementioned ratio did not differ significantly between the two groups in other studied samples.[39-41]

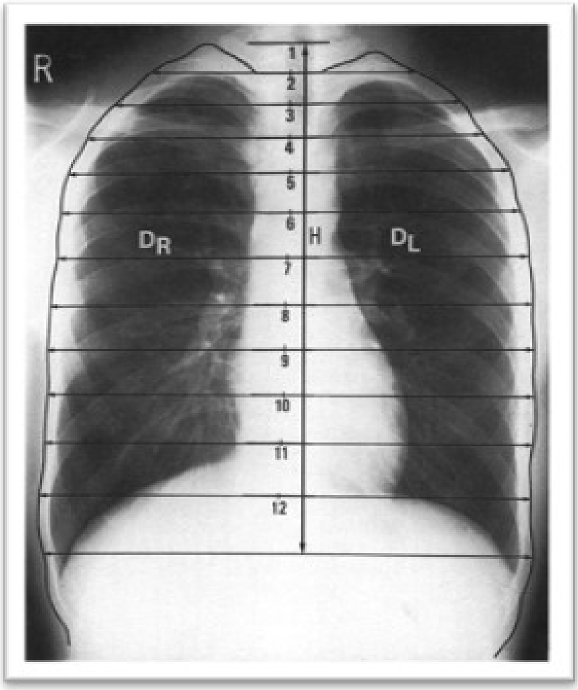
As mentioned earlier, it seems that the patho-biomechanics in the early stages and mild forms of IS may differ from those in more severe curves. The studies referenced above offer insight into whether there is an inherent disorder in vertebral body growth in mild to moderate IS. It was observed that the sagittal profile of these IS curves does not differ significantly from the profile of normal peers.[35] In other words, the growth potential in the sagittal plane (lateral spinal profile) for mild to moderate IS is similar to that of peers with normal spines, affecting both the vertebral bodies and intervertebral discs (IVDs). These two studies suggest that hypokyphosis is not a primary cause of the onset or progression of mild to moderate scoliotic curves, contrary to what has been reported elsewhere.[28] Moreover our view is consistent with views previously published.[43]

Initial changes in the spinal column: In transverse plane

In mild curves, the rotation of the apical vertebrae is minimal, this morphology plays a crucial role in obtaining an accurate sagittal profile. Since the sagittal profile in these cases is only minimally affected, it leads to more reliable measurements, which is essential for our assessment.[5, 44]

Initial changes in the thoracic cage, Impact of the thoracic on the spine deformity

Initial changes in the thoracic cage in Adolescent Idiopathic Scoliosis



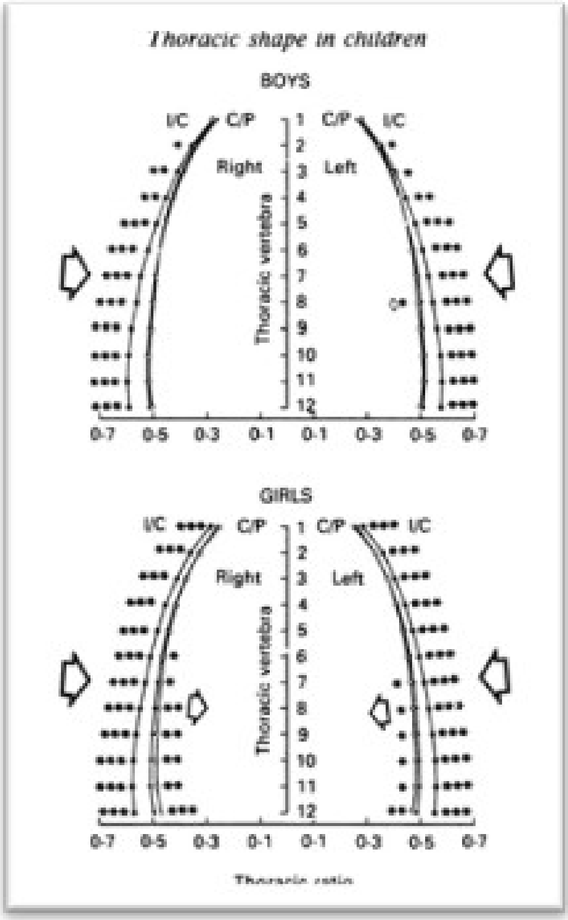


***Figure 8:** Segmental thoracic ratios (TRs): way of measurement and values for boys and girls in infancy, puberty and adolescents.*[60]

The study of the segmental (T1-12) RVAs and segmental rib-vertebra angle differences (RVADs), was reported as a new method (Fig 4, Fig, 5). The Infancy Childhood and Puberty (ICP) model of growth was used for analysis of these data.[46] It was hypothesized that RVAs are influenced by the central nervous system (CNS) mediated trunk muscle activity, and RVADs pattern reflects the common age, sex, and laterality patterns of IS. Extremes of such asymmetries may be an aetiological factor for both IIS and AIS. Segmental analysis of RVAs in AlS RC (Fig. 5), reveals crossed RVA asymmetry with aetiological implications.[45, 47]

The findings from these cross-sectional studies highlight the changes in the RC's structure by age and gender during growth. It is proposed that the funnel-shaped RC of neonates gradually transforms into a barrel-shaped structure as they grow, which, from an evolutionary perspective, may represent an adaptation of the RC to the human bipedal gait.[48, 49] The above led to a novel multifactorial theory for the pathogenesis of IS.[43]

A comparison of the RVAs between scoliotic and nonscoliotic children, involving 47 children with T, TL and L curves ranging from 10-20 degrees of Cobb angle and an average age of 12.4 years, and 60 age-matched non-scoliotic children, revealed that the RC of the late onset scoliosis (LOS) children had significantly lower RVAs ($p<0.01$) at nearly all thoracic levels.[49] It was reported that RVAs is an expression of the opposing muscle forces, that act on each rib, and that RVA asymmetries are aetiological for IS by weakening the spinal rotation defending system.[43] This study showed that scoliotic children with mild curves have underdeveloped RC compared to normal (Fig. 6). The differences are most pronounced in scoliotic children with thoracic curves. It has been suggested that the variations in RVAs between the right and left sides in this group reflect asymmetric muscle forces acting on the RC. We concluded that these asymmetric muscle forces

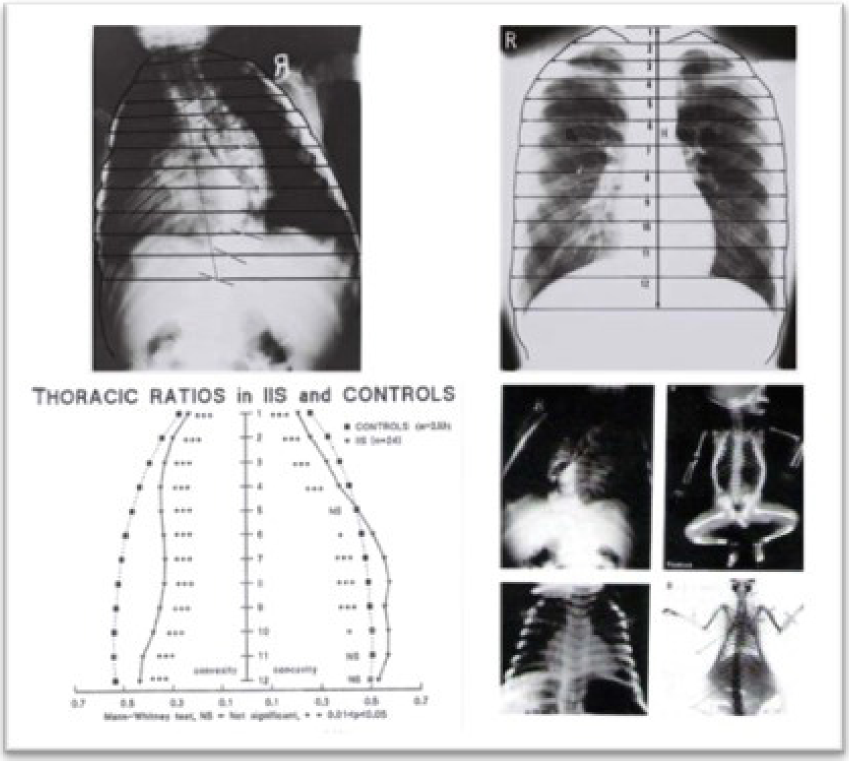


Figure 9: *The rib-cage deformity in infantile idiopathic scoliosis-the funnel-shaped upper chest.*[60]

contribute to the pathogenesis of IS by deforming the RC prior to affecting the spine.[49]

One characteristic of the deformation of thorax in IS is the drooping of RVAs. Measurement of the drooping value in convex RVA is equally important as that of initial convex RVA or RVAD in the literature.[50]

Interesting, Sevastik et al 1997, studying the RVAs in IS, concluded that the typical pattern of the RVAs on the concave and convex sides seems to be independent of the underlying cause of the spinal curvature.[51]

Canavese et al. (2011) reported that in their study of AP digital radiographs of 44 female patients with right convex idiopathic scoliosis and 14 normal females, the RVAD and RVARa values in the scoliotic segment were higher in patients with untreated scoliosis greater than 30° compared to those with untreated deformities of less than 30° or normal subjects. A significant difference was observed between the groups for the RVA, RVAD, and RVARa variables. They also recommended that measurements of RVA, RVAD, and RVARa should be conducted not only at or near the apex of a thoracic spinal deformity but should also encompass the entire thoracic spine.[52] Foley et al (2012) commented that RVAD 3D provides additional information to Mehta's RVAD on the torsional nature of the deformity.[53]

Initial changes in the thoracic cage in lumbar AIS

Grivas et al. (2016 in their study of idiopathic and normal lateral lumbar curves (LLC), discussed the presence of asymmetry in the length of the 12th rib associated with these curves.[54] They proposed a pathomechanical role for the quadratus lumborum (QL), based on the novel finding of bilateral length asymmetry of the 12th rib in relation to IS and minor non-scoliotic LLC (Fig. 7). To the 12th ribs are attached numerous small muscles, including the diaphragm, QL, internal and external intercostals, serratus posterior inferior, short and long rib elevators, external oblique abdominal, internal oblique abdominal, transversus abdominis, iliocostalis and

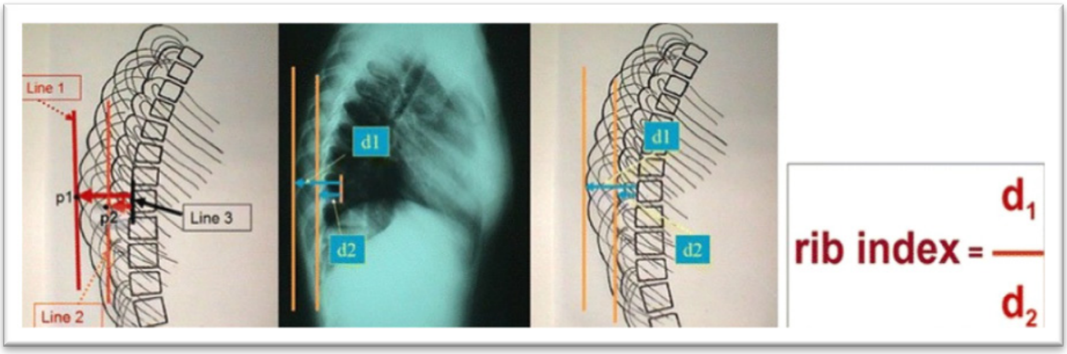


***Figure 10**. The way the RI is assessed on the standing lateral spinal radiographs.*[64]

***Figure 11:** The way the segmental RI (SRI) is assessed on the standing lateral spinal radiographs.*[65]

longissimus thoracis. The largest of these muscles is the QL, which attaches to the pelvis, 12th ribs, and the transverse processes of the lumbar vertebrae, likely exerting the greatest forces on the 12th ribs. Two theories were proposed: a) the relatively increased activity of the right QL muscle causes the LLC curves, and b) the QL muscle counteracts the lumbar curvature as part of the body's attempt to compensate for the curvature.[55] Grivas et al. (2016) suggested that one mechanism behind the relatively increased length of the right 12th rib is mechanotransduction,[54] in line with Wolff's and Pauwels' laws (Fig. 7).[55-58]

Based on the research outlined above, the implication is that the rib cage, particularly the asymmetry of the 12 pairs of ribs, precedes and plays a role in the pathogenesis of IS, contributing to the development of lumbar spinal deformity.

Initial changes in the thoracic cage in Infantile idiopathic scoliosis - Segmental thoracic ratios (TR) and Segmental TR differences (TRs)

Segmental thoracic ratios (TRs) were measured at each segment (T1-T12) in chest radiographs of 412 children, aged 0-17 years, who visited the hospital with minimal disorders or diseases (193 boys, 219 girls). A new method for measuring TRs was employed, which calculates the width of the left hemithorax, right hemithorax, and the total thorax relative to the T1-T12 distance.[59] The data were analysed in 3 age groups--infancy, childhood and puberty, after the classification of Karlberg (1989).[46] The study's analysis revealed several key findings. In the coronal plane, the chest broadens from T1 to

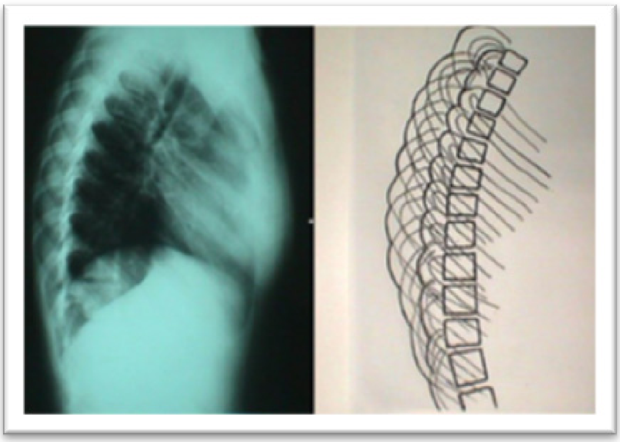


Figure 12. the contours of the two hemithoraces were always overlapping the one over the other, and this overlapping is the "double rib contour sign" (DRCS).[61-63]

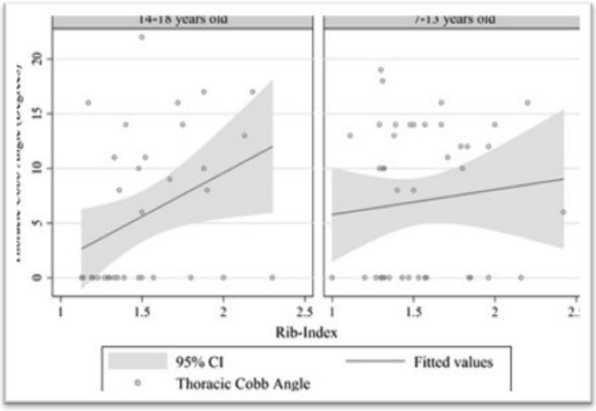


***Figure 13.** The linear relationship between thoracic Cobb angle and RI is graphically depicted. There is only linear association between thoracic Cobb Angle and rib-index in the age group of 14–18 years.*[34] *(Predicted Thoracic Cobb Angle = - 6.357 + 7.974 X (Rib-Index).*[63, 72, 84]

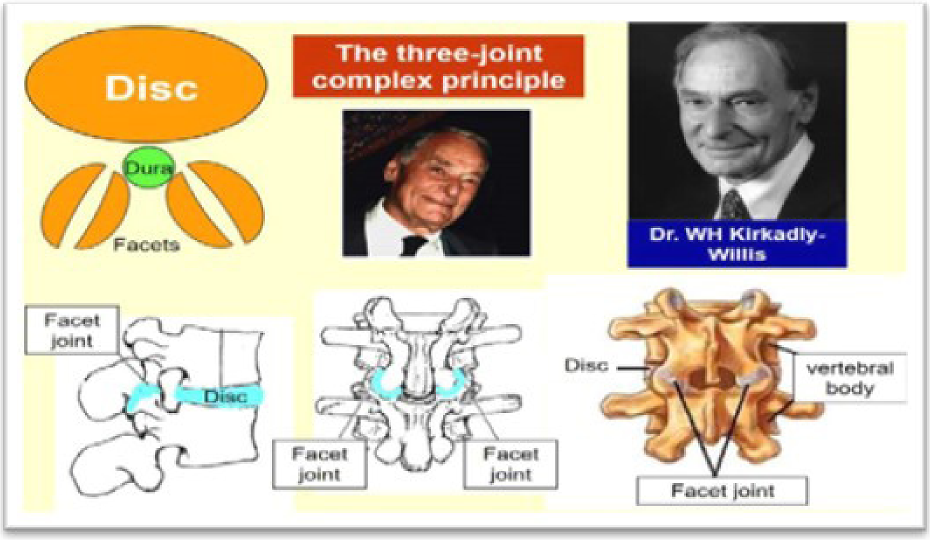


***Figure 14:** the three-joint complex of Dr WH Kirkadly-Willis.*[98]

about T10-11 between infancy and childhood, while relative to its length, the chest narrows from top to bottom, particularly in the lower chest. Between childhood and puberty, the chest narrows further in girls (but not in boys) in the lower half below T6. This relative narrowing of the chest during growth appears to result from several mechanisms: (1) elevation of the upper rib-vertebra angles (above 90 degrees); (2) drooping of the lower rib-vertebra angles (below 90 degrees); and (3) impaired linear rib growth in relation to thoracic spinal growth in the lower ribcage (T6-12) of girls between childhood and puberty (Fig. 8).[45]

The role of the rib cage in the development of progressive infantile idiopathic scoliosis (IIS) was investigated by Grivas et al. (2006) using segmental thoracic ratios from posteroanterior (PA) spinal radiographs of 24 patients with progressive IIS, with a mean age of 4.1 years. Thoracic ratios (TRs), including segmental convex and concave TRs, Cobb angle,

Figure 15: *The imbibed water (+ H2O) mainly in the apical IVD but also in the adjacent discs must be in a greater amount in the convex side than in the concave due to convex-wise asymmetrical distribution of glycosaminoglycans (GAGs) in NP collagen network type II. This results in: 1) asymmetrical pattern of water distribution, 2) Due to DV, asymmetrical convex-wise, concentrated cyclical loads to the IVD during the 24h, the convex side of the wedged IVD sustains greater amount of expansion than the concave side and as an eventual result the vertebra deforms.*[99]

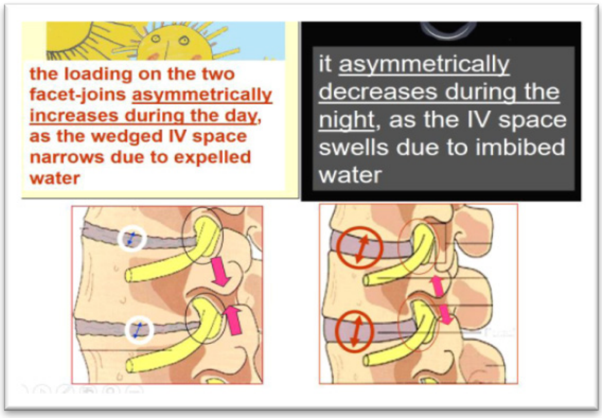


Figure 16: *The loading on the two facet-joins and IVDs is asymmetrical. The asymmetrical loading during the day occurs as the wedged IVD space narrows due to the expelled water, and decreases asymmetrically during the night as the IVD space swells due to the imbibed water. This results in asymmetrical growth of vertebral bodies and their posterior elements and also this is reflected in minor fluctuation of Cobb angle during the 24hour period, as was reported in Zetterberg et al 1983,*[101] *in the younger and more skeletally immature individuals.*[99]

segmental vertebral rotation, and vertebral tilt were measured (Fig. 9)[60].

Additionally, in a control group of 233 subjects with a mean age of 5.1 years, the segmental left and right TRs and the total width of the chest (left plus right TRs) were measured in PA chest radiographs. Statistical analysis, including Mann-Whitney, Spearman correlation, multiple linear regression, and ANOVA, was performed. The comparison showed that the scoliotic thorax is significantly narrower than that of the controls at all spinal levels. The upper chest in IIS is funnel-shaped, and vertebral rotation at T4 early in management significantly correlates with apical vertebral rotation at follow-up. The IIS thorax is narrower than that of the control group, with a funnel-shaped upper chest. Vertebral rotation at the upper limit of the thoracic curve in IIS is predictive, reflecting impaired rib control of spinal rotation, likely due to neuromuscular factors, which also contribute to the funnel-shaped chest (Fig. 9).[60]

Double Rib Contour Sign (DRCS) – Rib Index (RI) and Segmental Rib Index (SRI)

The "double rib contour sign" and the rib index (DRCS and RI), were introduced in 1999 (Fig 10) by the first author and lately the Segmental Rib Index at all levels from T1 to T12 (Fig 11).[61-66]

The significance of using these parameters lies in their contribution to scoliogenesis.[63, 65, 67]

Additionally, the rib index (RI) has been confirmed to a) serve as a strong surrogate for scoliometric readings in idiopathic scoliosis (IS),[68] and b) assist in the documentation of the thoracic deformity in the transverse plane,[61] the assessment of physiotherapy outcomes–(PSSEs),[70]

tracking the results of brace treatment,[71, 72] assessing pre- and post-operative thoracic deformity cor-

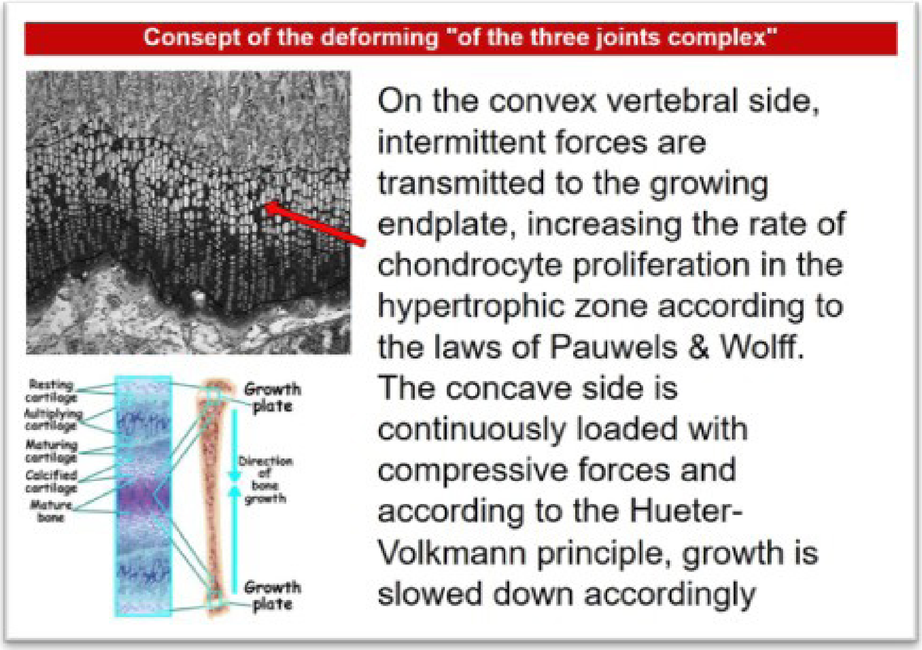


Figure 17: *Pauwels' law states that intermittent pressure within the normal range of stress and strain stimulates the growth plate of a healthy bone. Wolff's law states that bones in a healthy individual will adapt to the loads they receive. If the load is increased, the bone will progressively remodel to become stronger to withstand the load. Hueter-Volkmann principle "Continuous increased axial compression on the growth plate retards growth".*

rection with different types of instrumentation,[73-82] the use in prognosticating the accelerated deterioration in skeletally mature adolescent idiopathic scoliosis (AIS) curves of 40-50 degrees,[83] and helps in recognition of the proper rib level for thoracolpasty/costoplasty.[82]

During the clinical assessment of children with truncal asymmetry (ATR ≥ 5 degrees) referred from the SSS program, it was observed that in their lateral spinal radiographs, the contours of the two hemithoraces consistently overlapped, appearing asymmetrical. This observation was systematically noted in these asymmetric children, regardless of whether their spine was scoliotic or not. This overlapping was termed the "double rib contour sign" (DRCS) (Fig 12).

Consequently, the need for quantification of the degree of this overlapping, that is the asymmetry of this DRCS, in other words the thoracic deformity in terms of the hump, in the transverse plane, triggered the introduction of the RI (Fig 10).[63] The use of the RI helps prevent metric errors caused by variations in magnification on films showing the thorax. Furthermore, when plotting the RI against the Cobb angle, it was found that in girls under 13 years of age, there was no statistically significant correlation between their RI and Cobb angle. In other words, the spinal deformity was not related to the thoracic deformity assessed by the RI. It was also observed that in this age group, an RI of 2.5 corresponded to a Cobb angle of less than 10°. In older girls of age, the RI was statistically significant correlated with the Cobb angle (Fig. 13).[34] A 2.5 RI expresses a progressed thoracic deformity.[83]

The impact of growth on the correlation between spinal and rib cage deformities is evident. Growth significantly influences the relationship between thoracic and spinal deformities in girls with IS. Therefore, it must be considered when assessing spinal deformities from surface measurements. Based on the research outlined above, the implication is that rib cage deformity precedes spinal deformity in the pathogenesis of IS, particularly for thoracic and thoracolumbar curves. This perspective aligns with

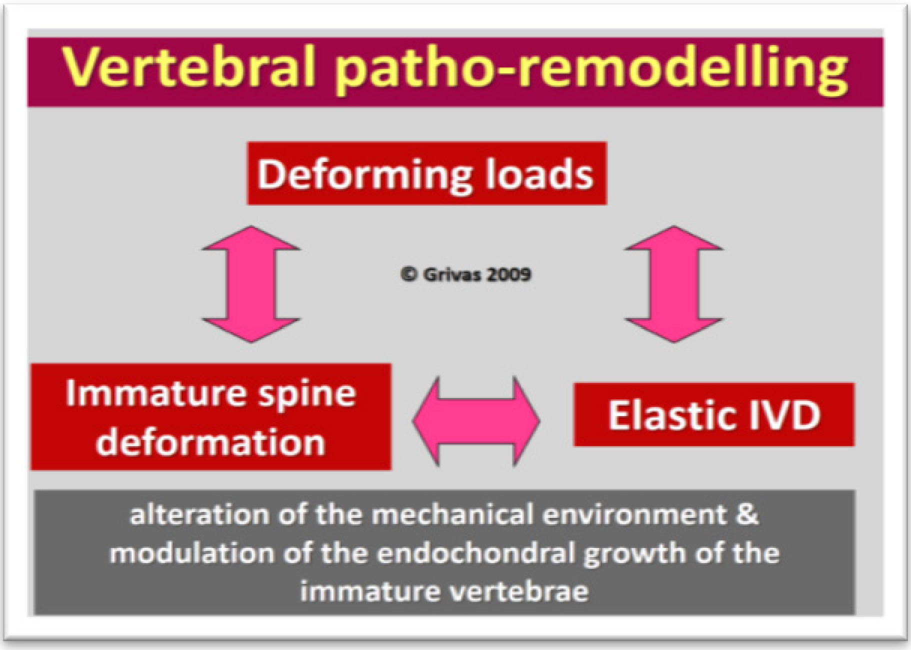


Figure 18: *The vicious cycle of patho-remodeling in apical and adjacent vertebrae in a IS curve, due to alteration of the mechanical environment and modulation of the endochondral growth of the immature vertebrae. (Modified from our citation.*[99]

previously reported views.[85-97]

The impact of the spinal operations on the thorax for correction of AIS

The rotation of the trunk and vertebral bodies, though interrelated, are analyzed as distinct parameters. It was shown that while surgery straightens the spine, the rib hump (RH) is corrected only to the extent of the spinal derotation achieved through the surgeon's instrumental adjustments. Additionally, not only is the hump incompletely corrected, but it also recurs and worsens during follow-up, particularly in skeletally immature scoliotic children who have undergone surgery. The only way to more effectively correct the RH is through costoplasty. The primary reason for this phenomenon is that RH deformity (RHD) is mainly caused by asymmetric rib development, rather than the rotation of the vertebrae in the thoracic spine. Surgery on the spine cannot address rib asymmetry or halt the mechanism that leads to their uneven growth. The findings from all the reviewed studies highlight the crucial role of RHD in scoliogenesis, as it precedes the development of the spinal deformity.[82]

The Progression of Idiopathic Scoliosis due to the Diurnal Variation "accordion"-like Phenomenon of Wedged Intervertebral Discs

In 1983, Dr. Kirkaldy-Willis described the intervertebral articulation as a "three-joint complex", including the disc anteriorly and the two facet joints posteriorly (Fig 14).[98]

Grivas (2021) proposed a concept for the progression of idiopathic scoliosis (IS) that emphasizes the role of diurnal variation in the asymmetric water distribution of the eccentric nucleus pulposus in the deformed scoliotic IVD, and how this affects the mechanical environment due to intermittent forces acting on the adjacent vertebral growth plates. These intermittent forces, driven by diurnal variation (DV), lead to asymmetrical vertebral growth and the progression of the IS deformity, a process referred to as the "accordion-like phenomenon." The supporting data for this concept draws on mechanobiology, the mechanotransduction process, as well as the fundamentals of spinal column embryology and biology. It also connects to the normal and deformed intervertebral disc, the diurnal variation phenomenon, concepts of IS scoliogenesis, the three-joint complex, sleep phases, and muscular tone. This background information aims to clarify and make understandable the concept of "the diurnal variation accordion-like phenomenon of wedged intervertebral discs," which is proposed as a key 3D progression factor in IS (Fig 14, Fig 15).[84]

The asymmetrical anatomical growth changes not only in vertebral bodies but also in the posterior vertebral elements have been confirmed.[100]

The DV "accordion"-like Phenomenon of wedged IVDs is actually a 3D model of inducing skeletal patho-remodeling in the spine by means of a vicious cycle occurring in apical and adjacent vertebrae in a IS curve, due to alteration of the mechanical environment and modulation of the endochondral growth of the immature vertebrae, according to Pauwels', Wolff's and Hueter-Volkmann principle laws (Fig 17, Fig 18).[99]

This original concept could be highly beneficial for tailoring treatment for children with IS. Current treatment methods to address the progression of IS include PSSEs, bracing, or a combination of both.[102]

The greatest advantage for these children would be an unfused spine, as it was naturally designed. However, the high costs associated with traditional surgical treatments could be avoided if non-operative treatments are properly applied, based on prevention of the changes outlined in this concept.[5, 99, 103, 104]

It is crucial to emphasize the point made by Dr. TK Taylor in 1981, while the effectiveness of early detection and surgical techniques cannot be denied, orthopedic surgery must still be responsible for investigating the cause and pathogenesis of scoliotic curvature. Spinal fusion for scoliosis contradicts the core principle of orthopedic surgery— the preservation of musculoskeletal function— a principle that Trueta strongly upheld throughout his surgical career. Clearly, sacrificing spinal mobility should not be considered an acceptable final solution to the condition.[105]

In conclusion this opinion article presents the recent knowledge on the initial skeletal patho-remodeling during scoliogenesis based on the current pertinent literature.

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T.B.G.: conceptualization, literature investigation, and writing—original draft preparation; review and editing; EV and KG literature investigation and editing, TBG, EV, KG, LD, NS, CM, AM, DP, EB, KE: participation in our SSS program, review; All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest:

The authors declare that they have no conflict of interest concerning this article

Abbreviations

AIS = Adolescent Idiopathic Scoliosis;
AL = apex lumbar lordosis
ATR = Angle of Trunk Rotation;
CIS = childhood idiopathic scoliosis
CNS = central nervous system
DRCS = Double Rib Contour Sign;
IS = Idiopathic Scoliosis
IIS = infantile idiopathic scoliosis
ICP = Infancy Childhood and Puberty model
ILSP = intervertebral values for LSP
KA = kyphosis apex
KA (VPDM)) = kyphosis apex mean distance
L = lumbar
LA (VPMD) = lordotic apex
LLC = lateral lumbar curves
LOS = late onset scoliosis
LSP = lateral spinal profile
MD = mean distance
MD = Mean distance
PA = posteroanterior
RI = Rib Index;
RC= rib cage
RVA = rib vertebra angle
RVAD = rib vertebra angle diference
SSS = School Scoliosis Screening;
SSSP = school scoliosis screening programs, (SSSP
SRS = Scoliosis Research Society
SRI = Segmental Rib Index
STR = Segmental thoracic ratios
TR - thoracic ratios
T = thoracic
TL = thoraco-lumbar
TA = Truncal Asymmetry.
VP = vertebra prominence
VPDM = vertebra prominence mean distance
QL = quadratus lumborum

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