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# DEFINING CLINICALLY-RELEVANT VALUES FOR DEVELOPMENTAL SPINAL STENOSIS: A LARGE SCALE MRI STUDY

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*Structured Abstract (300 words)


## Abstract

**Study Design:** Case-control study

**Objective:** The aim of this study was to define clinically-relevant relative and critical (absolute) MRI values of lumbar spinal stenosis in a cohort of 100 surgical cases and 100 asymptomatic controls.

**Summary of Background Data:** Developmental spinal stenosis is a precipitating factor in patients presenting with lumbar canal stenosis. Yet due to a lack of agreement on definitions and methods of assessment, as well as ethnic-specific normative values, its prevalence and significance is not known.

**Methods**: This was a case-control study comparing 100 age and sex-matched asymptomatic, volunteers to that of 100 patients who underwent surgery for spinal stenosis. All patients were of Chinese ethnicity and their details were blinded to two observers. Spinal stenosis parameters were measured based on axial (pedicle level) and sagittal (mid-sagittal) MRI scans.

**Results**: Anteroposterior (AP) spinal canal diameters changes with levels. At each level, patients were found to have significantly narrower AP canal diameters compared with controls. By use of receiver operating characteristic (ROC) curve, we defined developmental spinal stenosis if the AP canal diameter at L1<20mm, L2<19mm, L3<19mm, L4<17mm, L5<16mm and at S1<16mm based on a value including 50% of controls and demonstrated best sensitivity and specificity. Furthermore, for L4, L5 and S1, critical stenosis values could be defined, below which almost all subjects needed surgery, these were L4<14mm, L5<14mm and S1<12mm.

**Discussion**: This is the largest MRI-based study with standardized measurements and comparable groups to determine clinically-relevant radiographic criteria for lumbar spinal stenosis. The findings strongly suggest that developmental stenosis plays an important role in the pathogenesis of symptomatic spinal stenosis. Critical values of stenosis below which symptoms were highly likely were defined. These will need to be validated by longitudinal studies in future. However, they may possess clinical utility in determining the appropriate levels requiring canal-widening surgery.

**Key Words**: Developmental; Spinal; Stenosis; MRI; Axial; Sagittal; Bony; Canal; Diameter; Critical

## Key Points

1. Patients requiring surgery for spinal stenosis were found to have narrower bony spinal canal diameters than normal subjects.

2. Critical values of stenosis by axial AP diameter of the bony spinal canal were defined for L4 (14mm), L5 (14mm), and S1 (12mm) which indicated the patients who require decompression surgery.

3. Values of developmental spinal stenosis were defined as L1:20mm, L2:19mm, L3:19mm, L4:17mm, L5:16mm and in S1:16mm which identified subjects with a probable chance of developing symptoms of spinal stenosis requiring surgery and should be closely followed-up.

**Mini-Abstract**

In this MRI-based study of 200 cases and controls, patients were found to have narrower bony lumbar spinal canal diameters than controls, strongly implicating developmental stenosis in the pathogenesis of symptomatic lumbar stenosis. Critical values of narrowing predicting the need for surgery, and level-specific values of developmental stenosis were defined.

## INTRODUCTION

Lumbar developmental spinal stenosis is likely a genetic disturbance during both fetal and postnatal development of the lumbar vertebrae until maturity.[1-3] Several mutations have been associated with spinal stenosis such as COL9A2, Trp2 and Trp3 indicating that genetic factors have an important role in its pathogenesis.[4-6] These findings suggest that the genetic predisposition is similar to that of disc degeneration.[4,7,8] In the presence of a narrow lumbar canal, changes associated with degeneration or aging, such as intervertebral disc bulging and facet hypertrophy, may readily cause compressive symptoms.

Verbiest[2] defined developmental narrowing of the lumbar canal by an abnormally short antero-posterior diameter on plain radiographs (**Figure 1**), and an absolute value of less than 10mm as developmental stenosis. This is still a commonly accepted criterion although the rationale for this value is not known. Throughout the years, numerous other criteria have been proposed[2,3,9-16] based on imaging (**Table 1**). However, these studies utilized inconsistent imaging modalities including radiographs, CT and MRI,[3,9,12,15,16] some were based on heterogeneous populations,[3,9,10,12,15,17,18] some lacked control groups,[3,9,10,12,18] while others based definitions on generalized measurements of the entire lumbar spine.[3,9,10,12,15-18] In addition, absolute values of anatomic parameters are likely to vary between ethnic groups, and no comparative anatomic studies have been carried out in the Chinese population, which represent a third of the world's population.

Due to the limitations of our understanding of developmental lumbar spinal stenosis as stated above, the aim of this study was multi-faceted. For one, we aimed to confirm whether patients presenting for surgery with symptoms of spinal stenosis had narrower canals when compared to an asymptomatic control group. Secondly, we aimed to define the value for lumbar spinal stenosis for a Chinese population. Thirdly, we endeavored to define a critical value of anatomic narrowing of the lumbar bony spinal canal that has diagnostic utility in determining surgical candidates.

## MATERIALS AND METHODS

### *Study Design*

Following approval by the institutional review board, a case-control study design assessing 100 asymptomatic individuals and 100 patients who underwent surgery for spinal stenosis between December 2001 and December 2011 was performed. All subjects were of Chinese ethnicity. The control group was sex- and age-matched, and randomly selected based on those criteria from the Hong Kong Disc Degeneration Cohort Study.[19-22] This is a population-based cohort of approximately 3,500 individuals with MRI information, whose recruitment was not predicated on condition. Control subjects for the current study were only selected if there was no past history of low back or leg pain, spinal pathologies or surgery. The 100 surgical patients were selected at random from a pool of patients who underwent surgery for spinal stenosis in the past 10 years. All included patients were diagnosed to have spinal stenosis by a senior spine surgeon

based on symptoms of neurogenic claudication. All patients required MRI assessment to confirm the diagnosis and level of involvement. Patients were offered decompression surgery if symptoms persisted despite 6 weeks of conservative management that includes avoidance of spine extension positions, physical therapies (core muscle strengthening and aerobic conditioning), and non-steroidal anti-inflammatory medications. Subjects with congenital deformities, previous infections, tumors, trauma or spondylolisthesis of the lumbar spine were excluded from the study.

*Measurements*

Sagittal and axial MRI images of the lumbar spine from L1-S1 were utilized for all subjects. Lumbar sagittal T2-weighted and axial T1 or T2-weighted MRIs from L1-S1 were assessed in all subjects. All controls had T1-weighted axial MRI films. Eight subjects of the patient group only had T2-weighted axial MRI films for measurement. Data was collected as usual as our previous study had shown that T1 and T2-weighted MRI films have comparable spinal canal measurements.[23] Two investigators (JPYC, HS), blinded to all clinical information, performed the measurements. A consensus on the standardized method of measurements was made prior to data collection. For reliability testing, ten random subjects retrieved from the cohort of controls were used for intra-observer and inter-observer reliability assessments. The first and second round of measurements was performed at least one month apart. All images were measured using the Centricity Enterprise Web V3.0 (GE Medical Systems, 2006), VirtualDrive Pro (FarStone) and ImageJ (version 1.45) software.

Measurements were performed in both MRI axial (**Figure 2 and 3**) and sagittal (**Figure 4**) scans. The axial image used for measurement was the cut with the thickest pedicle diameter while the sagittal image used was the mid-sagittal cut that bisected the spinous processes. Measurements in the axial scan **(Figure 2)** included: midline anteroposterior (AP) vertebral body diameter, mid-vertebral body width, midline AP bony spinal canal diameter, midline AP dural sac diameter, bony spinal canal width/interpedicular distance, pedicle width (right and left), and lamina angle (**Figure 3)**: angle made from two lines crossing from the base of the spinous process along the lamina to the base of the pedicles. Measurements in the sagittal scan **(Figure 4)** included the midline AP body diameter, mid-vertebral body height and AP bony spinal canal diameter (from the most prominent tip of the spinous process, taking a perpendicular line to the vertebral body).

Most measurements, except for the AP bony spinal canal diameter and the lamina angle, in this study have been previously reported.[2,3,9,10,13,15,16,24-29] The lamina angle was a bony measurement used to assess spinal stenosis since it could represent the lamina shape and were measured with an angle from the base of the spinous process to the pedicles. This measurement had not been verified by previous studies and was constructed by the authors at the start of the study. It was postulated that a more acute lamina angle (narrower space between the laminas) would lead to a narrower bony spinal canal.

*Statistical Analysis*

Descriptive and frequency statistics were performed of the data. Reliability assessment was based on Cronbach's alpha analysis. Excellent and good reliability were noted in alpha values of 0.90-1.00 and 0.80-0.89, respectively.[30] Following normality testing of the data using

the Shapiro-Wilk test, paired t-tests were performed to detect image measurement differences between the two groups. A p-value of less than 0.05 was considered significant.

Receiver operating characteristic (ROC) curve was used to identify the most significant imaging measurement based on area under the curve (AUC) analysis. ROC analysis was also used to identify cut-off critical values for symptomatic developmental spinal stenosis between the control and patient groups. The critical values for absolute spinal stenosis were noted as the value with the highest sensitivity in symptomatic cases. Absolute stenosis or critical stenosis acts as the cut-off value for the axial bony spinal canal AP diameter; therefore, any subject with a narrow canal diameter regarded as having absolute stenosis would most likely require surgery for spinal stenosis. For relevant stenosis or developmental stenosis, the defining value was based on the cut-off value of AP bony spinal canal diameter for patients that would include approximately 50% of the controls and also demonstrating the best sensitivity and specificity for identifying this subject group. These relative values indicate which subjects are likely to develop spinal stenosis symptoms requiring surgery in the future. Although having the 50% cut-off point may not include all patients with developmental narrowing, the authors believe that a clinically useful definition that has a bearing on the future risk of symptom development is preferable. As such, using the proposed criteria, half of the subjects with diameters less than this value have developed symptoms. Having a respectable sensitivity and specificity is important to determine a cut-off value that does not miss many actual patients with developmental narrowing and avoids including too many normal subjects, which would heavily burden a follow-up clinic for these patients.

## RESULTS

The mean age for controls was 45 years (SD ±1.4, range 20-69) while the patient group was 62.6 years (SD ±14.9, range 15-86). There were 50 males and 50 females in the control group and 48 males and 52 females in the patient group. Good to excellent inter-observer reliability (a=0.88-0.97) and excellent intra-observer reliability between the two observers (a=0.94-0.99 and a=0.94-0.99) were noted. The mean body weight was 63.4 kilograms (SD ±12.5, range 43-98), body height was 1.65 meters (SD ±0.1, range 1.45-1.84) and the BMI was 23.1 $kg/m^2$ (SD ±3.5, range 16.1-34.1). No differences were found after age stratification for gender (p=0.984), body weight (p=0.821), body height (p=0.135) and BMI (p=0.262) between groups.

Comparing the two subject groups, controls had significantly wider AP bony spinal canal diameters than patients (**Table 2/Figure 5**). While, as would be expected for symptomatic subjects, the AP dural diameter was narrower **(Table 3).** For other measured MRI parameters of the spinal canal (**Table 3**), there were no statistically significant differences between the two groups.

Based on AUC analysis of the measured imaging dimensions, axial AP bony spinal canal diameter was deemed most predictive for developmental spinal stenosis (**Table 4**). Since all patients had symptomatic levels at L4, L5 or S1, absolute stenosis values of only these three levels were reported (**Table 5**). Level-specific values of relative stenosis were also suggested (**Table 5**).

## DISCUSSION

Our results showed significantly wider bony spinal canal diameters in controls as compared to patients. Thus, confirming our hypothesis that patients with symptomatic spinal stenosis requiring surgery have narrowed canals making them more prone to developing symptoms. Moreover by use of the ROC curve, we were able to identify critical values of canal diameter below which was evident in all patients who require surgery for spinal stenosis. Since defining critical stenosis requires a comparison of control and symptomatic subjects, and that the majority of patients presented with symptoms only between L4 and S1, we could only define critical stenosis values for these three levels. Nevertheless, excellent sensitivity and specificity results for these three levels were obtained. As all controls had wider bony spinal canal diameters, any subject with canal sizes reaching these critical levels may potentially benefit from pre-emptive canal widening surgery. Further longitudinal studies based on these observed values are required to demonstrate any benefit of surgery for asymptomatic canal narrowing. By performing a single stage canal widening surgery initially, these patients may avoid repeat surgery at adjacent levels; however, further studies are needed to assess the clinical utility of our observed values in this context.

There are no guidelines as to how developmental stenosis could be defined. Since in a population, such measurements are a continuous variable, to have an arbitrary cut-off at a specific diameter, may not be usefully clinically. Thus, we based the definition of developmental stenosis on a value that includes approximately 50% of the controls with demonstrated best possible sensitivity and specificity results to identify this at-risk group. These relative values are

indicative with adequate sensitivity and specificity as to which subjects may develop future spinal stenosis symptoms requiring surgery. The 50% cut-off point was an arbitrary yet appropriate value since it would only be relevant if we could at least distinguish 50% of our possible patients. By applying this cut-off value, individuals with relatively narrowed spinal canals can still be followed-up without overloading a busy clinic.

Based on our criteria, it is highly likely that patients who require surgery for spinal stenosis would have critically narrowed axial bony spinal canal AP diameters; while patients with relatively narrowed axial bony spinal canal AP diameters should be closely followed-up because at least 50% of patients have similar sized spinal canals.

Reoperation is not an uncommon event and occurs in 13% of patients with approximately 50% of reoperations performed at adjacent levels.[31] This leads to an average reoperation rate of 3.3% of patients per year. Other studies showed that reoperation after decompressive laminectomy varied from 5-23%.[32-34] Based on this study, one could hypothesize that patients with pre-existing narrow canals are more likely to develop symptoms of spinal stenosis, and are also more at risk from developing symptoms from adjacent level degeneration.

Obtaining accurate measurement of different variables was important for comparison. It has been demonstrated that measurements of canal diameters using either T1 or T2-weighted MRI images were comparable and accurate.[23] Hence both types of images were used in the current study. The key measured variable discussed in this study was the AP bony spinal canal diameter. Also known as the pedicle length, this parameter equated to the space available for the neural elements to coexist with other pathologies such as osteophytes, disc protrusions or hypertrophied soft tissues. Most studies lacked a uniform method of measurement for the bony spinal canal diameter.[2,9,10,13-16,24,25,28] Some studies used the mid-vertebral level on sagittal cuts,

while others used the disc or endplate level on axial and sagittal cuts. These methods may be subject to wide variability as the posterior curvature of the vertebral body may affect mid-vertebral level assessments at the sagittal level and disease may affect the accuracy of measurements at the disc and endplate levels. In this study, the bony spinal canal diameter can be better appreciated at the pedicle level because of the consistent landmarks.

Inevitably, this study had some limitations. Of note was that the MRI protocol was not standardized between the groups. This might have led to some errors in measurement if the cuts were not absolutely comparable between the controls and patients. Sagittal scans might have posed some problems since the mid-sagittal cut might not be consistent in the presence of scoliosis or poor patient positioning in the MRI scanner. Sagittal vertebral body width and height were subject to the individual's degree of degenerative disc disease and this might affect the accuracy of measurements. In such instances, special attention was required to avoid pitfalls, such as including osteophytes found on the edge of the vertebral bodies (usually more hypointense than the bone in the vertebral body) and degenerated disc spaces and endplates (hypointense lining) into the measurements. This was likely the cause of finding controls to have taller and wider vertebral bodies on the sagittal scan than patients. The height might be decreased due to collapse from elderly age and difficulty in distinguishing the bony contour from the endplates or osteophytes which again was more prominent in the older subjects. Thus, there was a limitation in direct comparison between the controls and patients for vertebral body measurements.

This is the largest MRI based study (**Table 1**) on lumbar spinal stenosis conducted in a Chinese population. Patient parameters were blinded to the two observers and the measurement techniques were uniform. Inter and intra-observer reliability analyses were performed, noted as

good to excellent. Patients were found to have narrower bony spinal canal diameters than controls. Our study identified absolute critical values of spinal stenosis of L4 to S1. Furthermore, our study noted level-specific suggested values from L1-S1 of developmental spinal stenosis.

## CONCLUSIONS

Our study further broadens the understanding of developmental spinal stenosis. Understanding its critical values throughout the lumbar spine may provide the rationale and patient selection for preemptive canal widening surgery to prevent future development of symptoms. However, to confirm this, future prospective follow-up studies of these at risk subjects would be required to see whether they develop symptoms at developmentally stenotic levels. This study also further elaborates on the phenotype of stenosis, which may serve as the foundation for future genetic analysis. For genome-wide association studies, these quantitative values described in this study can help differentiate study subjects into having either normal or developmentally narrowed spinal canals. By identifying the gene polymorphisms responsible for spinal canal narrowing, functional genes and possible gene therapies can be introduced.

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# TABLES

## Table 1: Previous studies addressing developmental spinal stenosis

| Author | Journal (Year) | Imaging | Subjects | Age | Findings | Limitations |
|---|---|---|---|---|---|---|
| **Boden**[17] | Journal of Bone and Joint Surgery (American) (1990) | MRI$^{+}$ | 67 asymptomatic subjects | 20-80yrs | 35% had bulging discs | Subjective readings only |
| **Bolender**[9] | Journal of Bone and Joint Surgery (American) (1985) | CT$^{*}$ and cadaveric | 24 patients | Unknown | Narrowed dural sac equates to stenosis | Unknown measurement level |
| **Chatha**[10] | Bulletin NYU (2011) | MRI$^{+}$ | 100 patients | 4-94yrs | 0.9cm as cut-off for stenosis | Uncertain method of obtaining patients |
| **Fang**[12] | Journal of Spinal disorders (1994) | CT$^{*}$ | 100 patients | 18-60yrs Chinese population | Canal narrows with level Minimum sagittal diameter 10.8mm | No controls |
| **Lee**[15] | Spine (1995) | Cadaveric | 90 (cadaveric) | 19-70yrs | Narrowing of canal AP from cranial to caudal then widens at L4-5 (14.5-15.4mm) | Cadaveric study |
| **Santiago**[35] | European Spine Journal (2001) | CT$^{*}$ | 119 patients, 39 controls | Mean 42yrs | No difference in central canal | No standardized measuring level |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Singh**[16] | The Spine Journal<br><br>(2005) | MRI[+] and XR[#] | 15 patients, 15 controls | 41-65yrs | Body to pedicle length ratio: 0.36 is critical value in MRI and 0.43 for XR | Small sample size<br><br>Arbitrary endpoint for pedicle length measurement |
| **Verbiest**[3] | Spine<br><br>(1976) | XR[#] | 116 patients | Unknown | Absolute stenosis: <10mm<br><br>Relative stenosis: 10-12mm | All vertebral levels measured<br><br>Generalized criteria |

[+]: Magnetic Resonance Imaging.

[*]: Computed tomography.

[#]: X-ray radiograph.

**Table 2: Comparison of anteroposterior bony spinal canal diameters between control subjects and patients**

| | Controls<br>Mean (±SD) | Patients<br>Mean (±SD) | p-value |
|---|---|---|---|
| **L1** | 21.8 (2.5) | 19.7 (2.3) | <0.001* |
| **L2** | 21.9 (2.5) | 19.7 (3.5) | <0.001* |
| **L3** | 22.4 (3.0) | 19.2 (3.5) | <0.001* |
| **L4** | 20.2 (2.9) | 17.3 (3.3) | <0.001* |
| **L5** | 19.6 (2.9) | 16.0 (2.8) | <0.001* |
| **S1** | 12.9 (7.8) | 16.1 (2.7) | <0.001* |

* Asterisk denoted statistical significance.

**Table 3: Measurement comparisons between control subjects and patients**

| Measurement | Controls<br>Mean mm (±SD), except for lamina angle[#] (°) | Patients<br>Mean mm (±SD), except for lamina angle[#] (°) | p-value |
|---|---|---|---|
| **Axial AP[+] vertebral body diameter** | | | |
| **L1** | 28.6 (2.6) | 28.5 (3.7) | 0.899 |
| **L2** | 30.1 (2.9) | 30.3 (3.5) | 0.701 |
| **L3** | 31.7 (2.8) | 31.8 (3.2) | 0.803 |
| **L4** | 31.8 (3) | 31.9 (3.2) | 0.958 |
| **L5** | 32.5 (3.1) | 32.4 (3.6) | 0.808 |
| **S1** | 24.3 (14.5) | 33 (3.6) | <0.001* |
| **Axial vertebral body width** | | | |
| **L1** | 37.5 (3.2) | 37.7 (4) | 0.749 |
| **L2** | 38.4 (3.7) | 37.8 (4) | 0.385 |
| **L3** | 38.8 (3.9) | 39.5 (4.4) | 0.268 |
| **L4** | 41.5 (3.9) | 41.5 (4) | 0.973 |
| **L5** | 44.7 (4.8) | 47.1 (5.4) | 0.001* |
| **S1** | 26 (27.5) | 52.3 (4.9) | <0.001* |
| **Axial Spinal Canal AP[+] diameter** | | | |
| **L1** | 21.8 (2.5) | 19.7 (2.3) | <0.001* |
| **L2** | 21.9 (2.5) | 19.7 (3.5) | <0.001* |
| **L3** | 22.4 (3) | 19.2 (3.5) | <0.001* |
| **L4** | 20.2 (2.9) | 17.3 (3.3) | <0.001* |
| **L5** | 19.6 (2.9) | 16 (2.8) | <0.001* |

| | | | |
|---|---|---|---|
| **S1** | 12.9 (7.8) | 16.1 (2.7) | <0.001* |
| **Axial Dural Sac AP[+] diameter** | | | |
| **L1** | 16 (1.8) | 14.8 (1.7) | 0.004* |
| **L2** | 15.4 (1.9) | 13.8 (2.5) | <0.001* |
| **L3** | 15 (2.1) | 12.6 (1.9) | <0.001* |
| **L4** | 13.6 (2.1) | 11.3 (2) | <0.001* |
| **L5** | 13.4 (2.6) | 11 (2.4) | <0.001* |
| **S1** | 8.3 (5.5) | 10.3 (3.5) | 0.004* |
| **Axial interpedicular distance** | | | |
| **L1** | 22.5 (1.9) | 23.5 (2.3) | 0.026* |
| **L2** | 22.8 (1.9) | 23.1 (1.7) | 0.339 |
| **L3** | 24 (1.9) | 24.2 (1.8) | 0.298 |
| **L4** | 25.3 (2.2) | 25.3 (2.1) | 0.974 |
| **L5** | 30 (2.8) | 30.7 (3.2) | 0.043* |
| **S1** | 25.2 (14.8) | 33.3 (2.3) | <0.001* |
| **Axial right pedicle width** | | | |
| **L1** | 6.1 (1.4) | 5.2 (1.6) | 0.005* |
| **L2** | 6.1 (1.5) | 5.9 (1.4) | 0.408 |
| **L3** | 7.8 (2) | 7.3 (1.7) | 0.093 |
| **L4** | 9.7 (2.1) | 9.1 (1.9) | 0.033* |
| **L5** | 14.2 (2.6) | 13.2 (2.4) | 0.005* |
| **S1** | 13.3 (8.9) | 18.4 (3.1) | <0.001* |
| **Axial left pedicle width** | | | |
| **L1** | 6.4 (1.7) | 5.6 (1.5) | 0.038* |

| | | | |
|---|---|---|---|
| **L2** | 6.4 (1.6) | 6.3 (1.5) | 0.718 |
| **L3** | 7.6 (1.9) | 7.7 (1.8) | 0.584 |
| **L4** | 9.7 (2.3) | 9.7 (1.9) | 0.835 |
| **L5** | 13.3 (2.7) | 13.3 (2.8) | 0.962 |
| **S1** | 13.3 (8.9) | 18.5 (3.3) | <0.001* |
| **Axial lamina angle**[#] | | | |
| **L1** | 120.6 (8.5) | 119.5 (7.2) | 0.523 |
| **L2** | 120.5 (8.8) | 121.7 (11.5) | 0.489 |
| **L3** | 118.4 (8.7) | 121.2 (9.5) | 0.031* |
| **L4** | 111 (10.1) | 110.6 (8.6) | 0.757 |
| **L5** | 94.6 (27.9) | 98 (9.5) | 0.259 |
| **Sagittal Vertebral Body Width** | | | |
| **L1** | 28.7 (2.8) | 26.9 (3.1) | <0.001* |
| **L2** | 30.3 (3.1) | 28 (3.5) | <0.001* |
| **L3** | 32 (3.3) | 29.6 (3.6) | <0.001* |
| **L4** | 32 (3) | 30.3 (2.9) | <0.001* |
| **L5** | 31.2 (3.5) | 29.8 (2.9) | 0.003* |
| **S1** | 23.5 (4) | 22.2 (3) | 0.010* |
| **Sagittal Vertebral Body Height** | | | |
| **L1** | 24.4 (2.1) | 22.3 (2.2) | <0.001* |
| **L2** | 25.1 (1.7) | 23 (1.9) | <0.001* |
| **L3** | 25 (1.8) | 22.7 (1.8) | <0.001* |
| **L4** | 24.4 (1.9) | 22 (2.2) | <0.001* |
| **L5** | 23.9 (1.8) | 21.5 (1.9) | <0.001* |
| **S1** | 25.8 (2.7) | 24.3 (2.4) | <0.001* |

| **Sagittal Spinal Canal Width** | | | |
|---|---|---|---|
| **L1** | 15.5 (1.5) | 15.3 (1.7) | 0.338 |
| **L2** | 14.5 (1.4) | 14.7 (1.8) | 0.468 |
| **L3** | 13.7 (1.6) | 13.8 (2.1) | 0.888 |
| **L4** | 13.8 (2) | 13.7 (2) | 0.578 |
| **L5** | 14.1 (2.1) | 14.2 (2.9) | 0.727 |
| **S1** | 12.5 (3.2) | 12 (2.5) | 0.204 |

* Asterisk denoted statistical significance.

[+]: Anteroposterior.

[#]: Lamina angle was measured with an angle from the base of the spinous process to the pedicles.

**Table 4: Receiver operating characteristic (ROC) analysis for anteroposterior bony spinal canal diameter**

| | Area Under the Curve (AUC) | p-value | 95% CI[+] |
|---|---|---|---|
| L1 | 0.66 | 0.028* | 0.518-0.803 |
| L2 | 0.66 | 0.030* | 0.523-0.794 |
| L3 | 0.81 | <0.001* | 0.712-0.916 |
| L4 | 0.84 | <0.001* | 0.725-0.946 |
| L5 | 0.82 | <0.001* | 0.715-0.933 |
| S1 | 0.55 | 0.523 | 0.399-0.694 |

[+]: A 95% confidence interval (CI) value below the value 1 indicates statistical significance.

* Asterisk denotes statistical significance.

**Table 5: Receiver operating characteristic (ROC) analysis of critical stenosis and developmental stenosis for anteroposterior bony spinal canal diameter**

| | **Critical Stenosis**[+] | **Sensitivity** | **Specificity** |
|---|---|---|---|
| L4 | 14mm | 100% | 80% |
| L5 | 14mm | 98.7% | 85% |
| S1 | 12mm | 97.3% | 90% |
| | **Developmental Stenosis*** | **Sensitivity** | **Specificity** |
| L1 | 20mm | 50% | 76% |
| L2 | 19mm | 30% | 93.3% |
| L3 | 19mm | 55% | 93.3% |
| L4 | 17mm | 65% | 92% |
| L5 | 16mm | 45% | 92% |
| S1 | 16mm | 50% | 68% |

[+]: Critical (absolute) stenosis acts as the cut-off value for the axial bony spinal canal anteroposterior diameter; thereby, any subject with a narrow canal diameter regarded as having critical stenosis would most likely require surgery for spinal stenosis.

[*]: Developmental (relative) stenosis was based on the cut-off value of the anteroposterior bony spinal canal diameter for patients that would include approximately 50% of the controls, with best sensitivity and specificity for identifying this subject group. These values indicate which subjects are likely to develop spinal stenosis symptoms requiring surgery.

## Figure Legends

**Figure 1**: Sagittal radiograph of a patient with spinal stenosis showing generalized short pedicles, which are decreasing in trend from cranially to caudally.

**Figure 2:** Axial MRI measurements: (A) midline AP vertebral body diameter; (B) mid-vertebral body width; (C): midline AP spinal canal diameter; (D): AP dural sac diameter; (E) spinal canal width/interpedicular distance; and (G): pedicle width (right and left).

**Figure 3:** Axial MRI measurement of the lamina angle (angle made from two lines crossing from the base of the spinous process along the lamina to the base of the pedicles).

**Figure 4:** Sagittal MRI measurements: (H) midline AP body diameter; (I) mid-vertebral body height; and (J) AP spinal canal diameter (from the most prominent tip of the spinous process, taking a perpendicular line to the vertebral body).

**Figure 5:** Bar graph showing patients (red bar) have narrower AP spinal canal diameters than controls (blue bar) at all levels (L1-S1), which was statistically significant.

Figure 2
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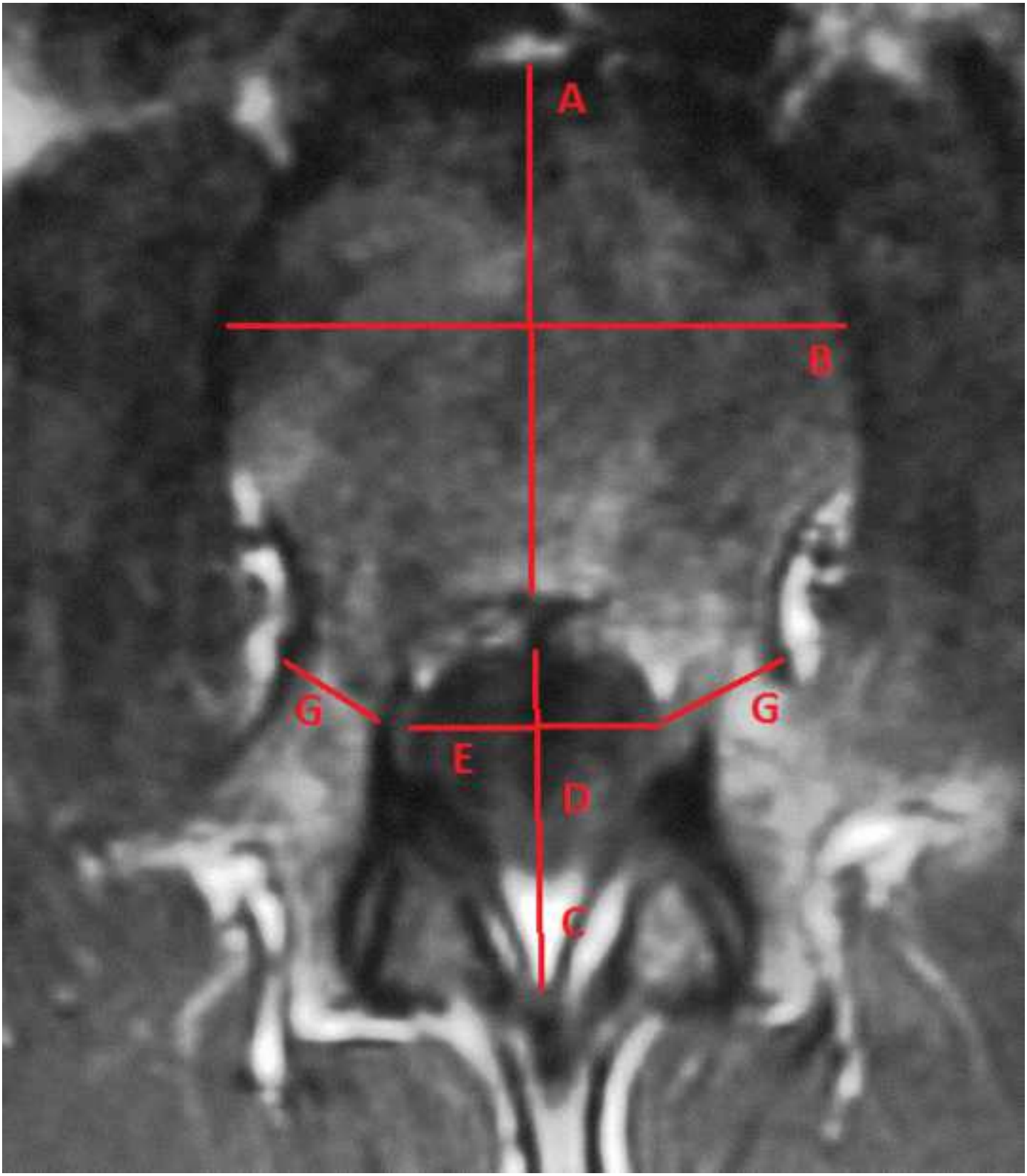

Figure 3
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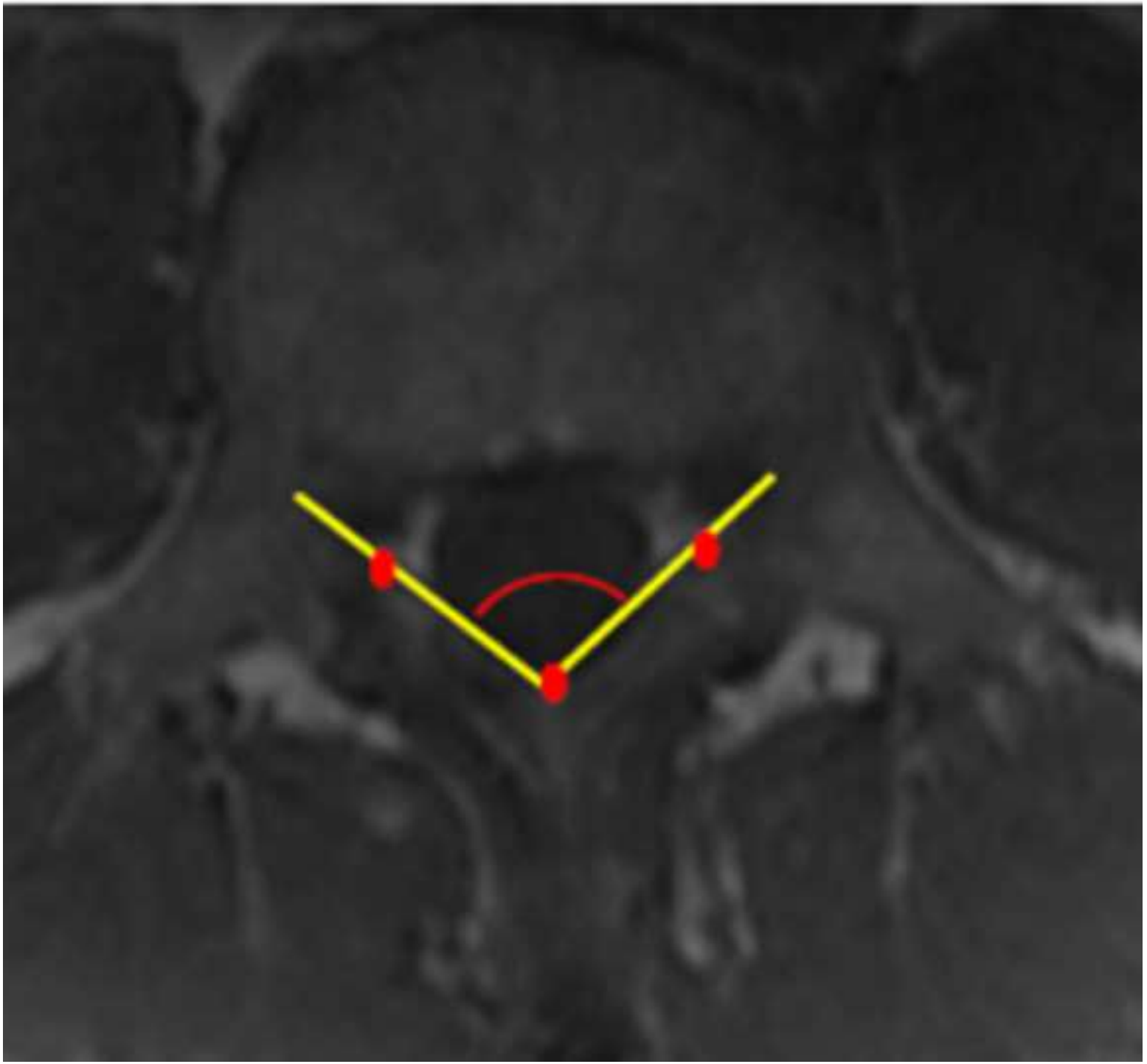

Figure 4
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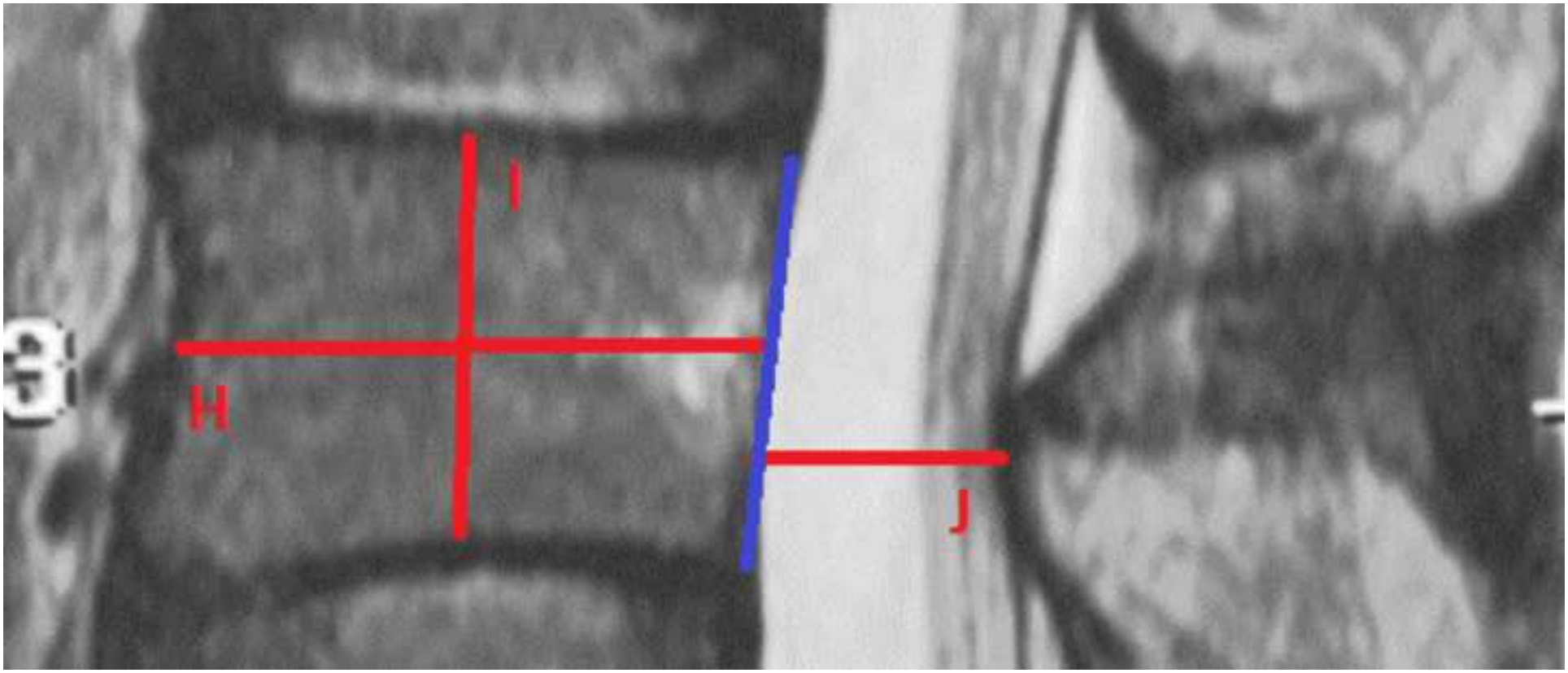

Figure 1
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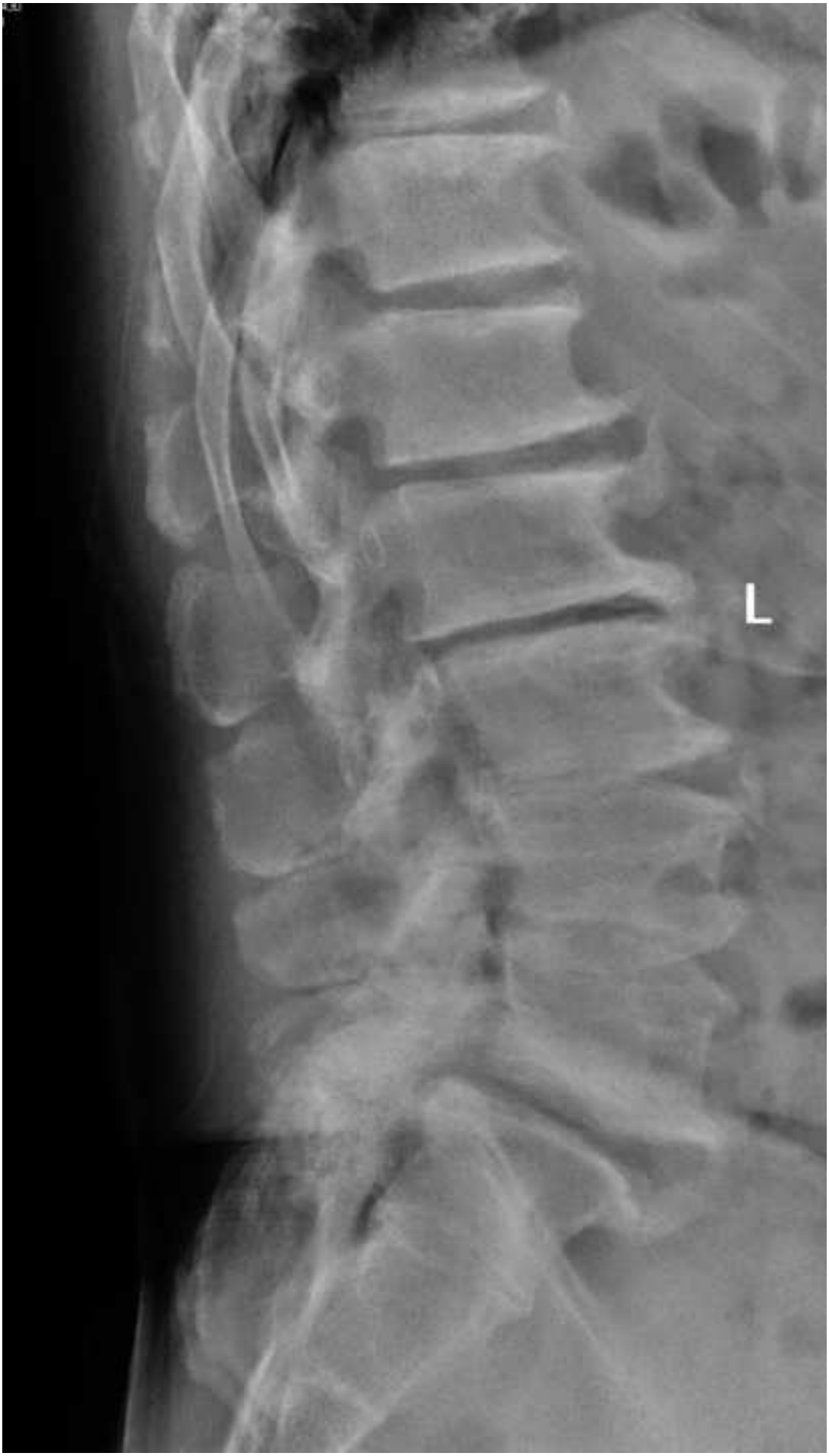

Figure 5
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