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ADJACENT SEGMENT DISC DEGENERATION AFTER FUSION IN ADOLESCENT IDIOPATHIC SCOLIOSIS: THE IMPORTANCE OF A BALANCE-CENTERED APPROACH: A REVIEW

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ABSTRACT

The aim of this narrative review is to summarize current evidence regarding the epidemiology, pathophysiological mechanisms, and risk determinants of adjacent segment disc degeneration (ASDD) following adolescent idiopathic scoliosis (AIS) surgery and to emphasize the importance of a balance-centered, rather than level-centered, surgical planning strategy for long-term spinal health. Published data were synthesized within a descriptive framework focusing on selection of fusion levels [upper and lower instrumented vertebra (LIV)], coronal and sagittal alignment parameters, TK restoration, pelvic incidence-lumbar lordosis (PI-LL) harmony, and distal disc geometry. The reported incidence of ASDD following AIS surgery increases with follow-up duration, reaching approximately 25% at 10 years and exceeding 30% after 14 years. The development of ASDD is not solely dependent on the level of the LIV. Local and global alignment characteristics-such as LIV translation, adjacent disc wedging, sagittal vertical axis, insufficient LL, and PI-LL mismatch-have been consistently identified as major risk factors. Fusion extending to L4 or more distal levels has been associated with an increased risk of degeneration, particularly in the presence of sagittal imbalance. Nevertheless, with the widespread adoption of modern segmental pedicle screw-rod systems and three-dimensional correction techniques, the isolated impact of fusion level selection appears to be attenuated. ASSD following AIS surgery represents a multifactorial process rather than a purely mechanical consequence of fusion length. Global spinal balance, sagittal alignment, and the quality of surgical correction play pivotal roles in long-term outcomes. Strategies aimed at minimizing the risk of degeneration should prioritize achieving near-neutral sagittal balance, adequate TK, and optimal distal segment geometry, while preserving the shortest feasible fusion. In this context, balance-centered surgical planning emerges as a fundamental principle for achieving durable radiological and clinical outcomes following AIS surgery.

Keywords: Adolescent idiopathic scoliosis, adjacent segment disease, junctional failure

INTRODUCTION

Adolescent idiopathic scoliosis (AIS) is a three-dimensional spinal deformity with multifactorial etiology that affects approximately 2-3% of adolescents[1,2]. The primary goals of treatment are to halt curve progression, restore trunk and shoulder balance, and preserve motion segments by achieving the shortest feasible fusion[1,3-5]. Flat-back deformity and distal overload, common in the Harrington era, have markedly declined with the advent of segmental pedicle screw-rod systems and three-dimensional correction techniques[3,6]. Nevertheless, over time, adjacent segment disc degeneration (ASDD) may develop in the mobile segments caudal to the fusion mass[2,6-11].

ASDD is characterized by increased biomechanical stress, impaired diffusion, and structural dysfunction occurring in the mobile discs distal to the fusion[12-14]. Clinically, it may manifest as low back pain, stiffness, or functional loss; radiologically, it is typically defined by the Pfirrmann grading on magnetic resonance imaging (MRI)[14-16] and, when present, Modic end-plate changes[7,8,17]. Contemporary meta-analyses report ASDD rates rising to 25% within 10 years and to 32% by 14 years after AIS surgery[7]. However, the correlation between radiological findings and clinical symptoms is generally weak to moderate[6,8,11,16,18]. This indicates that ASDD is not merely a mechanical outcome, but a multifactorial process closely linked to the quality of surgical alignment and the patient's biomechanics[7,9].

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The aim of this review is to examine, in light of current literature, the epidemiology, pathophysiology, risk determinants, and clinical implications of ASDD following AIS surgery, thereby highlighting the importance of a balance-centered rather than a level-centered surgical approach. To this end, the literature on ASDD following AIS surgery was systematically searched in international biomedical databases, primarily PubMed, using a systematic search strategy; the findings of the included studies were narratively synthesized in terms of their epidemiological, biomechanical, and clinical dimensions.

Selecting Fusion Levels: From Traditional to Balance-centered Concepts

In AIS surgery, the selection of fusion levels influences not only deformity correction but also long-term spinal health. Historically, the Lenke et al.[1] and King et al.[5] classifications have provided the fundamental framework for defining structural curves and determining fusion limits. In modern concepts, Trobisch et al.[3] emphasize that fusion planning should consider not only structural vertebrae but also global balance and sagittal alignment-a strategy termed balance-centered fusion.

Selection of the Upper Instrumented Vertebra (UIV)

UIV selection plays a pivotal role in preventing proximal junctional kyphosis and shoulder imbalance. Because the thoracic spine is naturally stabilized by the rib cage, motion preservation is of secondary importance; the principal goals are maintaining shoulder symmetry and sagittal balance.

Trobisch et al.[3] recommend jointly evaluating T1 tilt, shoulder level, and the rigidity of the proximal thoracic (PT) curve during planning. When T1 tilt and shoulder imbalance are concordant, inclusion of the PT curve in the fusion is warranted; when discordant, stopping at T2-T3 may suffice[3,19]. Ilharreborde et al.[19] identified the T1 tilt-shoulder balance relationship as an independent determinant, whereas Kuklo et al.[20] found the clavicle angle to be the best predictor of postoperative shoulder balance.

In summary, UIV selection should not rely solely on curve morphology; rather, it should follow balance-centered planning principles based on PT rigidity, shoulder balance, and sagittal alignment[3].

Selection of the Lower Instrumented Vertebra (LIV)

The choice of the LIV is a key determinant of ASDD risk after fusion[20]. Beyond the selected vertebral level, the geometric characteristics of the LIV-particularly tilt, translation, and the angle of the subjacent disc-directly affect long-term load distribution and mechanical balance[9]. Lonner et al.[9] demonstrated that an LIV translation ≥2 cm and a subjacent disc wedge ≥5° increase the 10-year risk of ASDD by approximately sixfold.

Traditional approaches, based on the Lenke et al.[1] and King et al.[5] classifications, advocate ending the fusion at the neutral vertebra closest to the central sacral vertical line[1,5]. However, Knapp et al.[21] reported that in King type IV (long thoracic) curves, stopping one level proximal to the stable vertebra (often at L3) may be safe and preserve an additional motion segment. Burton et al.[22] suggested that, for optimal LIV selection, the disc below should be neutral or opening opposite on bending, and the rotation of the vertebra below should be ≤15°. Similarly, Suk et al.[23] emphasized that lumbar vertebral rotation is more important than curve magnitude or flexibility; planning based on the neutral rotated vertebra-end vertebra relationship is decisive for surgical success. Finally, Trobisch et al.[24] noted that inadequate preservation of sagittal parameters- pelvic incidence-lumbar lordosis (PI-LL) harmony, sufficient thoracic kyphosis (TK), and near-neutral sagittal vertical axis (SVA)- leads to increased distal loading and early disc degeneration.

Consequently, the modern approach focuses not only on "where" the fusion ends but also on "how" it is aligned. Optimal LIV selection should aim to balance coronal alignment, sagittal harmony, and distal segment biomechanics[9,23,24].

Epidemiology and Clinical Implications

Burgos et al.[7] reported ASDD incidences of 24.8% at 10 years and 32.3% at a mean of 13.8 years following AIS surgery. MRI-based studies tend to show higher rates than series defined solely by radiography[7]. Chiu et al.[16] and Nohara et al.[25] observed that degenerative changes cluster predominantly at L4-5 and L5-S1, attributed to increased mechanical load transfer distal to the fusion.

ASDD is often asymptomatic. Green et al.[6] reported minimal radiologic changes at juxta-fusion levels and low pain scores during long-term follow-up with modern segmental systems. In contrast, Jakkepally et al.[11] and Bartie et al.[18] found lower scoliosis research society-22 questionnaire (SRS-22) scores and a higher prevalence of low back pain when the fusion extended further distally. Collectively, these data indicate that ASDD is not merely a morphologic phenomenon; sagittal balance, pelvic parameters, and age-related biologic factors substantially influence clinical expression[7,16].

Pathophysiology: From Mechanics to Molecules

Fusion rigidifies the instrumented segment, shifting motion and loads to adjacent levels[11,24]. This redistribution results in excessive stress on posterior elements, increased intradiscal pressure (IDP), and enlargement of facet contact areas[10,11]. Auerbach et al.[12] demonstrated a significant increase in intradiscal pressure in caudal segments after fusion, potentially initiating degeneration. In combined *in vivo*+finite-element models by Zhou et al.[13], L4-S1 fusion produced a 0.8 mm decrease in posterior disc height, increased strain/stress in the posterolateral annulus at L3-4, and an ~0.29 MPa rise in IDP, quantitatively implicating biomechanical stress as a primary trigger of degeneration.

Such mechanical loading disrupts end-plate permeability and hampers nutrient diffusion into the disc[26]. Consequently, nucleus pulposus water content declines, annular fissures develop, and Pfirrmann et al.[15] grades progress. Histologically, proteoglycan loss and collagen remodeling trigger an inflammatory response consistent with Modic-type changes[14,26].

Factors Influencing ASDD

ASDD after AIS surgery is a multifactorial process that becomes more apparent with time. The most consistent observation is a time-dependent rise in incidence: a global rate of ~25% at 10 years increases to 32% by a mean of 13.8 years[7]. In series initiated in the Harrington era with 27-51 years of follow-up, the prevalence of disc degeneration reached 66-77%, accompanied by deterioration in sagittal parameters (SVA, PI-LL, PT)[17,27]. Increasing mean Pfirrmann grades with age further support this temporal effect[16].

The LIV is particularly decisive for long-term outcomes. Meta-analytic data suggest that stopping at L3 or above reduces the risk of degeneration compared with fusions extending below L3[7]. In very long-term cohorts, an LIV at L4 or below has been associated with reduced LL, increased SVA, and higher disc degeneration scores[26,27]. A 10-year prospective registry analysis identified L4 as carrying the highest risk for clinically significant degeneration[9]. Nevertheless, a meta-analysis restricted to modern pedicle screw-rod constructs found no significant MRI-based difference between L3 and L4, implying a potential effect of era and technique[2]. Clinically, fusions extending to L4 or below have been associated with worse pain-related scores[16].

The local geometry of the distal transition zone is a trigger for ASDD. Specifically, a subjacent disc wedge ≥5° and an LIV translation ≥2 cm increase the likelihood of degeneration by roughly sixfold[9]. Elevated L4 tilt/obliquity at baseline and at 10-year follow-up correlates with degeneration[25]. Thus, the critical question is not only "how far" but also "with what distal geometry"?

The number of remaining mobile segments also modulates load transfer. Fewer unfused discs are associated with higher distal Pfirrmann et al.[15] grades; similarly, Nohara et al.[25] 10-year follow-up found more frequent degeneration in patients with fewer mobile segments. Conversely, in a 9.1-year series, progression occurred in only one-quarter of patients and was typically limited to a single Pfirrmann grade, without a strong association with the number of mobile segments[11]. These discrepancies imply sensitivity to patient selection and correction quality.

Sagittal balance and restoration of thoracic contour have marked effects on long-term biomechanics. Smaller LL, higher SVA, greater PI-LL mismatch, and increased PT have been associated with degeneration during long-term follow-up[27]; notably, the L4-or-lower LIV group exhibits lower LL and higher SVA[17]. In the mid-term, thoracic hypokyphosis shows a significant inverse relationship with degeneration; inadequate kyphosis restoration creates an unfavorable milieu for distal discs[28].

Level-specific analyses suggest that L5-S1 (and to a lesser extent L4-5) is the most vulnerable link. Long-term MRI studies have identified most new pathologies at L5-S1, with the greatest jump in mean Pfirrmann grade at this level[6]; contemporary series employing direct vertebral rotation/rod derotation techniques similarly show marked increases at L4-5 and L5-S1 below the LIV[28]. Selective thoracic fusion preserves motion segments yet is associated, on follow-up, with modest increases in degeneration at unfused levels and greater facet degeneration at the first two levels below the LIV, while clinical scores often remain comparable[10]. Very long-term Harrington-era series underscore era-related differences, with higher rates of Modic changes and worse Oswestry disability index (ODI)/function scores[8].

Clinical impact is heterogeneous; nonetheless, meta-analysis demonstrates worsening of SRS-22 domains (function, self-image, satisfaction) in the presence of degeneration[7]. Pain outcomes tend to be worse when fusions extend to L4 or below[16], although some series report weak or inconsistent associations between imaging and SRS-22/ODI[6,9,18]. In aggregate, shared principles to mitigate ASDD risk include-when feasible-ending at L3 or above, minimizing distal disc wedging and LIV translation, adequately restoring TK, and optimizing global sagittal balance with appropriate LL-PI harmony[7,9,17,27,28].

The long-term effects of thoracic hypokyphosis extend beyond the lumbar spine to the cervical region. Young et al.[29] at a mean 30-year follow-up, reported substantially increased rates of cervical disc disease and surgery in AIS patients. The rate of anterior cervical discectomy and fusion was nearly tenfold higher than in the general population, and 58% of radiographically assessed patients exhibited moderate-to-severe cervical osteoarthritis and disc degeneration. Crucially, thoracic hypokyphosis was significantly associated with cervical disc degeneration p<0.01. Suggesting that inadequate TK restoration increases cervical loading and accelerates degenerative changes[29]. Taken together, these findings highlight the multifactorial nature of ASDD, as summarized in Table 1.

Table 1. Overview of risk factors, pathophysiological mechanisms, and outcomes of ASDD after AIS spinal fusion

Category	Summary of findings
Epidemiology	• ~25% at 10 years • ~32% at ≥14 years • Higher rates in very long-term Harrington-era cohorts (up to 66-77%) • MRI-based studies report higher prevalence than radiography
Biomechanical consequences	• Motion restriction • Altered load transfer • Reduced segmental mobility
Surgical and radiological risk factors	• Distal fusion to L4 or below • LIV translation ≥2 cm • Subjacent disc wedging ≥5° • Thoracic hypokyphosis • PI-LL mismatch • Increased sagittal vertical axis • Reduced number of mobile segments
Pathophysiological mechanisms	• Increased intradiscal pressure • Facet joint overload • Impaired disc nutrition and diffusion • Annular strain • Endplate microdamage
Radiological manifestations	• Pfirrmann grade progression • Disc height reduction • Decreased T2 signal intensity on MRI • Modic endplate changes
Clinical implications	• Frequently asymptomatic • Possible low back pain • Reduced SRS-22 and functional scores • Potential long-term impact on global spinal balance

ASDD: Adjacent segment disc degeneration, AIS: Adolescent idiopathic scoliosis, MRI: Magnetic resonance imaging, LIV: Lower instrumented vertebra, PI-LL: Pelvic incidence-lumbar lordosis, SRS-22: Scoliosis research society-22 questionnaire

CONCLUSION

In AIS, ASDD is a multifactorial process that should be managed with balance-centered planning. The L3 versus L4 decision is not singularly determinative; regardless of the terminal level, a horizontal/centralized LIV, near-neutral SVA, and LL targets appropriate for age and PI appear pivotal for long-term risk reduction. Avoiding thoracic hypokyphosis is essential not only to limit distal ASDD but also to reduce the risk of cervical degeneration.

Footnotes

Authorship Contributions

Surgical and Medical Practises: O.T., Ö.A., A.K., Concept: S.A., Design: Ö.A., A.K., E.A., Data Collection or Processing: O.T., A.K., Analysis or Interpretation: O.T., Literature Search: Ö.A., Writing: S.A.

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