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Interpedicular height as a predictor of radicular pain in adult degenerative scoliosis

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Abstract

Background Context—Spine surgeons must correlate clinical presentation with radiographic findings in a patient-tailored approach. Despite the prevalence of adult degenerative scoliosis (ADS), there are few radiographic markers to predict presence of radiculopathy. Emerging data suggest that spondylolisthesis, obliquity, foraminal stenosis and curve concavity may be associated with radiculopathy in ADS.

Purpose—The purpose of this study was to determine if radicular pain in ADS is associated with reduced interpedicular heights (IPHs) as measured on routine radiographs.

Study Design/Setting—Retrospective case-controlled study.

Patient Sample—The authors carried out a retrospective chart review at a tertiary care referral center that included ADS patients referred to scoliosis surgeons between 2012 and 2014. Inclusion criteria included patients with ADS and no prior thoraco-lumbar surgery. Data were collected from initial spine surgeon clinic notes and radiographs.

Outcome Measures—Clinical outcome data included presence, side(s) and level(s) of radicular pain; presence of motor deficits; and presence of sensory deficits.

Methods—Variables included age, gender, Scoliosis Research Society-30 (SRS-30) and Oswestry Disability Index (ODI) questionnaire data, and radiographic measurements. Radiographic measurements included Cobb angles and L1 to S1 IPHs on upright and supine radiographs. Associations between variables and outcome measures were assessed with univariate and multivariate statistical analyses. Authors have no conflicts of interests relevant to this study.

Results—A total of 200 patients with an average age of 51 years met the inclusion criteria. 60/200 presented with radicular pain. Increased age was associated with radicular pain, weakness

IRB approval: This work was approved by the Institutional Review Board at the Washington University Human Research Protection Organization.

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and sensory deficits. Patients that were 55 years or older were approximately 8 times more likely to have a radicular pain (OR = 7.96, 95% CI 3.73, 17.0; $p < 0.001$), 5 times more likely to have a motor deficit (OR = 5, 95% CI 2.55, 9.79; $p < 0.001$), and 5 times more likely to have a sensory deficit (OR = 5.2, 95% CI 2.65, 10.2; $p < 0.001$) than those younger than 55. More caudally-located nerve roots are more likely to develop radicular pain ($p < 0.001$). Motor deficits were associated with worse SRS-30 functional ($p = 0.02$) and ODI scores ($p = 0.005$), but radicular pain and sensory deficits were not associated with lower SRS-30/ODI scores. Ipsilateral and same-level radicular pain were associated with reduced IPH in supine radiographs ($p = 0.002$ and $p = 0.0002$, respectively). Finally, reduced IPH on upright radiographs was associated with side- and level-specific radicular pain ($p = 0.04$).

Conclusion—Radicular pain in ADS patients is associated with reduced IPHs and increased age. Measuring IPHs on routine radiographs may be helpful in associating clinical radiculopathy with radiographic measures to guide patient management and surgical planning.

Keywords

Adult degenerative scoliosis; radiculopathy; interpedicular height

Introduction

Adult scoliosis prevalence ranges from 1 to 10% but has been observed in 30% of elderly patients without a history of spinal disease.[1–5] Adult degenerative scoliosis (ADS) is one etiology of adult scoliosis and is typically diagnosed in late middle-age patients without a history of adolescent idiopathic scoliosis.[6] ADS patients typically present with worsening back pain, progressive skeletal deformity and/or neurological symptoms (*i.e.*, radicular pain, radiculopathy or neurogenic claudication).[2–4, 6] ADS results from age-related degenerative disc disease, joint arthropathy, and collapse and wedging of the disc spaces.[3, 4, 6, 7] ADS is typically observed in the thoraco-lumbar and lumbar spine, and often includes both a coronal-plane deformity and loss of lumbar lordosis.

Many patients are referred to scoliosis surgeons due to worsening back pain associated with a progressing scoliotic curve. Axial back pain has been associated with pelvic retroversion, disc-space obliquity, vertebral body listhesis, and sagittal imbalance.[3, 8–10] ADS patients alternatively present with neurological symptoms including radiculopathy and/or neurogenic claudication. There is a well-described association between lumbar stenosis and neurogenic claudication.[2, 11–13] Clinical association between radiographic lumbar stenosis and neurogenic claudication allows for efficacious surgical treatment by decompression.[11, 14] It is believed that severe foraminal stenosis may be present in a large fraction of patients with ADS[1] and may contribute to radiculitis and radiculopathy and poor clinical outcome. [15] Evaluation of computed tomography has also suggested an association between foraminal size and curve concavity with radiculopathy.[16] While foraminal size cannot be directly assessed on plain radiographs of the spine, we propose that the height between the pedicles that constitute the rostral and caudal boundaries of a foramen [or the interpedicular height (IPH)] could serve as a proxy measurement of foraminal size. Other clinical and radiographic modifiers likely play a role in the presentation and outcome of ADS. For example, we hypothesized that increased age may be associated with increased lumbar

spondylosis and lateral recess stenosis and hence radicular pain. Clinical performance indices such as those attained on the Scoliosis Research Society-30 questionnaire or by Oswestry Disability Index may also predict radicular pain. In addition to IPH, thoracolumbar and fractional lumbosacral cobb angles on radiographs may predict radicular pain. We hypothesize that reduced IPH would be associated with the presence of radicular pain. To test this hypothesis, we performed an exploratory retrospective review of ADS patients referred for scoliosis surgery to ascertain if there was an association between IPH and clinical radiculopathy symptoms, including radicular pain, motor symptoms and sensory deficits.

Methods

Database

After approval by the Washington University Institutional Review Board, patients with adult degenerative scoliosis were identified for retrospective review. We utilized a prospectively-collected database of spinal deformity patients to identify 200 consecutive patients treated for adult degenerative scoliosis at Washington University School of Medicine between 2012 and 2014. Given the exploratory nature of this study and the lack of preexisting data on the association of neuroforaminal height and radicular symptoms, a formal sample size calculation was not performed.

All the patients included had been referred to a Washington University School of Medicine scoliosis surgeon for surgical management of their scoliosis. The initial subject query for adult degenerative scoliosis utilized 207 subjects to collect complete data on 200 patients. Inclusion criteria for this study were (1) a patient with a diagnosis of ADS and (2) the availability of clinical and radiographic assessments prior to surgery. No revision patients or patients with prior thoracic/lumbar surgery were included in the initial query. Seven subjects were excluded to lack of clinical and radiographic data. The only data available on these subjects were sex and age. The 7 subjects included 6 females and one male and average age was 37.6 ± 18.9 years. To study the association between demographic, clinical and radiographic measures and clinical features, all data was collected on initial preoperative clinic visits. Data variables included age, gender, Scoliosis Research Society-30 questionnaire scores, Oswestry Disability Index, bilateral L1-S1 interpedicular heights on supine and upright radiographs, and thoracolumbar (TL) and fractional lumbosacral (FLS) cobb angles on supine and upright radiographs. Features of clinical presentation were collected from preoperative clinic notes from spine surgeons and included the presence of radicular pain (radiculitis), radicular pain side(s) and nerve roots involved, presence of motor deficit(s) and presence of sensory deficit(s). Subjects completed the SRS-30[17] and Oswestry Disability Index[18] forms during their preoperative visit. Of these 200 patients, all had upright radiographs, 123 had supine radiographs, and 156 had questionnaire data. Sixty patients presented with radiculopathy. Summary of missing data is included as Supplemental Table 1.

Radiographic measurements

Intersegment IPH was measured for each level from L1 to S1. Bilateral IPHs were measured on anterior-posterior radiographs from the center of the rostral pedicle to the center of the caudal pedicle (Figure, 1). TL Cobb angles and FLS Cobb angles were measured as previously described [3–6, 15].

Data Analysis

Unless specifically mentioned, all patient demographic, clinical and radiographic data were summarized as mean $\pm$ standard deviation or frequency. For the 60 patients with radiculopathy, each nerve root between L1 and S1 was classified with the presence or absence of radiculopathy. Statistical comparison of the prevalence of radiculopathy across nerve roots was performed for the 360 nerve roots (i.e., 6 nerve roots for 60 patients) with a chi-square (χ^2) test and a Cochran-Armitage test for trend in prevalence across progressively lower nerve roots.

For data analyses where age is an independent variable, one model was performed that included age entered as a continuous variable (years) and another model was performed where age was entered as a dichotomous, categorical variable that classified each patient as less than 55 years old versus 55 years or older. Age associations also included age as a category using median split as age <55 years (n=96, 52%) or age 55 and greater (n=104, 52%). The association of gender with age in years and categorized age was assessed using a Wilcoxon's and a χ^2 test, respectively. Univariable logistic regression models (one model per outcome per independent variable) were used to determine the independent association of gender and age with radiculopathy, motor deficits, and sensory deficits. When significant, univariable odds ratios (ORs) with 95% confidence intervals (95% CIs) are reported to reflect the increased odds of the presence of the outcome. Multivariable logistic regression models (one model per outcome per independent variable with age as a covariate) were used to determine if after adjusting for age (a) motor deficits, sensory deficits, and radiculopathy were associated; and (b) questionnaire scores were associated with each of the three outcomes specified in (a). When significant, adjusted odds ratios (aORs) and corresponding 95% CIs are reported to reflect the increased odds of the presence of the outcome for a one-unit increase in the independent variable, after adjusting for age. Due to the small number of males, there was inadequate statistical power to determine if the association between age and outcome was similar for males and females. Since age was previously determined to be more clinically relevant than gender [19], these multivariate analyses included continuous age as the covariate, except for when a significant Hosmer and Lemeshow Goodness-of-Fit test indicated a poor model fit and categorized age was used as the covariate instead.

For each patient, intersegment IPH and the presence of radiculopathy was measured bilaterally at each of the nerve root levels between L1 to S1. The effect of IPH on radicular pain side, nerve root and interactions was assessed across all subjects. The study was not powered enough to cohort into separate age groups. So that the combined effects of radiculopathy on the specified side and at the specified level could be evaluated, measurements from each side at each level were treated as independent observations (i.e., one observation denoting the presence/absence of radiculopathy per side per level). L1/2

IPH corresponded to the L1 nerve root. L2/3, L3/4, L4/5 and L5/S1 IPHs corresponded to the L2, L3, L4 and L5 nerve roots, respectively. Due to the difficulty in measuring S1/S2 IPH and the importance of lateral recess stenosis in S1 radiculopathy[20], L5/S1 IPH was used for S1 nerve root. Separately for supine and for upright IPH, statistical analyses assessed determined if radiculopathy was associated with IPH using generalized estimating equations (GEEs) with an exchangeable correlation matrix to account for the correlation of multiple measurements within each patient. The focus of these analyses was on the interaction between side and level, interactions which tested hypotheses about the equality of IPH depending on the presence of radiculopathy on the measured side at the measured level. When significant and within the GEE, least squares means were used to determine which combinations of side and level were significant. When the interaction was not significant, the interaction was dropped from the GEE and the main effects of side and level were evaluated. Statistical analyses were performed using SAS (SAS Institute, Cary, North Carolina). Statistical significance was defined as a p-value less than 0.05.

Results

Demographics of Adult Degenerative Scoliosis Patients

Clinical and radiographic data were investigated in 200 patients who had been evaluated for adult degenerative scoliosis (Table 1). The mean age was 50.7 ± 18.4 years (range 18.1–83.6 years). There were a larger number of females than males in the patient population evaluated (147 vs. 53, respectively). Questionnaires interrogating pain, functional status, self-image, mental health and disability were assessed for each patient. Subsections of the Scoliosis Research Society-30 (SRS-30) questionnaire evaluated pain, function, self-image and mental health: a value of 1 indicated a poor outcome/status while a value of 5 indicated a good outcome/status. The SRS-30 pain score ranged from 1 to 5 (mean, 3.1 ± 0.9) and the function score ranged from 1.2 to 4.8 (mean, 3.4 ± 0.8). The self-image score ranged from 1 to 4.5 (mean, 2.7 ± 0.7) and the mental health score ranged from 1.2 to 5.0 (mean, 3.8 ± 0.8). The Oswestry disability index, in which a higher score indicates a worse status, ranged from 0 to 88 (mean, 32.2 ± 18.4). The mean supine and upright TL Cobb angles were $34.6 \pm 17.7^\circ$ and $37.8 \pm 19.8^\circ$, respectively. The mean supine and upright FLS Cobb angles were $15.2 \pm 10.3^\circ$ and $15.1 \pm 9.6^\circ$, respectively. Sixty of the 200 patients presented with a radicular pain. Twenty-five patients presented with bilateral radicular pain while 22 and 13 patients presented with right and left-sided radicular pain, respectively. Sixty-five and 66 patients presented with motor and sensory deficits, respectively.

Prevalence of radicular pain is greater for caudal nerve roots

Evaluation of the 360 nerve roots in patients with radicular pain (L1-S1 in 60 patients) demonstrated that prevalence of radicular pain for either side was not the same across nerve roots ($p = 0.0007$, χ^2). Rather, the probability of radicular pain in ADS patients increased for caudal nerve roots. 16.67%, 20.00%, 26.67% 31.67%, 41.67 % and 48.33% of radicular pain patients had L1, L2, L3, L4, L5 and S1 root symptoms, respectively (Figure 2). The probability of radicular pain progressively increased in a linear fashion as the level of root became more caudal (Cochran-Armitage test for linear trend, $p < 0.001$).

Association and in-group comparisons between age and radicular pain, weakness and sensory deficits

There were statistically significant associations between age and presence of radicular pain, motor deficit and sensory deficits (Table 2). For each decade increase in age, the probability of radicular pain increased by 2.4 times (Table 2). The odds of radicular pain were approximately 8 times greater in patients 55 years or older (Table 2). Similarly, for each decade increase in age, the probability of a motor deficit increased by 1.5 times (Table 3). The odds of a motor deficit were 5 times greater in patients 55 years or older (Table 3). Finally, for each decade increase in age, the probability of a sensory deficit increased by 1.7 times (Table 4). The odds of a sensory deficit were approximately 5 times greater in patients 55 years or older (Table 4). In the patient population studied, there was an association between age and gender. The mean age of males and females were 40.5 ± 19.1 and 54.5 ± 16.7 years, respectively ($p < 0.0001$, Wilcoxon's test). When age was categorized, a larger proportion of patients that were 55 years or older were female as compared to male (85% versus 61%, $p = 0.0002$, χ^2). Although there was an association between gender and age, univariable logistic regression analyses failed to show independent associations between gender and radicular pain, motor deficits and sensory deficits.

Associations between radicular pain, motor deficits and sensory deficits

There is an association between radicular pain, motor deficits and sensory deficits in ADS patients. After adjusting for age, the odds of a motor deficit were approximately 4½ times greater in patients with radicular pain (Table 2). Similarly, the odds of a sensory deficit were approximately 6½ times greater in patients with radicular pain (Table 2). Finally, the odds of a sensory deficit were nearly 6 times greater in patients with motor deficits (Table 3).

Associations between questionnaire results and presence of radicular pain, motor deficits and sensory deficits

Comparison of questionnaire results failed to reveal any significant associations between SRS-30 and ODI scores and presence of radicular pain (Table 2) or sensory deficits (Table 4). There were no associations between SRS-30 pain, mental health or self-image scores and motor deficits. However, after adjusting for age, the odds of a motor deficit was reduced by about 50% for each unit increase in SRS-30 functional score (Table 3). Analogously, after adjusting for age, the odds of a motor deficit were increased by about 4% for each point increase in ODI score (Table 3). These findings demonstrate that radicular pain and sensory deficits in ADS are not associated with SRS-30 and ODI questionnaire deviations, but motor deficits in ADS patients were associated with worse SRS-30 functional and ODI questionnaire outcomes.

Association between radicular pain and reduced IPH

To assess for associations between radicular pain and IPH, a total of 1230 supine IPHs and 2000 upright IPHs were measured in 200 ADS patients (Table 5). Statistical comparisons of film measurements and radicular pain demonstrated an association between radicular pain and IPH for both supine and upright radiographs. For supine measurements, the interaction between radicular pain on the measured side and radicular pain at the measured root was not

significant ($p=0.36$, GEE). When evaluating the effect of side without considering the level, supine IPH was significantly smaller when there was radicular (3.11 $\pm$ 0.6 vs. 3.31 $\pm$ 0.57 cm; $p = 0.002$; Figure 3A). When evaluating the effect of level without considering the effect of side, supine IPH was significantly smaller when there was a radicular pain (2.85 $\pm$ 0.71 vs. 3.31 $\pm$ 0.5 cm; $p = 0.0002$; Figure 3B). These results suggest that reduced IPHs on supine radiographs are associated with radiculopathy.

Associations between IPHs and radicular pain was also evaluated in upright radiograph measurements. Statistical comparisons of the combined effects of radicular pain on upright film measurements showed an interaction between radicular pain on the measured side and radicular pain at the measured root ($p=0.01$, GEE). The IPH for a nerve root with radicular pain at the same level and same side was significantly less than an IPH at the same level but contralateral side (3.15 $\pm$ 0.69 vs. 3.28 $\pm$ 0.66 cm, respectively; $p = 0.04$; Figure 3C—*red vs. blue*; supplemental table 2). This suggests that the IPH at a symptomatic radicular pain nerve root is smaller than the IPH at the contralateral side and is in line with the concept of obliquity. Consistently, on the non-symptomatic side, the IPH at a symptomatic level is larger than that at a non-symptomatic level (3.28 $\pm$ 0.66 vs. 3.08 $\pm$ 0.61 cm, respectively; $p=0.03$ —*blue vs. orange*). IPH at a non-symptomatic level but symptomatic side was 3.25 $\pm$ 0.56 cm, which was not significantly different from other IPHs. Hence, reduced IPHs on upright radiographs are associated with radiculopathy at a level- and side-specific precision. When taken together in a clinically useful manner, these data demonstrate an association between a radicular pain and a reduced IPH.

Discussion

In this study, we tested the hypothesis that reduced IPH measured on routine radiographs can predict the presence of radicular pain in ADS patients. In both upright and supine radiographs, reduced IPH was associated with radicular pain. This data is consistent with previous literature. Schwab *et al.* reported that listhesis of the vertebral bodies, vertebral body obliquity, hyperlordosis and thoraco-lumbar junctional kyphosis are associated with pain.[3] Deviren *et al.* demonstrated that radicular pain is associated with vertebral body listhesis and increased age.[19] Liu *et al.* suggested that foraminal stenosis was more important for rostral lumbar radiculopathy while lateral recess stenosis was more important for L5 and S1 radiculopathy.[20] Pugely *et al.* showed that critically reduced foraminal size on computed tomography and curve concavity were associated with lower extremity radicular pain.[16] Here, we extend these findings to routine upright and supine radiographs and demonstrate, in a side- and level-specific manner, that smaller IPH is associated with radicular pain.

In concert with prior studies, the data presented here have clinical implications. Patient-tailored treatment of spine patients depends on correlating a patient's clinical features with radiological findings.[3, 4, 6] Lumbar, foraminal and lateral recess stenosis on magnetic resonance imaging or computed tomography myelography often provide radiological data needed to make this important clinical correlation.[3–6, 11–13] The association between reduced IPH on routine radiographs and radicular pain provides an additional tool to consider when evaluating a patient. In a study of 384 foraminas, Pugely *et al.* showed that

caudal lumbar foraminal stenosis $<40 \text{ mm}^2$ was associated with sciatic nerve pain and rostral lumbar foraminal stenosis $<30 \text{ mm}^2$ was associated with formal nerve pain. Furthermore, reduced foraminal size were associated with concavity of the curve [16]. Although direct measurements of foramina were not feasible in this study due to the lack of computed tomography in patient cohorts, IPH serves as a logical correlate.

In recent years, it has become dogma that proper alignment of the sagittal plane has the greatest bearing on patient outcomes [8, 10]. One result of this focus on sagittal plane considerations has been a de-emphasis of the coronal plane elements of a deformity. However, our findings demonstrate that reduced IPH, which occurs on the concavity of the lumbar or fractional lumbosacral curve, is strongly associated with the presence of radicular pain, and as such must not be ignored in the evaluation of the patient with ADS. Particularly in those patients who are older, and thus more likely to have a radicular pain, the surgeon must carefully evaluate for radiculopathic symptoms and the originating region of stenosis; addressing this site of stenosis, whether by direct decompression or by indirect decompression through restoration of IPH, may play a major role in patient outcomes. This begs the question, is improvement in radicular pain a result of *in-situ* stabilization (i.e. fusion without correction) or foraminal enlargement? The data presented here lack any postoperative outcome measures but corroborate the hypothesis that correction of coronal plane deformities to increase IPH may treat radicular pain. Transfeldt *et al.* evaluated 85 degenerative scoliosis patients with radiculopathy and found that correction of a Cobb angle from 39° to 19° led to better satisfaction than decompression alone [21]. Ali *et al.* reported clinical results after corrective surgery for adult scoliosis where the Cobb angle was corrected from 65° to 24° and found that instrumented fusion relieved symptoms in 74% of patients [22]. Alimi *et al.* reported on 23 patients and found that restoration of foraminal height and correction of a coronal Cobb angle deformity with an extreme lateral interbody fusion significantly reduced radicular pain by visual analog scale and Oswestry Disability Index measures [23]. Since axial loading slightly reduced IPH, one might suggest that a prone fusion operation alone (a.k.a. without axial load) may treat radicular symptoms in itself without additional need for correction. However, given the small changes measured between supine and upright radiographs, an *in-situ* fusion without correction carries the risk of inadequate nerve root decompression. While the data here suggests that only a few millimeters of increased IPH are necessary for improved pain, future studies can address the increase in IPH necessary to treat a radiculopathy and the extent to which patient outcomes can be impacted by treatments tailored for “problem areas” of reduced IPH.

The busy surgeon may not be inclined to add another film measurement, IPH, to the list of myriad measurements already considered essential to the evaluation of the spinal deformity patient. Furthermore, that exact millimeter measurements presented here may not be clinically translatable across all patients. However, we do believe that this measurement adds useful information in some cases. While MRI and CT provide the greatest resolution in evaluating the anatomy of a foramen or lateral recess at any given level, they are almost universally performed with the patient in a supine, non-weight-bearing position. It is well-known that coronal plane deformities (Cobb angle, apical vertebral translation and rotation) are worse and foraminal heights and reduced with patients in the upright position when compared to the supine position.[24–26] Similarly, we have found that IPH is lower on

upright films than on supine films. Supine measurements such as MRI and CT may therefore underestimate the degree of foraminal compression that occurs with the patient in the upright position, whereas measurement of IPH on upright films displays the full extent of foraminal compression as the spine sags while bearing weight. This information may prove useful in two distinct instances: 1) the patient presenting with radicular complaints but without evident foraminal compression on axial imaging; and 2) the patient with a multitude of symptoms, which may include radicular problems in multiple nerve distributions, but in whom the origin of the symptom is not entirely clear based on axial imaging. In both of these scenarios, measurement of IPH can display a site or sites at which exaggerated foraminal height loss while weight bearing leads to resultant nerve root compression, and thus can demonstrate levels that should be targeted for either direct or indirect decompression.

Prior data suggest that foraminal stenosis may be more important for rostral lumbar radiculopathy while lateral recess stenosis was more important for L5 and S1 radiculopathy [20]. Consistent with historical and anecdotal experiences, the data presented here show that caudal lumbar radiculopathies are more common than rostral lumbar radiculopathies in ADS patients. This is likely due to the combined effects of ADS, degenerative disc disease and lateral recess stenosis. Despite this root-specific finding, reduced IPH was independently predictive of radicular pain after removing nerve root number as a variable. Future studies to examine the combined and independent effects of lateral recess stenosis, IPH and Cobb angles with adjuvant tests such as nerve conduction studies may be helpful to clarify each variable's role in lumbar radicular pain.

Patient age and sex are not associated with curve progression in ADS.[7] However, consistent with other authors[19], we found that increased age was associated with radicular pain in ADS. Questionnaire analyses also found an association between motor deficits in ADS patients and impaired SRS-30 functional and ODI scores. This highlights the major impact of motor deficits on patient quality of life but also suggests that SRS-30 and ODI questionnaires may not be sensitive enough to measure effects of radicular pain or sensory loss in ADS patients.

There are several limitations to this study. First, although there was an association between gender and age in this ADS population, this study lacked sufficient power to assess the potential combined effects of age and gender on radicular pain in ADS. Second, the patient population studied was referred for surgical management of their scoliosis and therefore represent a surgically-biased cohort. For example, there may have been two sub-populations within this patient cohort: one referred for neurological symptoms such as radicular pain and a second referred for axial back pain associated with a progressive curve. Third, although this study focused on L1-L5 IPHs, the prevalence of S1 radicular pain exceeded those of other nerve roots. Indeed, L5-S1 IPH measurements were difficult and inconsistent in standard anterior-posterior radiograph views due to lumbosacral lordosis. Furthermore, the preponderance of S1 radiculopathy may be a consequence of L5/S1 degenerative disc disease in which an asymmetric "bulge" of the L5/S1 disc during weight bearing could be responsible for narrowing the lateral recess disproportionately on the concave side of the fractional lumbosacral curve. In these settings, degree of actual IPH loss would only be a

weak proxy indicator of this phenomenon. Future studies may be directed at performing similar measurements on a population that was not referred for surgical management. Direct foraminal height measurements were not possible due to the paucity of computed tomography and magnetic resonance imaging studies available. Because this study was limited to preoperative data, postoperative correction data were not available and clinical sequelae of foraminal diameter collapse as seen in posterior fusion fixation techniques were not assessed. Finally, although IPH intuitively could compress the exiting nerve and cause radicular symptoms, additional compressive factors likely play a role not assessed in this study. Future studies may evaluate the impact of soft tissue in the foramen such as a disc bulge, ligamentous hypertrophy, synovial bulge from facet arthropathy on radicular pain.

Conclusion

Reduced IPH on supine and upright radiographs and increased age were associated with radicular pain in ADS patients. Furthermore, radicular pain was more common in caudal nerve roots and is associated with motor and sensory deficits. Finally, motor deficits in ADS patients were associated with worse patient functional outcomes as measured on SRS-30 and ODI questionnaires. Measuring IPH on routine radiographs may be helpful in associating clinical radicular pain with levels of potential nerve root compression, and may serve to guide patient management and surgical planning.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Abbreviations

IPH	interpedicular height
ADS	Adult degenerative scoliosis
OR	odds ratio
aOR	adjusted odds ratio
SRS-30	Scoliosis Research Society-30
ODI	Oswestry Disability Index
CI	confidence interval

References

1. Kobayashi T, Atsuta Y, Takemitsu M, Matsuno T, Takeda N. A prospective study of de novo scoliosis in a community based cohort. *Spine*. 2006; 31(2):178–82. [PubMed: 16418637]
2. Ploumis A, Transfeldt EE, Denis F. Degenerative lumbar scoliosis associated with spinal stenosis. *The spine journal : official journal of the North American Spine Society*. 2007; 7(4):428–36. [PubMed: 17630141]
3. Schwab FJ, Smith VA, Biserni M, Gamez L, Farcy JP, Pagala M. Adult scoliosis: a quantitative radiographic and clinical analysis. *Spine*. 2002; 27(4):387–92. [PubMed: 11840105]
4. Silva FE, Lenke LG. Adult degenerative scoliosis: evaluation and management. *Neurosurgical focus*. 2010; 28(3):E1.
5. Smith JS, Shaffrey CI, Fu KM, et al. Clinical and radiographic evaluation of the adult spinal deformity patient. *Neurosurgery clinics of North America*. 2013; 24(2):143–56. [PubMed: 23561553]
6. Birknes JK, White AP, Albert TJ, Shaffrey CI, Harrop JS. Adult degenerative scoliosis: a review. *Neurosurgery*. 2008; 63(3 Suppl):94–103. [PubMed: 18812938]
7. Korovessis P, Piperos G, Sidiropoulos P, Dimas A. Adult idiopathic lumbar scoliosis. A formula for prediction of progression and review of the literature. *Spine*. 1994; 19(17):1926–32. [PubMed: 7997925]
8. Glassman SD, Bridwell K, Dimar JR, Horton W, Berven S, Schwab F. The impact of positive sagittal balance in adult spinal deformity. *Spine*. 2005; 30(18):2024–9. [PubMed: 16166889]
9. Mendoza-Lattes S, Ries Z, Gao Y, Weinstein SL. Natural history of spinopelvic alignment differs from symptomatic deformity of the spine. *Spine*. 2010; 35(16):E792–8. [PubMed: 20581754]
10. Schwab F, Lafage V, Patel A, Farcy JP. Sagittal plane considerations and the pelvis in the adult patient. *Spine*. 2009; 34(17):1828–33. [PubMed: 19644334]
11. Epstein, NE., Epstein, JE. Lumbar stenosis. In: Youmans, JR., editor. *Neurological Surgery*. Philadelphia: Saunders; 1996. p. 2396-7.
12. Porter RW. Spinal stenosis and neurogenic claudication. *Spine*. 1996; 21(17):2046–52. [PubMed: 8883210]
13. Lurie JD, Tosteson AN, Tosteson TD, et al. Reliability of readings of magnetic resonance imaging features of lumbar spinal stenosis. *Spine*. 2008; 33(14):1605–10. [PubMed: 18552677]
14. Weinstein JN, Tosteson TD, Lurie JD, et al. Surgical versus nonsurgical therapy for lumbar spinal stenosis. *The New England journal of medicine*. 2008; 358(8):794–810. [PubMed: 18287602]
15. Fu KM, Rhagavan P, Shaffrey CI, Chernavvsky DR, Smith JS. Prevalence, severity, and impact of foraminal and canal stenosis among adults with degenerative scoliosis. *Neurosurgery*. 2011; 69(6):1181–7. [PubMed: 21712739]
16. Pugely AJ, Ries Z, Gnanapragasam G, Gao Y, Nash R, Mendoza-Lattes S. Curve Characteristics and Foraminal Dimensions in Patients with Adult Scoliosis and Radiculopathy. *Journal of spinal disorders & techniques*. 2013
17. Baldus C, Bridwell K, Harrast J, et al. The Scoliosis Research Society Health-Related Quality of Life (SRS-30) age-gender normative data: an analysis of 1346 adult subjects unaffected by scoliosis. *Spine*. 2011; 36(14):1154–62. [PubMed: 21289576]
18. Fairbank JC, Pynsent PB. The Oswestry Disability Index. *Spine*. 2000; 25(22):2940–52. discussion 52. [PubMed: 11074683]
19. Deviren V, Berven S, Kleinstueck F, Antinnes J, Smith JA, Hu SS. Predictors of flexibility and pain patterns in thoracolumbar and lumbar idiopathic scoliosis. *Spine*. 2002; 27(21):2346–9. [PubMed: 12438982]
20. Liu H, Ishihara H, Kanamori M, Kawaguchi Y, Ohmori K, Kimura T. Characteristics of nerve root compression caused by degenerative lumbar spinal stenosis with scoliosis. *The spine journal : official journal of the North American Spine Society*. 2003; 3(6):524–9. [PubMed: 14609699]
21. Transfeldt EE, Topp R, Mehdor AA, Winter RB. Surgical outcomes of decompression, decompression with limited fusion, and decompression with full curve fusion for degenerative scoliosis with radiculopathy. *Spine*. 2010; 35(20):1872–5. [PubMed: 20802398]

22. Ali RM, Boachie-Adjei O, Rawlins BA. Functional and radiographic outcomes after surgery for adult scoliosis using third-generation instrumentation techniques. *Spine*. 2003; 28(11):1163–9. discussion 9–70. [PubMed: 12782986]
23. Alimi M, Hofstetter CP, Tsiouris AJ, Elowitz E, Hartl R. Extreme lateral interbody fusion for unilateral symptomatic vertical foraminal stenosis. *European spine journal : official publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society*. 2015; 24(Suppl 3):346–52.
24. Chung SS, Lee CS, Kim SH, Chung MW, Ahn JM. Effect of low back posture on the morphology of the spinal canal. *Skeletal radiology*. 2000; 29(4):217–23. [PubMed: 10855470]
25. Kimura S, Steinbach GC, Watenpaugh DE, Hargens AR. Lumbar spine disc height and curvature responses to an axial load generated by a compression device compatible with magnetic resonance imaging. *Spine*. 2001; 26(23):2596–600. [PubMed: 11725241]
26. Schmid MR, Stucki G, Duewell S, Wildermuth S, Romanowski B, Hodler J. Changes in cross-sectional measurements of the spinal canal and intervertebral foramina as a function of body position: in vivo studies on an open-configuration MR system. *AJR American journal of roentgenology*. 1999; 172(4):1095–102. [PubMed: 10587155]

Figure 1. Intersegment interpedicular heights (IPHs) were measured for each level from L1 to S1. Bilateral IPHs were measured on anterior-posterior radiographs from the center of the rostral pedicle to the center of the caudal pedicle.

Figure 2.

Prevalence of lumbar radicular pain for each level in adult degenerative scoliosis. The prevalence of radicular pain at each level is shown among 60 patients with radicular pain. The probability of a radicular pain increased for caudal nerve roots (Cochran-Armitage test for linear trend, $p < 0.0001$).

Figure 3.

Radicular pain in adult degenerative scoliosis was associated with reduced interpedicular heights (IPHs). (A) Supine IPH was smaller when there was radicular pain on the same side; $*p = 0.002$. (B) Supine IPH was smaller when there was radicular pain measured at that same nerve root level ($**p = 0.0002$). (C) Radicular pain was associated with reduced IPHs on upright radiographs. Illustration (*left*) describes anatomical location of a radicular pain (*grey*) relative to 3 IPH measurements: IPH at the same side and level (*red*), IPH at the same level but contralateral side (*blue*), and IPH at a different level and contralateral side (*orange*). On upright radiographs, there was a significant interaction between side and root level ($p = 0.01$). IPHs with radicular pain at the same level and on the same side was significantly smaller than IPHs at the same level but opposite side ($\#p = 0.04$, *red vs. blue*). IPHs at the opposite side but same level were significantly larger than IPHs at different levels and sides ($***p = 0.03$, *blue vs. orange*). Analyses were performed with generalized estimating equation. $N_{\text{supine}} = 1230$. $N_{\text{upright}} = 2000$ IPHs. Data represented as mean $\pm$ standard error.

Table 1**Patient Population Characteristics**

Total Number of Patients	200
Mean Age (years)	50.7 ± 18.4
Female (%)	147/200 (73.5%)
Questionnaire Scores	
SRS-30	
Pain	3.1 ± 0.9
Function	3.4 ± 0.8
Self-Image	2.7 ± 0.7
Mental Health	3.8 ± 0.8
Oswestry-Disability Index	32.2 ± 18.4
Supine Thoraco-Lumbar Cobb Angle	34.6 ± 17.7°
Supine Lumbo-Sacral Cobb Angle	15.2 ± 10.3°
Upright Thoraco-Lumbar Cobb Angle	37.8 ± 19.8°
Upright Lumbo-Sacral Cobb Angle	15.1 ± 9.6°
% Dextroscoliosis	34%
Number of patients with radicular pain	60/200 (30%)
Side	
Right only	22/60 (36.6%)
Left only	13/60 (21.6%)
Both	25/60 (41.7%)
Number of patients with motor deficit	65/200 (32.5%)
Number of patients with sensory deficit	66/200 (33%)

Data represented as number of patients/total number with percentage or mean ± standard deviation.

Table 2

Between-group differences and associations of age, gender and questionnaire scores with radicular pain

Variable	No	Yes	OR (95% CI)	P-Value
Age (years)	45.1 ± 17.6	63.7 ± 12.6	2.36 (1.74–3.2) **	<0.0001 [#]
Age 55 (%)	54/140 (38.6)	50/60 (83.3)	7.96 (3.73–17)	<0.0001 [#]
Female (%)	98/140 (70)	49/60 (81.7)		0.09 [#]
With motor deficit (%)	28/140 (20)	37/50 (61.7)	4.51 (2.16–9.42)	<0.0001
With sensory deficit (%)	25/140 (17.9)	41/60 (68.3)	6.58 (3.08–14.0)	<0.0001
Questionnaire Scores				
SRS-30 Pain	3.2 ± 0.9	2.7 ± 0.4		0.41
SRS-30 Function	3.4 ± 0.8	2.8 ± 0.6		0.29
SRS-30 Self Image	2.7 ± 0.7	2.7 ± 0.8		0.59
SRS-30 Mental Health	3.8 ± 0.8	3.4 ± 0.9		0.26
Oswestry-Disability Index	29.8 ± 18.4	43.9 ± 12.8		0.1

N = 200 patients. Data represented as number of patients/total number of patients (%total) or mean ± standard deviation; OR, odds ratio; CI, confidence interval. Statistics by multivariable logistic regression after adjusting for continuous age except where indicated by [#](univariable logistic regression).

** Odds ratio for each decade increase in age.

Table 3

Between-group differences and associations of age, gender and questionnaire scores with motor deficits

Variable	No	Yes	OR (95% CI)	P-Value
Age (years)	46.9 ± 18.7	58.5 ± 15.1	1.49 (1.22–1.81) **	<0.0001 [#]
Age 55 (%)	54/135 (40)	50/65 (76.9)	5.00 (2.55–9.79)	<0.0001 [#]
Female (%)	98/135 (72.6)	49/65 (75.4)		0.68 [#]
With sensory deficit (%)	25/135 (18.5)	41/65 (63.1)	5.73 (1.86–11.5)	<0.0001
Questionnaire Scores				
SRS-30 Pain	3.1 ± 0.8	3.1 ± 1.1		0.33
SRS-30 Function	3.5 ± 0.8	2.9 ± 0.9	0.49 (0.27–0.89)	0.02
SRS-30 Self Image	2.8 ± 0.7	2.5 ± 0.8		0.33
SRS-30 Mental Health	3.8 ± 0.8	3.8 ± 0.8		0.62*
Oswestry-Disability Index	28.5 ± 16.3	43.8 ± 19.8	1.04 (1.01–1.07)	0.005

N = 200 patients. Data represented as number of patients/total number of patients (%total) or mean ± standard deviation; OR, odds ratio; CI, confidence interval. Statistics by multivariable logistic regression after adjusting for continuous age except where indicated by [#](univariable logistic regression) and by * (multivariable logistic regression after adjusting for age category).

** Odds ratio for each decade increase in age.

Table 4

Between-group differences and associations of age, gender and questionnaire scores with sensory deficits

Variable	No	Yes	OR (95% CI)	P-Value
Age (years)	46.1 ± 18.8	60 ± 13.4	1.66 (1.34–2.05)**	<0.0001 [#]
Age 55 (%)	53/134 (39.5)	51/66 (77.3)	5.2 (2.65–10.2)	<0.0001 [#]
Female (%)	100/134 (74.6)	47/66 (71.21)		0.61 [#]
Questionnaire Scores				
SRS-30 Pain	3.1 ± 0.9	3.1 ± 0.8		0.24
SRS-30 Function	3.4 ± 0.8	3.1 ± 0.7		0.51
SRS-30 Self Image	2.7 ± 0.8	2.7 ± 0.6		0.59
SRS-30 Mental Health	3.8 ± 0.9	3.7 ± 0.7		0.83
Oswestry-Disability Index	30.1 ± 18.8	39.6 ± 14.7		0.34

N = 200 patients. Data represented as number of patients/total number of patients (%total) or mean ± standard deviation; OR, odds ratio; CI, confidence interval. Statistics by multivariable logistic regression after adjusting for continuous age except where indicated by [#](univariable logistic regression).

** Odds ratio for each decade increase in age.

Table 5**Interpedicular Heights in ADS**

Level	Supine*	Upright**	Change from Supine to Upright*,†
L1/2	3.33 ± 0.45 cm	3.10 ± 0.58 cm	-0.23 ± 0.44 cm
L2/3	3.42 ± 0.48 cm	3.16 ± 0.63 cm	-0.31 ± 0.45 cm
L3/4	3.38 ± 0.47 cm	3.13 ± 0.52 cm	-0.27 ± 0.52 cm
L4/5	3.39 ± 0.55 cm	3.13 ± 0.62 cm	-0.26 ± 0.64 cm

* N = 246 observations per level.

** N = 400 observations per level

† Change in IPH is calculated as upright minus supine.

Data represented as mean ± standard deviation.