aorta distance ranged from 11 to 52 mm with an average of 23.7 mm and from 36 to 72 mm with an average of 55.2 mm, respectively; the pedicular line–aorta distance ranged from −4 to 59 mm (average 18.3 mm) and from 33 to 75 mm (average 51.0 mm), respectively. From the cephalad to the caudal direction, the aorta was seen at the antero-lateral position of the vertebral body of T4 or T5. The aorta moved to the left side laterally and posteriorly as it descended, changing its course at T7 and moving medially and anteriorly. It located in front of the vertebral body at the left T12 pedicle. At the lumbar spine, the aorta moved to the right side.

The ratio of warning pedicles increased as the direction error or the screw length increased (Fig. 4). When the direction error was within 30° and the screw length was 40 mm, the ratio was highest at T4 with 69%, followed by T11 (67%), T5 (54%), T10 (46%) and T12 (39%), and this trend was consistent in any scenario.

No parameter of the main thoracic curve correlated with the *X*-unit of the left pedicle–aorta distance at the apex.

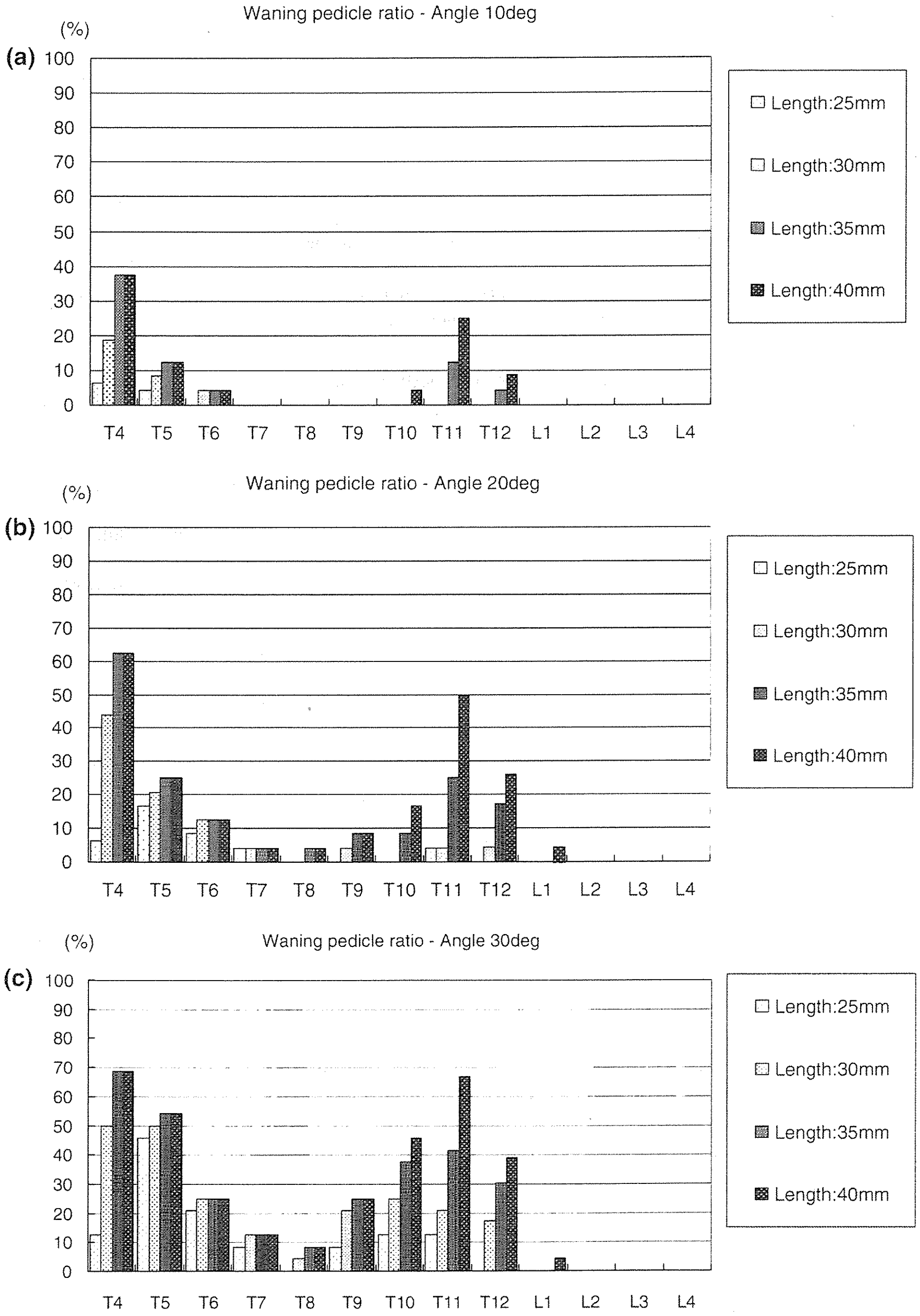

Fig. 4 Distribution of warning pedicle ratios from T4 to L4 in 12 scenario. In any scenario, there was a high percentage of warning pedicles at the thoracic spine except at T7 and T8. **a** The warning pedicle ratio when the direction error is within 10° and the screw length changes from 25 to 40 mm. **b** The warning pedicle ratio when the direction error is within 20° and the screw length changes from 25 to 40 mm. **c** The warning pedicle ratio when the direction error is within 20° and the screw length changes from 25 to 40 mm

Sagittal angle at T5–T12 in the sagittal plane significantly correlated with the *Y*-unit ("anterior–posterior" direction for the spine) of the left pedicle–aorta distance at the apex (-0.44; $p = 0.03$).

Discussion

Liljenqvist et al. [5] measured the distance from the aorta to the vertebral body, and reported that the closest distance averaged 6–7 mm between T4 and T9 and <5 mm between T10 and L4. Sucato and Duchene [11] analyzed the position of the aorta in patients with idiopathic scoliosis in magnetic resonance scans and found that the thoracic aorta in idiopathic scoliosis is positioned more posteriorly and laterally compared with straight spines. From their analysis, the aorta begins to be seen as the aortic arch in front of the T4 vertebral body and changes its position posteriorly and laterally as it descends. The aorta turns back anteriorly and medially at the apical region and passes in front of the T12 through the hiatus of the diaphragm. The present study supports their analyses.

Vaccaro et al. [13] analyzed a non-scoliotic thoracic spine and found that the aorta and the esophagus are at greatest risk of injury when a pedicle screw penetrates an anterior cortex of the vertebral body. Liljenqvist et al. [6] analyzed 22 patients with idiopathic scoliosis by computed tomography postoperatively. They found that 3 of 120 pedicle screws penetrated the anterior vertebral cortex and 1 of these three screws was replaced because of its direct proximity to the thoracic aorta.

When a pedicle screw is placed by a free-hand technique [3] or with a fluoroscope, the direction of placement largely depends on several landmarks of the explored surface of the spine: facet joints, transverse processes and laminae. Our new parameters defined by both sides of superior facet are easy to comprehend in posterior surgery. Additionally, we could compare the relative risk of pedicle screw placement between spine levels in various settings by the sensitivity analysis.

The present study elucidated that the aorta usually stays on the anterior or left-lateral side of the vertebral body at T4, T5 and at T10–T12, and a small breach of a pedicle screw outside the vertebral body at these levels may result in indentation of the aorta. Faro et al. [1] studied the influence of indentation of the aorta by a screw in their bovine model and found that the major impingement of vertebral screws on the aorta caused acute and chronic histopathologic and biomechanical changes in the vessel wall. Though sequelae of moderate to mild indentation of the aorta have not yet been known, screws will stay inside the body for over tens of years in this young population. It is recommended that any screw either in anterior or in posterior surgery be placed away from the aorta.

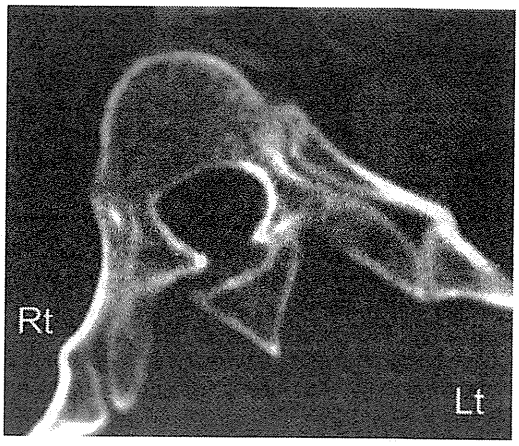

Fig. 5 A case with a typical position of the aorta around the apex level. Though a distance to the left base of the superior facet (an insertion point of a pedicle screw) is closer than other levels, the aorta often resides in the most lateral position from the spine and allows wider maldirection of the pedicle screw

The present study shows that the aorta at the middle thoracic spine is often located away from the spine and resides in front of a left rib (Fig. 5), which leads to a low percentage of dangerous pedicles at T7 and T8. However, in turn, the spinal cord deviates to the left concave pedicles at the apical area at the right thoracic spine [5]. Moreover, the aorta may not stay in the same position. Huitema et al. [2] examined 50 patients by computed tomography or magnetic resonance scans before surgery, and reported that the aorta moves more anteromedially in a prone position than in a supine position especially at levels T5–T10. Their study indicates that the aorta is fairly mobile at the mid-thoracic level when a subject changes his position. Though the present study showed a relative safety of the aorta at T6–T9, the aorta might reside closer to the spine when a subject is at another position. Admittedly, segmental pedicle screw instrumentation is a most powerful construct for correction and maintenance in spinal deformity. Surgeons, however, must be vigilant about the positions of the aorta and the spinal cord in placement of pedicle screws, especially on the left side, and screw breach may necessitate reoperation for replacement.

In summary, new parameters enable surgeons to intuitively understand the position of the aorta in their preoperative planning or during placement of a pedicle screw. When a left pedicle screw perforates an anterior/lateral wall of the vertebral body, the aorta may be at risk, especially at T4, T5 and T10–T12.

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Modified fenestration with restorative spinoplasty for lumbar spinal stenosis

Technical note

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The authors developed an original procedure, modified fenestration with restorative spinoplasty (MFRS) for the treatment of lumbar spinal stenosis. The first step is to cut the spinous process in an L-shape, which is caudally reflected. This procedure allows easy access to the spinal canal, including lateral recesses, and makes it easy to perform a trumpet-style decompression of the nerve roots without violating the facet joints. After the decompression of neural tissues, the spinous process is anatomically restored (spinoplasty). The clinical outcomes at 2 years were evaluated using the Japanese Orthopaedic Association (JOA) scale and patients' satisfaction. Radiological follow-up included radiographs and CT.

Between January 2000 and December 2002, 109 patients with neurogenic intermittent claudication with or without mild spondylolisthesis underwent MFRS. Of these, 101 were followed up for at least 2 years (follow-up rate 93%). The average score on the self-administered JOA scale in 89 patients without comorbidity causing gait disturbance improved from 13.3 preoperatively to 22.9 at 2 years' follow-up. Neurogenic intermittent claudication disappeared in all cases. The patients' assessment of treatment satisfaction was "satisfied" in 74 cases, "slightly satisfied" in 12, "slightly dissatisfied" in 2, and "dissatisfied" in 1 case. In 16 cases (18%), a minimum progression of slippage occurred, but no symptomatic instability or recurrent stenosis was observed. Computed tomography showed that the lateral part of the facet joints was well preserved, and the mean residual ratio was 80%. The MFRS technique produces an adequate and safe decompression of the spinal canal, even in patients with narrow and steep facet joints in whom conventional fenestration is technically demanding. *(DOI: 10.3171/2009.2.SPINE08358)*

Key Words • **decompression surgery** • **laminectomy** • **fenestration** • **lumbar spinal stenosis**

Laminectomy has been the standard surgical treatment for lumbar spinal stenosis (LSS).[20] An advantage of conventional laminectomy is that it provides good visibility and working space by removing posterior elements, including spinous processes and the interspinous-supraspinous ligament complex, which makes possible sufficient decompression. However, resection of the osteoligamentous structure sometimes causes secondary spinal instability.[1,7,14]

Fenestration has been developed to solve this problem of laminectomy.[19] This method, which does not remove the midline osteoligamentous structure, has an advantage in that it preserves spinal stability.[1,20] However, in fenestration, preserved midline structures limit access to the nerve tissues, leading to insufficient decompression in lateral recesses, especially in patients with narrow and steep facet joints.[12] The potential risk for neural injury in a small working space is also a problem.[1,13,20]

Against this background, we have developed an original surgical procedure, "modified fenestration with restorative spinoplasty" (MFRS), which has advantages of both laminectomy and fenestration, 2 major posterior decompression methods. Since 2001, we have used this method in the treatment of patients with symptomatic LSS, excluding patients in whom fusion is recommended, such as those with Meyerding Grade II spondylolisthesis.[9] In this present study, we describe our technique and report clinical results of 2 years of follow-up.

Methods

Patient Population

Patients with LSS accompanied by neurogenic intermittent claudication, in whom conservative therapy for at least 3 months was not effective, were considered to

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Abbreviations used in this paper: JAO = Japanese Orthopaedic Association; MFRS = modified fenestration with restorative spinoplasty; LSS = lumbar spinal stenosis.

be candidates for MFRS. Stenosis was confirmed by MR imaging, myelography, and CT myelography. Patients with LSS who had 1) Meyerding Grade II degenerative spondylolisthesis, 2) degenerative scoliosis with a Cobb angle[2] > 20°, 3) spondylolysis, 4) posttraumatic stenosis, or 5) restenosis after decompression surgery were excluded because they were considered candidates for fusion surgery. Between January 2000 and December 2002, 109 patients with the inclusion criteria underwent MFRS. Of these patients, 101 were followed up for at least 2 years (follow-up rate 93%). Of the 8 patients who were lost to follow-up, 2 died due to lung cancer and heart failure, 3 patients were relocated, and 3 could not be contacted. Of the 101 patients for whom adequate follow-up data were available, 12 patients with gait disturbance due to cerebral infarction, myelopathy, or dementia were excluded from the analysis. These conditions developed during the postoperative follow-up period. The remaining 89 patients constituted the study group.

Surgical Technique

While preserving the supra- and interspinous ligaments, the posterior portion of vertebral arches is exposed, keeping the capsule of the facet as intact as possible. The first step is to cut the spinous process in an L-shape at the proximal one-third using a bone cutter (Fig. 1A). The distal two thirds of the cut spinous process are caudally reflected together with the distal interspinous-supraspinous ligament complex. This procedure creates an ample working space to the spinal canal including lateral recesses and the entry zone of the foramina. Surgeons can perform an adequate decompression of the nerve roots from the opposite side using an osteotome or Kerrison rongeurs and make a trumpet-style decompression of the spinal canal while preserving the cranial parts of the vertebral arches and the lateral parts of the facet joints (Fig. 1B). The same procedure can be repeated when multiple-level decompression is necessary (Fig. 1C). After decompressing the neural tissues, the spinous process is repositioned and reconstructed with tight suturing using polyethylene cable[4] and nonabsorbable suture material (restorative spinoplasty) (Fig. 1D). We first make 2 small holes in the caudal portion of the spinous process. Then, we pass the polyethylene cable around the cranial margin of the residual spinous process and through the holes we made. The split spinous process is approximated by tightening the cable and tying it on the lateral surface. After reconstruction of the spinous process described above, we suture the

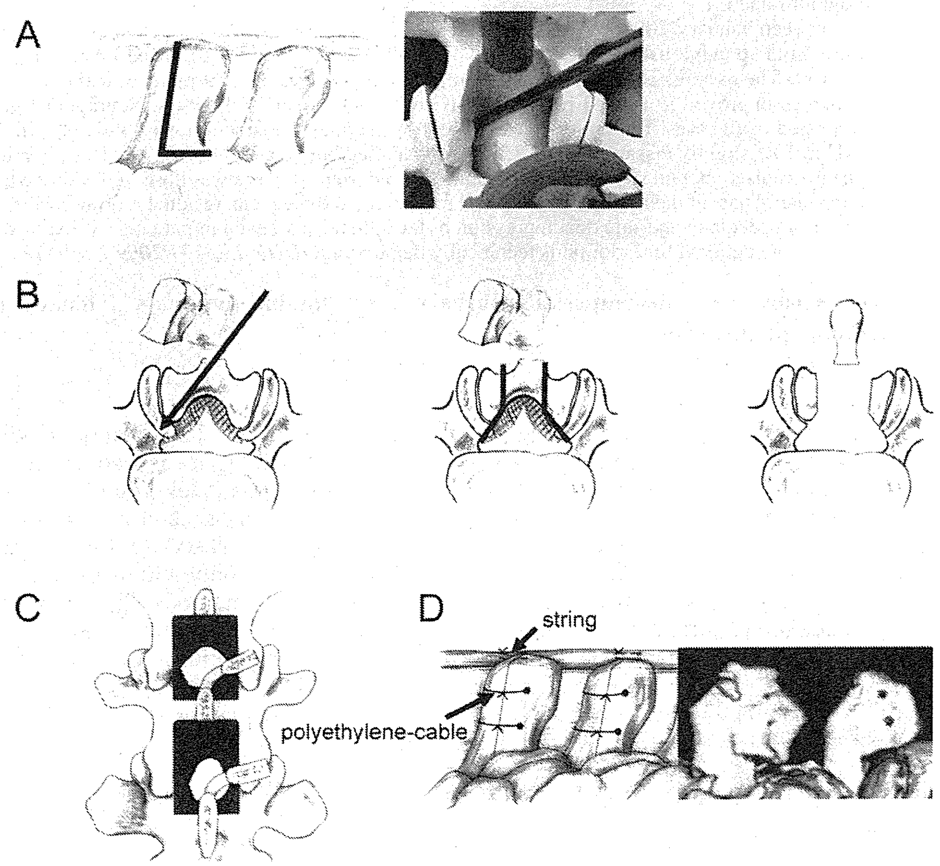

Fig. 1. Illustrations of surgical technique for MFRS. A: Spinous process is cut in an L shape and caudally reflected. B: Temporal spinotomy allows easy access to spinal canal including lateral recesses and makes it easy to perform a trumpet-style decompression. C: Spinotomy and laminotomy can be repeated to make multiple-level decompression. D: After the decompression, the spinous process is repositioned and reconstructed with tight suturing.

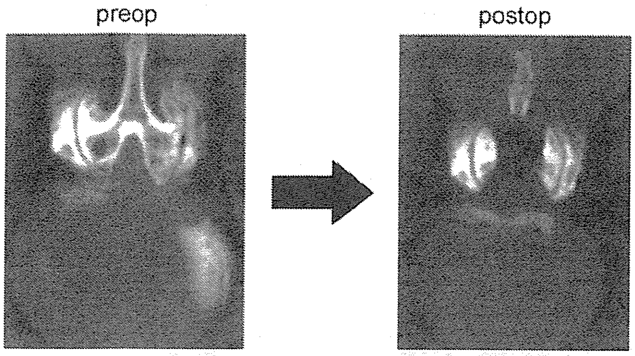

Fig. 2. Preoperative *(left)* and postoperative *(right)* CT scans. *Left:* Preoperative CT shows severe spinal stenosis with narrow and steep facet joints. *Right:* Postoperative CT shows a sufficient trumpeted decompression of the spinal canal with preservation of the facet joints.

supraspinous ligament with a nonabsorbable suture material using the mattress suture technique. Anatomical reduction is achieved between the residual spinous process and the repositioned spinous process. Using this technique, adequate decompression can be performed even in patients with narrow and steep facet joints and/or severe central stenosis in whom sufficient decompression with facet preservation is difficult to achieve by conventional fenestration (Fig. 2).

The patient is allowed to sit up and walk on the 1st or 2nd postoperative day with a soft lumbar support. This support is used for 3 months to prevent excessive flexion of the lumbar spine.

Clinical Outcomes and Radiographic Assessment

The clinical outcomes at 2 years were evaluated using 1) the JOA scoring system (Table 1) with the assessment performed by self-administration[6] and 2) patient satisfaction. Patient satisfaction was evaluated by self-assessment of 4 grades (satisfied, slightly satisfied, slightly dissatisfied, and dissatisfied). Postoperative complications were also investigated.

Radiological follow-up included radiographs and CT scans. To investigate pre- and postoperative radiological findings, we defined degenerative spondylolisthesis as a condition of $> 5\%$ anterior slippage according to the Taillard method,[16] and defined degenerative scoliosis as a condition of the Cobb angle $> 10°$. Shape of the inferior facet was assessed by anteroposterior radiograph and classified according to the system of Tsunoda:[17] X-type, M-type, and W-type (Fig. 3); M-type and W-type were defined as the narrow and steep facet joints.

TABLE 1: Summary of the JOA scoring system, excluding bladder function*

Items	Score
subjective symptoms (9 points)	
low-back pain	
none	3
occasionally mild	2
always present or sometimes severe	1
always severe	0
leg pain &/or numbness	
none	3
occasionally mild	2
always present or sometimes severe	1
always severe	0
walking ability	
normal	3
able to walk >500 m, w/ pain/numbness/weakness present	2
unable to walk 500 m due to pain/numbness/weakness	1
unable to walk 100 m due to pain/numbness/weakness	0
objective signs (6 points)	
SLR	
normal	2
30–70°	1
<30°	0
sensory function	
normal	2
mild disturbance	1
apparent disturbance	0
motor function	
normal (MMT normal)	2
slightly decreased muscle strength (MMT good)	1
marked decreased muscle strength (MMT < fair)	0
restriction of ADL (14 points)†	
none	2
moderate	1
severe	0
total score	29

* ADL = activities of daily living; MMT = manual muscle test; SLR = straight-leg raising.

† Activities of daily living include the following: turning over while lying down, standing, washing one's face, leaning forward, the ability to sit for approximately 1 hour, ability to lift or hold heavy objects, and ambulatory ability.

We measured the segmental sagittal alignment (Fig. 4), the intervertebral range of motion (Fig. 5), and the percentage of slip at the decompressed levels using both pre- and postoperative radiographs, including dynamic views. Postoperative progression of slippage was evaluated at 2-year follow-up; $> 5\%$ increase of slippage was defined as significant progression. Postoperative preservation of the facet was evaluated by a comparison between preoperative CT and postoperative CT performed 1 week after surgery (Fig. 6). The measurement was made at 3 levels of each facet joint: the caudal edge of the upper vertebra, disc level, and the cranial edge of the lower vertebra. The least residual ratio among 3 values for each facet joint was used. Union of the reconstructed spinous process was evaluated by lateral radiograph as follows: Grade 1, os-

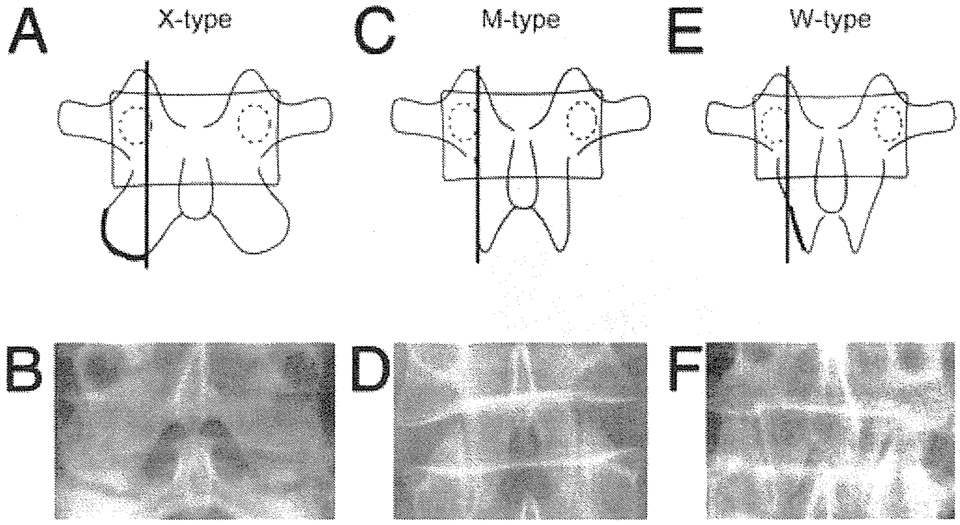

FIG. 3. Schematic drawings and radiographs illustrating the assessment of the shape of inferior facets proposed by Tsunoda. X-type: An outer border of an inferior facet is located outside of a vertical line passing the medial edge of a pedicle. M-type: An outer border of an inferior facet is located on a vertical line passing the medial edge of a pedicle. W-type: An outer border of an inferior facet is located inside of a vertical line passing the medial edge of a pedicle. M-type and W-type were defined as the narrow and steep facet joints.

seous fusion with no opening in the reconstructed area; Grade 2, clear zone of ≤ 1 mm without increase in flexion views; Grade 3, clear zone of > 1 mm, or clear zone with increase in flexion views (Fig. 7). Grades 1 and 2 were defined as union of the spinous process.

Statistical analysis was performed using the paired t-test and chi-square test (SAS version 9.1), with a probability value of 0.05 as the significance level. Related factors for "not fully satisfied" (patient satisfaction) were analyzed using logistic-regression analysis. Univariate and multivariate logistic-regression models were used to estimate ORs and the associated 95% CIs. For "not fully satisfied," the following variables were examined: age ($<$ 75 years/$\geq$ 75 years), sex, number of levels decompressed ($<$ 3 levels/$\geq$ 3 levels), presence or absence of complete block on myelography, presence or absence of preoperative degenerative spondylolisthesis and/or degenerative lumbar scoliosis, preoperative total JOA score ($<$ 10 points/$\geq$ 10 points), presence or absence of preoperative leg numbness at rest, presence or absence of dural tears, presence or absence of postoperative significant progression of slippage, and presence or absence of nonunion of reattached spinous process.

Results

The age at surgery of the 89 patients (56 men, 33 women) was 24–86 years (mean ± SD, 66 ± 11). Types of LSS were as follows: degenerative spondylolisthesis (Meyerding Grade I) in 38 patients, degenerative spondylosis in 23, degenerative scoliosis in 9, combined type with disc herniation in 16, achondroplasia in 2, and hyperostosis in 1. All the patients underwent preoperative myelography; 56 (63%) had severe central stenosis with a complete block on myelography, 66 patients (74%) had cauda equine symptoms and the others had unilateral radicular symptoms. Presence of resting numbness suggesting progressive cauda equina syndrome was observed in 40 patients (45%). Decompression was performed at a single level in 50 patients, 2 levels in 30, 3 levels in 5, and 4 levels in 4. There was no case of intraoperative conversion from the MFRS to laminectomy. The distribution of the types of inferior facet shape was as follows: X-type in 54 segments, M-type in 45 segments, and W-type in 42 segments. Thus, the total percentage of M- and W-type, indicating narrow and steep joints, was 62%.

Neurogenic intermittent claudication improved in all cases after surgery. The overall mean pre- and postoperative JOA scores (± SD) were 13.3 ± 4.1 and 22.9 ± 4.1, respectively. In self-assessment of subjective symptoms in the JOA, the mean preoperative and postoperative scores, respectively, were as follows: low-back pain, 1.4 ± 0.6 and 2.3 ± 0.7; leg pain and/or numbness, 1.0 ± 0.5 and 2.0 ± 0.8; and walking ability, 0.7 ± 0.8 and 2.4 ± 0.8. Scores of each item improved in all cases and the change in scores was statistically significant for each item (Table 2). The patient assessment of satisfaction for the treatment was "satisfied" in 74 cases, "slightly satisfied" in 12, "slightly dissatisfied" in 2, "dissatisfied" in 1. Thus 97% of patients (86 of 89) reported that they were either "satisfied" or "slightly satisfied," and 17% of patients (15 of 89) were not fully satisfied.

As for complications, dural tears occurred in 4 patients (4%); the tears were repaired and needed no additional treatment. Neither nerve root injury nor deterioration of neurological symptoms was observed. In 3 cases in which multilevel decompression was performed, intraoperative insufficiency fracture occurred at the cranial portion of the spinous processes. The spinous processes were successfully reconstructed as follows: we made 2

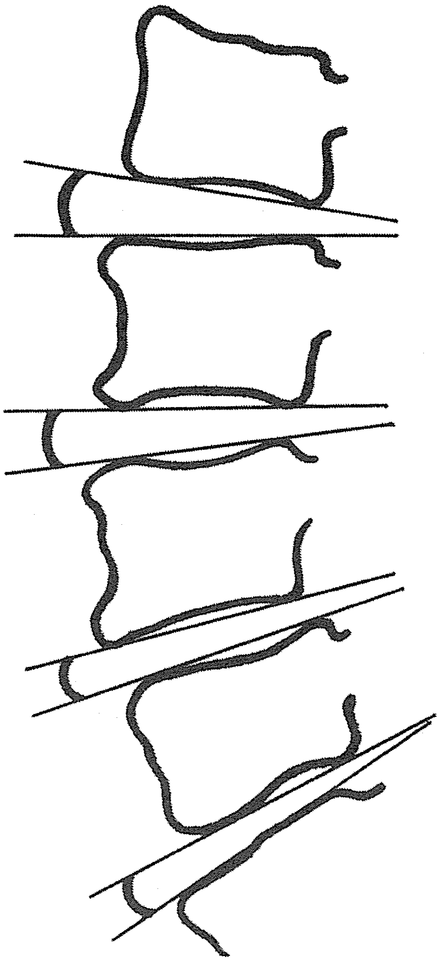

FIG. 4. Schematic illustration of radiographic measurements for segmental sagittal alignment. Segmental sagittal alignment was defined as the angle between the inferior margin of the superior vertebra and the superior margin of the inferior vertebra on neutral position in a lateral radiograph. This angle was measured at each of the levels decompressed.

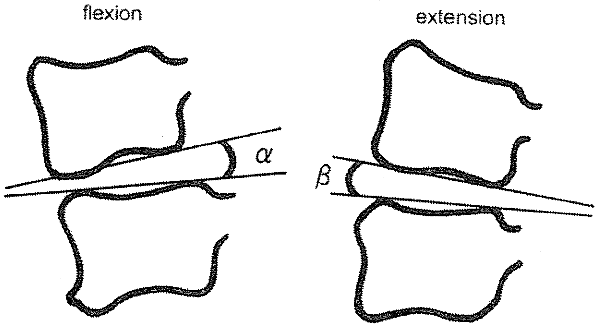

FIG. 5. Schematic illustration of the radiographic measurements for intervertebral range of motion. Intervertebral range of motion was determined on dynamic view as the following: α – (–β).

small holes in the residual lamina, passed a length of nonabsorbable suture material through the holes, and tied it to the supraspinous ligaments. There was one superficial infection, but no deep infection. One patient had pseudomembranous enteritis, which was conservatively treated. During follow-up, lumbar disc herniation at the surgically treated level and compression fracture occurred in one patient each, and both were cured with conservative therapy. During the follow-up period of this study, no patients underwent repeated spinal surgery because of progression of instability, restenosis, adjacent segment degeneration, or other spinal disease.

The mean segmental sagittal alignment of a total of 141 segments was 3.9 ± 3.6° before surgery and 3.7 ± 3.5° at 2 years' follow up ($p < 0.0001$). The mean intervertebral range of motion decreased slightly from 8.1 ± 4.2° to 7.6 ± 4.1° ($p < 0.0001$). The percentage of slippage increased slightly from 4.4 ± 6.7% to 5.8 ± 7% ($p < 0.0001$); in 45 segments with preoperative degenerative spondylolisthesis, it increased from 13.0 ± 5.5% to 15.4 ± 5.9% ($p < 0.0001$). Of the total of 141 segments, 26 (18%) showed radiological progression of slippage, but did not progress

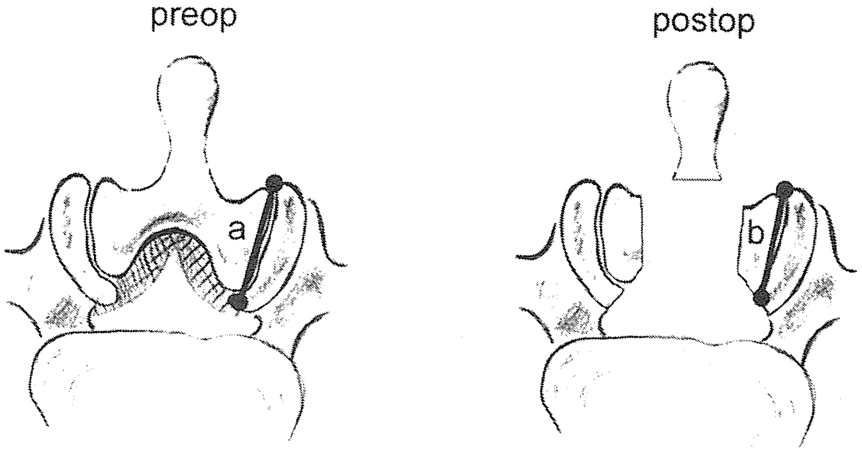

FIG. 6. Illustrations of the radiographic measurements of facet preservation. The residual ratio of the lateral part of a facet joint on CT scans was determined as the following: b/a * 100%

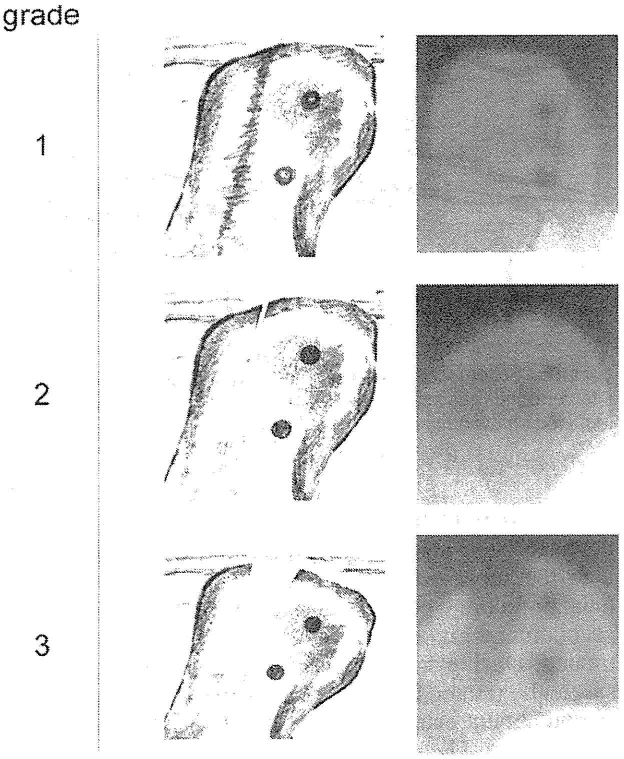

FIG. 7. Evaluation of the union of the reconstructed spinous process on lateral radiographs obtained 2 years after surgery. Grade 1: osseous fusion with no clear zone in the reconstructed area. Grade 2: clear zone opening ≤ 1 mm without increase in flexion views. Grade 3: clear zone > 1 mm, or with increase in flexion views. Grades 1 and 2 were judged as union.

to Grade II and did not need stabilization. Of the 45 segments with preoperative degenerative spondylolisthesis, 8 segments (18%) showed postoperative progression. Of the 96 segments without degenerative spondylolisthesis, 18 (19%) had postoperative progression. There was no statistically significant difference between the 2 groups. On CT, the lateral parts of facet joints were well preserved, and the mean residual ratio was 80 ± 16%. Facetectomy of > 50% was observed only in 6 (4%) of the 141 segments. Union of the reconstructed spinous process was assessed as Grade 1 in 90 segments, Grade 2 in 34, and Grade 3 in 17, and there was no obvious dislodgement requiring repeated surgery. The union rate (percentage assessed at Grades 1 and 2) was 88%. No fracture of the cranial portion of the spinous process occurred, but in 6 of the 17 with Grade 3 union, bone absorption of the caudal fragment was seen.

In the 45 segments with preoperative degenerative spondylolisthesis, the union rate was 87% (39 spinous processes), and in the 96 segments without degenerative spondylolisthesis, the union rate was 89% (85 spinous processes). No statistically significant difference was found between the 2 groups ($p = 0.7499$). In the 26 segments with radiological progression of slippage, the union rate was 77% (20 spinous processes), and in the 115 segments without radiological progression of slippage, the union rate was 90% (104 spinous processes). There were no significant differences between the groups, and nonunion of the spinous process was not a statistically significant cause of progression of slippage ($p = 0.0884$).

Related factors for satisfaction assessment of "not fully satisfied" were analyzed using logistic-regression analysis. No patient in the "not fully satisfied" group had both a dural tear and a nonunion of a reattached spinous process; therefore, an OR could not be calculated, and the final multivariate models excluded these 2 variables. The results of logistic-regression models are shown in Table 3. Preoperative leg numbness at rest was the only significant factor in the univariate model (OR 4.27, 95% CI 1.24–14.69) and in the multivariate models (OR 5.43, 95% CI 1.28–23.08).

Discussion

In the present report, we showed that LSS patients treated with MFRS had good clinical outcomes despite the high rate of a complete block on myelograms and cauda equina symptoms. However, 15 patients (17%) were "not fully satisfied" with their treatment, and the only factor found to have a statistically significant association with satisfaction was preoperative leg numbness at rest. It is generally believed that preoperative resting numbness tends to remain, because it represents irreversible neuronal changes.[5,11] The presence of preoperative degenerative spondylolisthesis and/or degenerative lum-

TABLE 2: Mean preoperative and postoperative JOA scores in 89 patients*

	JOA Score			
Item (score range)	Preop (SD)	Postop (SD)	Change (SE)	p Value†
low-back pain (0–3)	1.4 (0.6)	2.3 (0.7)	0.9 (0.1)	<0.0001
leg pain &/or numbness (0–3)	1.0 (0.5)	2.0 (0.8)	1.0 (0.1)	<0.0001
walking ability (0–3)	0.7 (0.8)	2.4 (0.8)	1.8 (0.1)	<0.0001
objective signs (0–6)	4.5 (1.3)	5.2 (1.0)	0.7 (0.1)	<0.0001
restriction of ADL (0–14)	6.8 (2.3)	10.9 (2.2)	4.1 (0.3)	<0.0001
total score (0–29)	13.3 (4.1)	22.9 (4.1)	9.6 (0.5)	<0.0001

* SD = standard deviation; SE = standard error.
† Determined by means of paired t-test.

TABLE 3: Univariate and multivariate logistic regression models of patient satisfaction for "not fully satisfied"*

Variable	Univariate		Multivariate	
	OR	95% CI	OR	95% CI
age (≥75 years)	0.61	0.12–2.98	0.41	0.06–2.74
sex (female)	0.37	0.10–1.41	0.29	0.07–1.30
no. of levels decompressed (≥3 levels)	2.83	0.62–12.90	2.61	0.44–15.50
complete block on myelography	0.86	0.28–2.68	0.60	0.13–2.79
preop DS and/or DLS	1.42	0.46–4.40	1.90	0.48–7.58
preop total JOA score (<10 points)	2.58	0.75–8.92	1.69	0.38–7.50
preop leg numbness at rest	4.27	1.24–14.69	5.43	1.28–23.08
significant progression of slippage	0.28	0.03–2.31	0.17	0.02–1.62

* Data were calculated by logistic regression analysis on 89 patients. Abbreviations: DS = degenerative spondylolisthesis; DLS = degenerative lumber scoliosis.

bar scoliosis, postoperative progression of slippage, and nonunion of reattached spinous processes did not have a major impact on patient satisfaction.

The occurrence of postoperative instability and restenosis has been considered a disadvantage of laminectomy. Robertson et al.[14] reported that 58% of 33 patients, including 11 with preoperative spondylolisthesis, experienced progression of more than 5% slippage 1 year after laminectomy. Johnsson et al.[7] reported that slippage of more than 2 mm (equivalent to 5%) was observed in 43% of 36 patients more than 1 year after laminectomy and that preoperative spondylolisthesis was a risk factor for progression of listhesis. In the MFRS method, radiological studies performed 2 years postoperatively showed > 5% slippage in 18% of patients, but none required surgical stabilization for secondary instability. The occurrence of slippage progression was the same in the segments with or without preoperative degenerative spondylolisthesis. (The presence or absence of preoperative spondylolisthesis did not influence the occurrence rate of postoperative progression of slippage.) Even in patients with degenerative spondylolisthesis of Grade I, there was no occurrence of symptomatic instability after MFRS.

To overcome the disadvantage of laminectomy, the fenestration technique has been developed.[10,19] Fenestration allows preservation of the spinous process and supra- and interspinous ligaments, but these retained midline structures limit visualization and access to the lateral recesses, especially in patients with severe central stenosis or narrow and steep facet joints.[12,13] The rate of intraoperative conversion from fenestration to laminectomy has not been well documented and the postoperative evaluation of residual facet joints has not been reported. Unilateral laminotomy through one side, another treatment option, seems to limit access to the ipsilateral lateral recess.[3] The MFRS is applicable for any type of narrow facet, as was confirmed by postoperative CT scan; in this study, it provided the same visibility as laminectomy, and intraoperative complications were minimal.

Other techniques of spinous process osteotomies to facilitate decompression have been reported,[8,15,18] but in these techniques, osteotomized spinous processes were not tightly reconstructed to ensure stability of the spinous process. A key characteristic of our technique is an anatomical restoration of the spinous process that provides continuity with the vertebral arch.

Nevertheless, there remain several problems to be solved in this method. The union rate of reconstructed spinous processes was high in our study, but not perfect. The polyethylene cable has the potential to stretch with the passage of time and to cause a loosening of the fixation.[4] There is still room for improvement in the material and/or technique of restorative spinoplasty in order to achieve a perfect union rate. In this study, insufficiency fracture at the cranial portion of the spinous process occurred in 3 patients with multiple lesions during decompression. Careful maneuvering of the residual spinous process is essential in patients with osteoporosis and multiple lesions. One of the limitations of the present study is that this is not comparative. The benefits of spinal instrumentation for LSS with or without mild listhesis have been controversial. A comparative study and long-term follow-up are necessary to establish true indications for MFRS.

Conclusions

Modified fenestration with restorative spinoplasty, which has advantages of both laminectomy and fenestration, provides a safe and adequate decompression of the spinal canal with preservation of the posterior elements. The 2-year outcomes as determined by patient self-assessment were satisfactory.

Disclaimer

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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Diameter, Length, and Direction of Pedicle Screws for Scoliotic Spine

Analysis by Multiplanar Reconstruction of Computed Tomography

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Study Design. A morphometric study of thoracic and lumbar spine in scoliosis.

Objective. The purpose of the present study was to evaluate the appropriate values of diameter, length, and direction of pedicle screws with a straightforward trajectory in scoliosis.

Summary of Background Data. Several authors have analyzed the pedicle shape and evaluated the feasibility of pedicle screws in the scoliotic spine. To date, however, none of them have reported analysis by multiplanar reconstruction of computed tomography.

Methods. Computed tomography with a thickness of 1.25 mm was obtained before surgery in 41 Japanese with scoliosis. A total of 1100 pedicles were evaluated by simulating screw placement with the straightforward approach in a multiplanar reconstruction image. We chose the optimal slice where the insertion point and direction were determined to get the largest diameter of a screw in every vertebra. Length from the insertion point to the tip of the simulated screw was measured.

Results. Screws of L1 and L2 were significantly smaller than those of T12 and L3 ($P < 0.001$). On the concave side, 37% of T3–T9 pedicles did not accept a 4-mm diameter screw even with 25% expansion. Length on the convex side was shorter at T5 and T7–T9 than that on the concave side ($P < 0.05$). On the convex side, 11% at T4–T8 vertebrae did not accept a 25-mm length screw. Average angle of screws of T1, T2, and L5 was greater than 15° and 17% of the screws at T7–T10 were placed in the lateral direction.

Conclusion. In T3–T9 on the concave side, pedicle screws with a straightforward trajectory are not held within 37% of pedicles even with plastic deformation. We recommend that surgeons consider combined use of various types of anchoring when preoperative evaluation reveals narrow pedicles for screw placement.

Key words: scoliosis, pedicle screw, multiplanar reconstruction, computed tomography. **Spine 2009;34:798–803**

Pedicle screws are now the dominant anchorage in posterior instrumentation. It is preferred that they are placed inside vertebrae for the safety of vital tissues around the spine. Several authors analyzed the pedicle shape and evaluated the feasibility of pedicle screws in the thoracic spine.[1–5]

Tilting and rotation of the scoliotic spine hinder surgeons from understanding its precise shape. Computed tomography (CT) scan is an ideal technique, but a gantry can be aligned only in the sagittal plane and not in the frontal plane. Therefore, all vertebrae except the apical ones are transected obliquely. A tilt of over 10° in the coronal plane resulted in the inaccurate measurement of the pedicle diameter in scoliosis.[6] Acquisition volumes of magnetic resonance imaging (MRI) can be adapted to an individual spinal curvature and 2 investigators adopted MRI to analyze the morphometry of pedicles in scoliosis.[1,3] However, MRI depicts cortical structures with less clarity and precision. CT with multiplanar reconstruction enables investigators to set an arbitrary gantry in any plane for each vertebra and to analyze a clear bony shape. To date, however, no researcher has morphometrically analyzed the scoliotic spine by multiplanar reconstruction of CT.

Purpose

The purpose of the present study was to evaluate the appropriate values of diameter, length, and direction of pedicle screws with a straightforward technique in scoliosis from analysis of multiplanar reconstruction of CT.

Materials and Methods

Forty-one Japanese with scoliosis were recruited: the condition was idiopathic in 23 patients, Chiari malformation in 5, Noonan syndrome in 1, tuberous sclerosis in 1, and multiple epiphyseal dysplasia in 1. There were 34 women and 7 men with an average age of 17.4 years (10–29 years). The Cobb angle of the main curve ranged 50° to 100° (average, 65.7°). Curve classification by Lenke *et al*[7] was type 1 in 13 patients, type 2 in 11, type 3 in 2, type 4 in 4, type 5 in 4, and type 6 in 7. Proximal or cephalad fractional curves at the thoracic spine were right-convex in 2 curves and left-convex in 26. Main thoracic curves were right-convex in 33 and left-convex in 5. Thoracolumbar/lumbar or caudal fractional curves were right-convex in 6 and left-convex in 34.

Preoperative CT with a slice thickness of 1.25 mm was obtained for computer-assisted surgery. All CT files were transferred to a personal computer and analyzed by a DICOM viewer program (ExaView LITE: Ziosoft, Tokyo, Japan). All parameters were measured by the first author (K.T.) who exclusively handles DICOM files for navigation surgery in scoliosis at the University of Tokyo Hospital. Window level and diameter were optimized for the measurement of bony struc-

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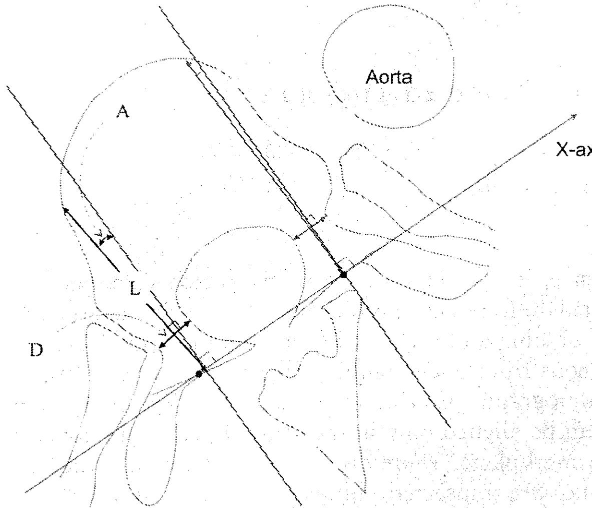

Figure 1. Diameter (D), length (L), and angle (A) of simulated pedicle screws in a transverse plane. The abscissa-axis is determined by connecting both of the middle points of the superior facet base. Diameter is set to obtain the largest value among multiple true-orthogonal axial images in individual vertebra.

ture. Among various techniques available for pedicle screw placement, we chose the straightforward technique because of its prevalence and its biomechanical superiority over the anatomic technique.[8] Three parameters of diameter, length, and angle on both sides of a pedicle were measured in a true-orthogonal image of each vertebra. We chose the optimal slice where an insertion point and direction were determined to get the largest diameter of a screw in every vertebra. We measured diameter in the transverse plane (Figure 1) as well as diameter in the coronal plane at the outer cortex of a pedicle. Shorter one was adopted. Length from the insertion point to the tip of the simulated screw was measured. For description of the angle, we defined a new Cartesian coordinate system. A line connecting both sides of the middle of the superior facet base was defined as the abscissa-axis. Angle was measured with reference to the ordinate-axis, with a positive value when a screw was aimed at the vertebral body.

We analyzed 1100 pedicles from T1 to L5 vertebrae after excluding those pedicles outside the curves. Each parameter at 1 side was compared with a value on the contralateral side. Statistic analysis was performed with unpaired *t* test. Difference was regarded as significant when a value was below $P = 0.05$. Intraobserver and interobserver interclass correlation coefficients (ICCs) in 3 parameters were calculated in 30 vertebrae of 2 patients.

Results

Diameter

All screws except a few in T1 and L5 had shorter diameter in the axial image than in the coronal image (Table 1). Diameter of the screws decreased in the middle thoracic spine. Screws of L1 and L2 were significantly smaller than those of T12 and L3 ($P < 0.001$). The diameter of T2–T10 on the concave side was significantly shorter than that on the convex side ($P < 0.01$) (Figure 2). Sixty-two percent of the concave T3–T9 screws were less than 4 mm and 37% did not hold a 4-mm diameter screw even with 25% expansion (4.0/1.25 = 3.2 mm) (Figure 3). Our data indicates that pedicles of right T3–T5 in the proximal thoracic curve and those of left T4–T9 in the main thoracic curve do not hold a 4-mm diameter screw in a typical right thoracic curve. Diameter of the screw at the main curve did not correlate with the Cobb angle nor with a patient's age (correlation coefficient, 0.039; $P = 0.82$, 0.13; $P = 0.55$).

Table 1. Diameter of Pedicle Screws (From the Outer Cortex of Pedicles)

	T1	T2	T3	T4	T5	T6	T7	T8	T9
Concave									
Mean	6.0	4.9	3.3	2.7	3.0	3.5	3.7	3.8	4.1
SD	1.1	1.0	1.3	1.1	1.2	1.1	1.1	1.2	1.3
Min	4.1	3.3	0.5	0.8	0.6	1.4	1.6	1.4	1.8
Max	7.9	6.5	5.7	4.4	5.0	6.7	6.7	6.3	7.2
N	24	28	30	32	33	34	35	36	37
Convex									
Mean	6.3	5.5	4.7	4.3	4.5	4.4	4.6	4.6	4.9
SD	0.9	0.9	0.9	0.9	0.8	1.0	0.8	0.8	1.0
Min	4.6	3.8	2.8	2.4	3.0	2.3	2.7	2.3	3.3
Max	8.8	7.0	6.2	6.0	7.2	7.0	6.1	5.9	8.2

	T10	T11	T12	L1	L2	L3	L4	L5
Concave								
Mean	5.2	6.7	6.8	5.8	6.3	7.8	9.0	9.1
SD	1.2	1.4	1.5	2.0	1.7	1.3	1.3	1.0
Min	2.9	3.7	3.8	2.6	3.3	5.7	6.9	7.3
Max	7.8	8.9	10.0	10.9	11.5	10.8	11.5	10.5
N	39	40	40	41	36	32	22	11
Convex								
Mean	6.0	7.2	7.1	5.6	5.9	7.4	8.7	10.0
SD	1.2	1.8	1.6	1.5	1.4	1.3	1.8	1.5
Min	3.6	3.6	2.3	3.2	2.5	3.9	5.6	8.1
Max	8.4	11.0	10.0	9.8	8.6	10.1	12.2	12.1

SD indicates standard deviation; min, minimum value; max, maximum value.

Length

Length of screws decreased at the middle thoracic spine as shown in Table 2. All but 1 vertebra accepted a 20-mm length screw. Eleven percent of T4–T8 vertebrae on the convex side required screws shorter than 25 mm. The length required on the convex side were shorter at T5 and T7–T9 than that on the concave side ($P < 0.05$) (Figure 4).

Angle

Screws were aimed in the medial direction in the upper thoracic and lower lumbar spine (Table 3) and the average angle of screws of T1, T2, and L5 was greater than 15°. Seventeen percent of screws at T7–T10 were aimed in the lateral direction (Figure 5). Angles on the concave side did not significantly differ from those on the convex side ($P = 0.08$).

ICC of diameter was 0.957 (2-sided 95% confidence interval: 0.929–0.974) in the intraobserver measurement and 0.929 (0.864–0.961) in the interobserver measurement. ICCs of length and angle were 0.936 (0.895–0.961) and 0.922 (0.972–0.952) in the intraobserver measurement and 0.932 (0.889–0.959) and 0.896 (0.829–0.937) in the interobserver measurement.

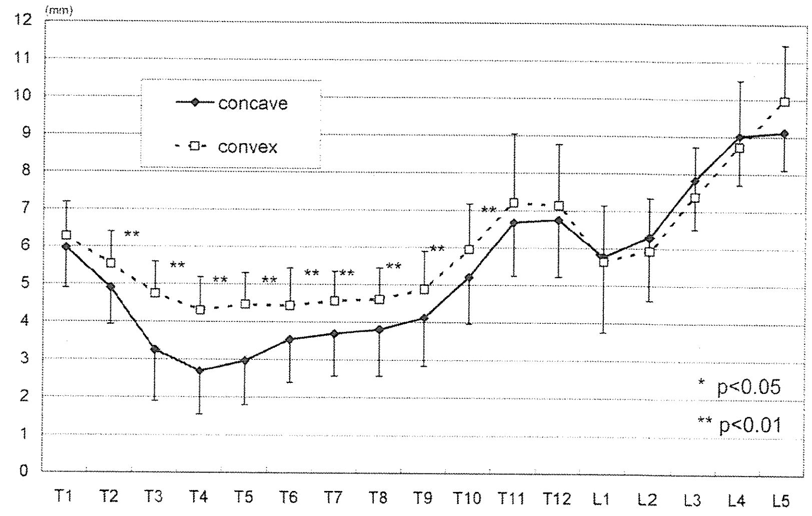

Figure 2. Diameter of pedicle screws.

Discussion

MRI Versus *CT*

Liljenqvist *et al* reported 2 fine analyses of pedicle morphology with scoliosis and revealed smaller pedicles on the concave side. In their CT study,[2] tilt of an individual vertebra was partially resolved by sagittal tilting of gantry in 29 patients with idiopathic scoliosis. Liljenqvist *et al* did not adopt multiplanar reconstruction because the 3-mm interval was too large and reconstruction processing would result in an inaccurate value. In the present study, CT data were obtained with a diameter of 1.25 mm for the navigation surgery in which the accuracy and measurement of MPR images are guaranteed. Second, Liljenqvist *et al* analyzed a pedicle shape in 26 patients using MRI which compensated the tilting in scoliosis.[3] Concurrently, an inherent issue of analyzing bony structures by MRI emerged.

Both of the Liljenqvist's studies measured the inner cortical width of a pedicle; we chose to measure the outer width for 2 reasons. One was ease of measurement because of the clearer border of the outer cortex. Especially in a thin pedicle, the inner surface of the cortex was obscure even in CT. That may be the reason for disagreement at the upper thoracic spine between the present study and Liljenqvist's MRI study, though the outer cortical diameter in the present study largely agreed with the inner cortical diameter in 2 reports of Liljenqvist. Second is an elastic characteristic of a pedicle.[5,9,10] We agree with O'Brien *et als* suggestion[5] of measuring the outside pedicle dimension by taking plastic deformation into account.

Diameter

Our present data suggested that a large proportion of thoracic pedicles on the concave side were too small to accept the 4-mm diameter screw. Even if a pedicle allows 25% enlargement as Rinella *et al* reported,[9] the outer diameter should be over 3.2 (=4.0/1.25) mm. The present data suggests that 37% (88/237) of concave T3–T9 pedicles will be fractured if a screw for the thoracic spine is placed in them.

One possible solution may be to use the anatomic trajectory, although a screw placed by the anatomic trajectory is biomechanically weaker than one placed by the straightforward trajectory.[8] Moreover, the screw-head

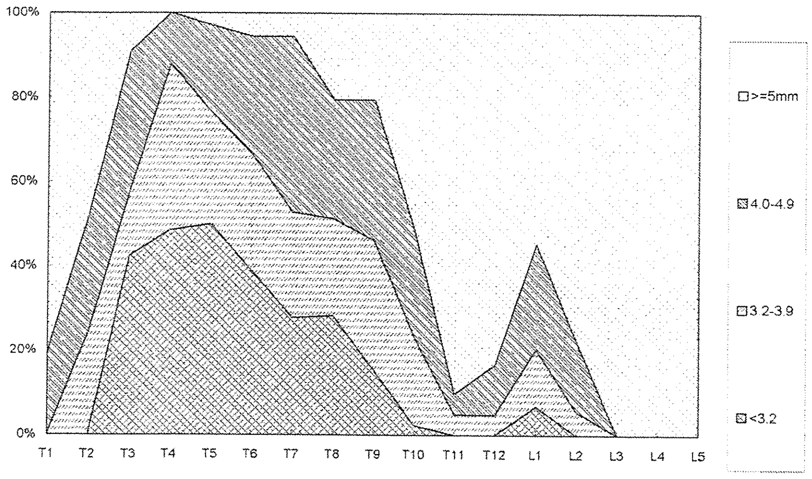

Figure 3. Bimodal distribution of diameter of pedicle screws on the concave side.

Table 2. Length of Pedicle Screws

	T1	T2	T3	T4	T5	T6	T7	T8	T9
Concave									
Mean	28.5	30.4	30.5	30.5	31.6	31.7	32.5	33.9	34.0
SD	3.3	3.5	3.8	4.2	4.3	3.5	3.5	4.7	4.6
Min	22.9	24.0	23.3	21.3	25.0	25.2	25.8	26.2	22.0
Max	35.0	37.4	42.8	41.3	40.3	40.8	40.9	51.6	41.8
Convex									
Mean	29.2	30.7	30.3	29.4	29.0	30.2	29.9	30.2	31.6
SD	2.9	2.8	3.1	3.2	3.7	4.0	5.0	4.3	4.3
Min	23.6	24.5	22.4	21.8	21.2	22.4	19.1	23.0	23.3
Max	34.7	37.2	37.1	35.7	36.7	40.9	43.3	38.8	40.1

	T10	T11	T12	L1	L2	L3	L4	L5
Concave								
Mean	35.1	35.2	37.2	42.6	44.6	45.6	44.8	43.5
SD	4.1	3.6	4.0	4.5	5.2	3.9	3.9	6.1
Min	26.4	28.7	29.4	32.8	33.3	38.2	37.4	34.1
Max	43.8	48.5	46.9	53.4	59.1	54.0	52.4	52.7
Convex								
Mean	33.4	33.6	36.1	41.8	44.4	45.7	43.8	44.7
SD	3.8	5.6	4.6	4.8	5.1	3.8	3.5	4.9
Min	24.6	21.5	27.9	32.8	24.0	38.9	37.1	37.8
Max	41.6	51.7	50.5	54.9	54.5	53.2	49.9	51.5

Table 3. Direction of Pedicle Screws

	T1	T2	T3	T4	T5	T6	T7	T8	T9
Concave									
Mean	27.1	17.4	13.5	8.4	7.1	4.0	4.3	4.6	4.0
SD	5.8	5.8	3.8	6.2	5.5	5.2	5.0	5.5	5.4
Min	17.0	7.0	7.0	−9.0	−7.0	−10.0	−4.0	−4.0	−10.0
Max	39.0	36.0	20.0	18.0	17.0	16.0	14.0	15.0	16.0
Convex									
Mean	26.9	17.3	9.4	7.1	5.2	5.0	3.3	2.2	4.4
SD	4.8	4.1	4.1	4.0	4.8	5.1	4.9	4.8	6.1
Min	17.0	9.0	0.0	0.0	−4.0	−8.0	−7.0	−9.0	−10.0
Max	36.0	27.0	17.0	15.0	14.0	16.0	13.0	9.0	13.0

	T10	T11	T12	L1	L2	L3	L4	L5
Concave								
Mean	5.8	6.3	4.6	7.9	10.6	13.1	15.1	24.5
SD	5.7	4.8	4.7	5.0	3.6	4.8	4.5	10.1
Min	−12.0	−5.0	−3.0	−5.0	3.0	4.0	4.0	11.0
Max	19.0	18.0	20.0	18.0	19.0	22.0	23.0	42.0
Convex								
Mean	3.7	4.9	5.8	8.0	9.7	13.6	14.8	22.5
SD	5.0	5.1	6.5	5.4	5.0	4.3	4.1	12.3
Min	−10.0	−8.0	−15.0	−5.0	−4.0	2.0	9.0	0.0
Max	13.0	15.0	17.0	21.0	18.0	20.0	25.0	38.0

needs to be tilted for rod settlement and a multiaxial screw with a relative large head is mandatory. From our experience of 50 scoliosis surgeries done using the navigation system, pedicles too narrow for the straightforward technique were usually impracticable even with the anatomic technique. We did not try to simulate the anatomic trajectory because simulation of screw placement would have been too complicated. Future analysis of feasibility of using the anatomic trajectory is warranted.

Another solution might be to use the in-out-in technique. However, pull-out testing showed the extrapedicular screw had inferior pull-out strength compared with a transpedicular screw,[11] and the authors are doubtful of its strength and safety when a lateral force is exerted especially on the concave midthoracic side.

Though powerful correction force and maintenance by segmental pedicle screw instrumentation is very fascinating, surgeons need not to always use pedicle screws but can use other anchoring methods like hooks and wires when preoperative evaluation reveals narrow pedicles which are not appropriate for pedicle screw placement.

Length and Direction

Inappropriate length or direction of a pedicle screw can be more hazardous than inappropriate diameter. A screw directed too medially can put the spinal cord in jeopardy. A screw advanced too anteriorly or too laterally poses a potential risk of aorta injury. Vaccaro *et al* analyzed nonscoliotic thoracic spine and found that the aorta and the esophagus are at greatest risk of injury when a pedicle screw penetrates an anterior cortex of the vertebral body.[4] The present study showed 11% of the T4–T8 vertebrae did not accept a 25-mm length screw on the convex side. Though the middle thoracic vertebrae ac-

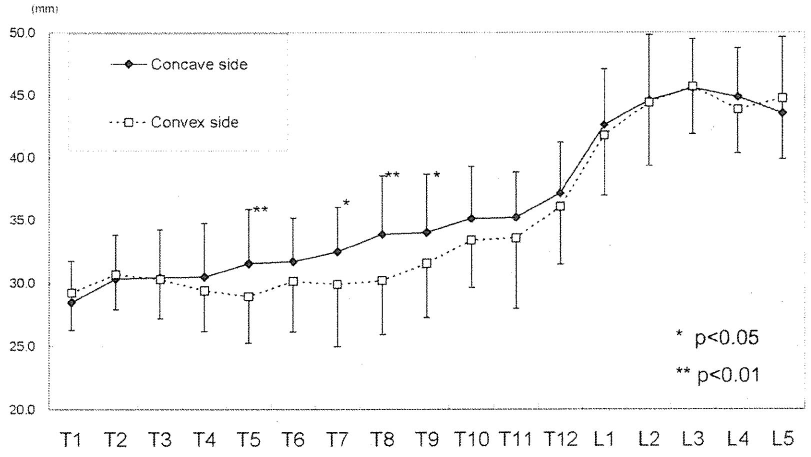

Figure 4. Length of pedicle screws.

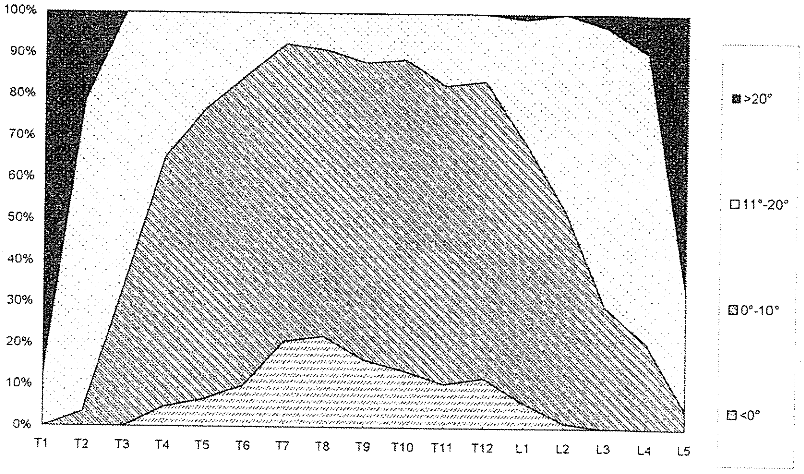

Figure 5. Distribution of angle of pedicle screws. Angle shows lowest value at T7–T8.

cept screws of this length, the aorta usually resides just lateral of the vertebral body on the left side.[12] Considering the lateral force exerted during a correction maneuver, special attention should be given to place screws on the concave side.

We designed a new abscissa-axis with which surgeons can estimate the direction from the explored spine in posterior surgery. The present study showed that 23% of screws at T7–T8 aimed in a lateral direction on the convex side from the perspective of the posterior spine. Large lateral tilt at T1–T2 pedicles in the present study suggested that multiaxial screws seem practical for smooth connection with adjacent screws.

Limitation

ICCs of length and angle were smaller than that of diameter in the repeatability test. As shown in a report of a funnel technique by Yingsakmonkol *et al*,[13] length and direction of a pedicle screw sometimes allows a range of values. Length may differ by several millimeters depending on selection of the insertion points because some of these points are determined at the base of a pedicle, and some at the transverse process. Because we wanted to simulate the same-screw placement as we actually use the navigation system, a more consistent method of measurement had not been considered.

Radiation Exposure by CT

Projected exposure dose by 1 CT is estimated to be 30 mGy in our university hospital. Our experience of pedicle screw placement with a navigation system by preoperative CT substantially decreased screw breach from 7% by free-hand technique to 2%. We believe that reduction of screw breach by the navigation system overweighs the additional exposure for patients.

In summary, 37% of T3–T9 concave pedicles were too small for a 4-mm diameter screw even with 25% expansion. At the middle thoracic spine on the concave side, the direction and length of a pedicle must be carefully determined. We recommend that surgeons consider combined use of various anchoring when preoperative evaluation reveals that pedicles are narrow for screw placement.

■ Key Points

- We evaluated appropriate diameter, length, and direction of pedicle screws in patients with scoliosis by multiplanar reconstruction of CT.
- Thirty-seven percent of pedicles at T3–T9 on the concave side were too small for a 4-mm diameter screw even with expansion.
- Eleven percent of pedicle screws at T4–T8 on the convex side were less than 25 mm in length and 17% of screws at T7–T10 were placed in the lateral direction.
- Surgeons should not use pedicle screws when preoperative evaluation reveals that pedicles are too narrow for proper screw placement.

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研究成果の刊行に関する一覧表

【H21. 4. 1～H24. 3. 31】

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内科医のための腰部脊柱管狭窄症の必須知識　（概　念）

2．腰椎の臨床解剖

田口　敏彦*
（たぐち　としひこ）

- 腰痛を理解するための腰椎部の臨床解剖について述べる．
- 頸椎，腰椎の前弯は立位になるために生後獲得された形態である．
- 脊柱は，おおよそ30度の傾きのある骨盤の上に立っている．
- 腹筋は，腹腔は硬いラグビーボールのようにして腰椎を前方から支える．
- 腰椎椎間関節は滑膜を有する真の意味での関節で，機械的なストレスを受けやすく，急性腰痛の原因になりやすい．また一方では炎症性変化や変形性変化もきたし，慢性腰痛の原因にもなりやすい．
- 椎間板は，加齢とともに，ショックアブソーバーとしての機能は低下し，遊びの動きが出てくる．これが椎体骨棘の成因になったり，椎間関節の変形性変化を生じさせ，腰部脊柱管狭窄症の原因になる．

Key Words　腰椎，解剖，椎間板，椎間関節，腰痛，腰部脊柱管狭窄症

厚労省の毎年の発表を待たずとも，腰痛はいつも日本人のcommon symptomの3大症状の1つに挙げられている．臨床上，腰部脊柱管狭窄症に限らず，腰痛を訴える患者に対して，その病態や治療を考えるうえで，腰椎部の基本的な解剖を知っておくことはきわめて大切である．本稿では，腰痛を理解するための腰椎部の臨床解剖について述べる．

□ 脊椎の形態

成人の脊椎は，側面からみると，頸椎が前弯，胸椎が後弯，腰椎が前弯となっている（図1-d）．しかし，頸椎や腰椎の前弯は後天的に得られたカーブであり，胎生期には脊椎全体は，後弯を呈している（図1-a）．生後3〜4ヵ月の頸定のころになると首を伸展させ頭の重量を支えるために，頸椎の前弯が形成される（図1-b）．また，生後10ヵ月ごろに，つかまり立ちし立位をとるころになると腰椎の前弯が形成される．その結果として，

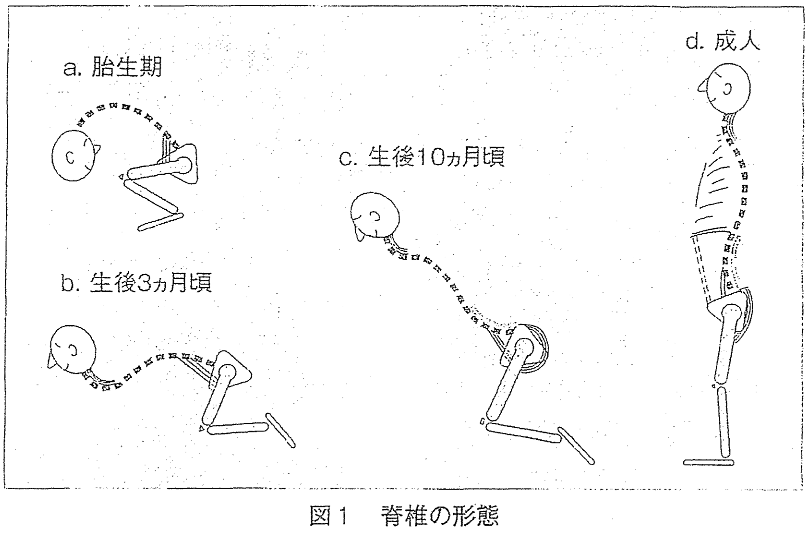

図1　脊椎の形態

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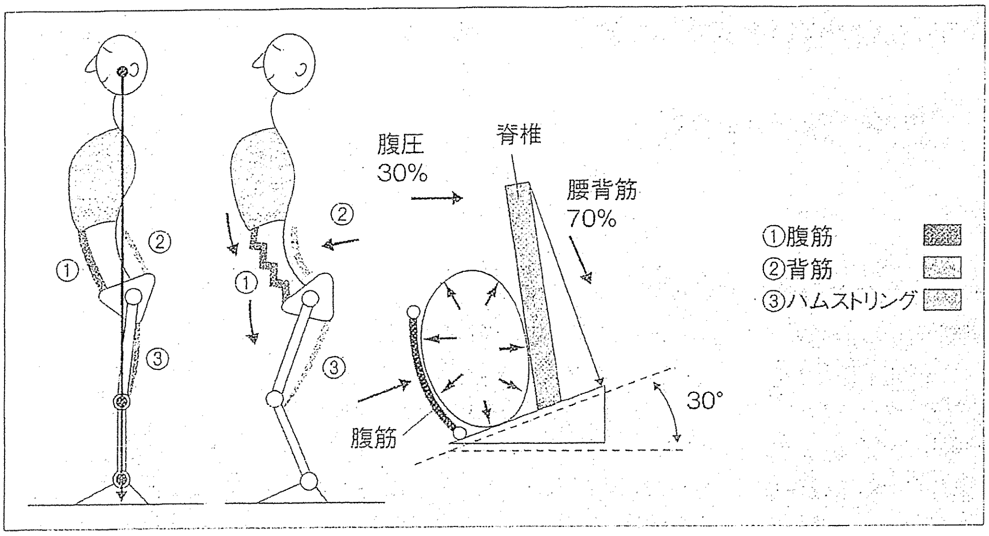

図2　脊椎と筋肉バランス

全体では頸椎前弯，胸椎後弯，腰椎前弯の形態をとる（図1-c）．したがって，もともとあった脊椎の形態は胸椎部の後弯に残っているのみで，頸椎，腰椎の前弯は立位になるために生後獲得された形態である．垂直方向の荷重を受けるにも，また立位を保持するにもこのカーブが力学的に有利といわれている[1]．

しかし，人が立位を保持できるためには，さらに脊柱が骨盤の上に立つ必要がある．脊柱は水平な骨盤の上に立っているのではなく，おおよそ30度の傾きのある骨盤の上に立っている（図2）．これは進化の過程で特に設計変形することなく4足歩行から2足歩行に変わったためといわれている．たとえれば，スキー場で30度の斜面といえば，かなりの急斜面である．脊柱はそのような急斜面の上で上半身を支えることになる．

脊柱が垂直に立ち，姿勢を保持するためには図2のような筋肉のバランスの上に成り立っている．すなわち脊柱は腹筋，背筋，大腿後面のハムストリングスで支えられている．腹筋は直接腰椎を支えるというのではなく，腹腔を介して腰椎を前方から支えることになる．したがって，この腹筋をしっかりさせることで腹腔は硬いラグビーボールのようになり腰椎を前方から支えてくれるようになる．腹筋が緩んでくると，このラグビーボールは柔らかくなり，腰椎は前方からの支えをなくすことになる．その結果，背筋の負担が大きくなり，腰痛の原因となる．腰痛の予防に腹筋を鍛える理由はここにある．また，腰部の軟性コルセットの役割は，腰部の固定というよりは，腹筋を補助することで腹腔を硬いラグビーボールのようにして腰椎を前から支えるためである．

□ 腰椎の骨・関節

腰椎は5つの椎骨からなり，そのそれぞれは椎間板と左右1対の椎間関節によってつながっている（図3）．

腰椎は，頸・胸椎に比較して横突起，棘突起が大きく突出しており，椎骨全体の表面積を大きくし，多くの大きな筋肉が付着しやすい構造になっている．

腰椎椎間関節は滑膜関節であり，関節面は硝子軟骨よりなり，滑膜と関節包に包まれる．関節内にはmeniscoidもみられ，真の意味での関節を形成している[2]．したがって椎間関節は機械的なストレスを受けやすく，急性腰痛の原因になりやすい．また一方では炎症性変化や変形性変化もきたし，慢性腰痛の原因にもなりやすい．

椎間関節の機械的な特性としては，椎体間の動きを制限することと，軸方向の荷重を受けることである．腰椎を後屈位にすると，体軸方向の荷重は椎間板で約80%，椎間関節で約20%がかかる構造になっている．脊椎に変性があると70%ぐらいまでの荷重を受けるようになるといわれてお